CLIMATE CHANGE SOLUTIONS

V. RAMANATHAN
(Editor)

BENDING THE CURVE

ADAM MILLARD-BALL (Co-editor)
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About the Cover

The Age of Humans and Climate Disruption We are living in the age of humans, and there is no denying that the technologies innovated by *Homo sapiens* have turned us into a major geologic force. The resulting modification of the land, the oceans, and the atmosphere has poisoned our bodies, imperiled our environment, and disrupted the planet's climate. The composite image on the cover acknowledges the inextricable link that humans have with our planet. To solve the imminent problem of climate disruption, human beings have to realize that we all belong to the same *Homo sapiens* species. We must work together for the common good since the problems we face require global solutions. Think local, to protect your family and community, but act global. This is the spirit of the book you are about to read. It describes how the climate change problem can still be solved.

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V. RAMANATHAN (Editor)

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FOREWORD

Climate change is among the most urgent risks we face in the twenty-first century. Across the globe, natural disasters are becoming more prevalent and weather patterns are turning more volatile. We're witnessing an increase in wildfires, rising sea levels, and the extinction of plants and animals. Accelerating changes in our climate are affecting everything from disease management and food security to immigration patterns and water resources.

These developments impact not only our natural environment, but also our economy, our national security, and our very way of life.

Over my 25-year career in public service, I've observed the widespread effects of climate change on communities across the United States. As Governor of Arizona, I saw how a warming climate contributed to dangerous weather conditions such as drought and extreme heat across the American Southwest. Later, as the U.S. Secretary of Homeland Security, I worked to counter negative climate impacts on our nation's critical security infrastructure, from airports to military facilities to our transportation networks.

Over time, it became clear to me that climate change was—and is—a greater threat to our security, and to the futures of citizens around the globe, than any other. For the most vulnerable populations—including children, the elderly, and low-income and indigenous communities—the risk is even more severe.

This conviction has shaped my focus on sustainability as the President of the University of California. As a pioneer in climate research for decades, UC was already a hub for ambitious sustainability work when I arrived. In one of my first acts as UC President, I launched the UC Carbon Neutrality Initiative, a bold effort to leverage the university's climate expertise to achieve systemwide carbon neutrality by 2025. I knew that eliminating greenhouse gas emissions from our campuses, medical centers, and laboratories would be challenging. But by setting

this audacious goal, we mobilized dozens of efforts that are transforming our institutional approach to sustainability.

In 2014, the Carbon Neutrality Initiative brought together 50 researchers and scholars from across the UC system—led by UC San Diego Professor Ram Ramanathan—to collaborate on the groundbreaking *Bending the Curve* report. It outlined 10 solutions that could change the trajectory of global carbon emissions and guide other institutions in their sustainability efforts. Modeled off of UC's own institutional sustainability commitments, the report broke new ground with its interdisciplinary focus, relying on the knowledge of experts from a broad spectrum of fields ranging from climate science to ethics, economics, ecology, energy, environmental justice, political science, and religion.

The practical, cross-sector approach outlined in the *Bending the Curve* report has rippled across other UC sustainability efforts. Inspired by the report, faculty members developed a new multi-disciplinary online course that challenges students to identify locally and globally scalable climate solutions. The class has been launched on six UC campuses, and in 2018 San Diego State University became the first California State University institution to pilot the course. In line with UC's focus on scalability, the course is designed to be rapidly expanded at universities across the U.S. and abroad, with the goal of creating a new generation of engaged climate experts.

In further recognition of the need to share expertise and best practices, in 2018 UC spearheaded the launch of the University Climate Change Coalition, a collective of 20 research universities across the US, Canada, and Mexico who are working together to advance local and regional climate action. Our coalition has since brought together more than 2,600 leaders from the public, private, and academic sectors to collaborate on climate solutions and challenges.

With their emphasis on research and innovation in service of the public good, universities like UC are well positioned to generate the discoveries and innovations the world will need to address climate change. By using our campuses and facilities as living laboratories of sustainability—powered by the expertise and the energy of our faculty and students—we can determine what technologies and approaches work, and how they can be scaled up.

Fortunately, universities aren't the only institutions working to generate new solutions and train the next generation of climate champions. Across the country, we have seen a massive groundswell of institutions—cities and states, the private sector, foundations and nonprofits, and citizen advocates—stepping up to this challenge. Many of them have been working on this issue for decades. What unites all of us in our efforts is the recognition that making a real change on a large scale will require creativity, persistence, and collaboration.

We have that responsibility as scientists, leaders, and citizens of the planet. Let us work together and hold each other to that great responsibility.

Janet Napolitano
University of California, Office of the President

Janet Napolitano is the twentieth president of the University of California. She previously served as the US secretary of homeland security from 2009 to 2013, as governor of Arizona from 2003 to 2009, as attorney general of Arizona from 1998 to 2003, and as US attorney for the District of Arizona from 1993 to 1997.

PREFACE

The book you are reading is years—centuries, even—in the making. You can trace its inspiration back to the start of the Industrial Revolution, when advances in manufacturing processes triggered massive changes in all aspects of daily life, including how human beings interacted with their environment and one another. These advances, however, did not come without a cost. As the global population grew and communities adapted to a higher quality of life, the amount of heat-trapping gases released into the atmosphere that could be traced to human activity increased markedly.

The title of this book refers to the resulting rise in global temperature, represented as an ever-steepening curve over time. Bending that upward curve to decrease the unsustainable trajectory of an increasing global temperature requires a significant focus on reducing the release of emissions of carbon dioxide and four short-lived climate pollutants into the air. Without mitigation, the warming will reach dangerous levels before 2050 and we will be transitioning from climate change to climate disruption. The timeline for bending the warming curve is aggressive. Mitigation actions have already begun in many cities, states, and nations. It must proceed at a rapid pace such that emissions of all climate-warming pollutants will be reduced by 50% to 80% by 2050, followed by ongoing carbon neutrality before 2100. We must also be prepared to extract as much as 500 billion to a trillion tons of carbon dioxide from the air during this century. Bending the curve of climate change has emerged as the challenge of our time.

In 2013, University of California President Janet Napolitano announced the Climate Neutrality Initiative, a landmark initiative that commits the university to emitting net zero greenhouse gases from its vehicle fleet and physical structures by the year 2025. This commitment to the health of the planet brought together more than 50 UC researchers and scholars in the fall of 2015 to identify solutions that can flatten

the curve of climate change. Out of this collaboration emerged *Bending the Curve: 10 Scalable Solutions for Carbon Neutrality and Climate Stability* (V. Ramanathan et al.). The executive summary was published in 2015, while the full report appeared in 2016.

This book is an offshoot of the *Bending the Curve* report. Within those 10 solutions is a call to "foster a global culture of climate action through coordinated public communication and education at local to global scales." The University of California now offers a multidisciplinary undergraduate course based on the report that consists of 18 original lectures by 23 faculty representing 9 UC campuses and national laboratories. The course is unique in that it goes beyond the scientific underpinnings of climate change and focuses on solutions to the problems that global warming has created. With this book our aim is to further extend the call to bend the curve with 19 chapters that expand on those solutions, many written by the same UC scholars and researchers who shaped the *Bending the Curve* report and contributed lectures to the course.

Bending the curve of climate change is a battle against time and a battle for the well-being of our children and grandchildren. To tackle this crisis, we need a million climate stewards to safeguard the planet and those who call it home. Fortunately, there is still time and this book gives you the tools to help solve the defining problem of our age.

Scott Friese
University of California, Office of the President

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INTRODUCTION

Climate change is one of the most far-reaching social and political challenges that humans have ever faced. "Climate change is the defining issue of our time…we face a direct existential threat," says UN Secretary-General António Guterres. The Pope calls climate change "a global problem with grave implications" and "one of the principal challenges facing humanity in our day." Climate change is part of a much broader problem of unsustainable consumption of natural resources, as captured in the declaration by the Kenyan Nobel Laureate, Wangari Maathai: "Today we are faced with a challenge that calls for a shift in our thinking, so that humanity stops threatening its life-support system. We are called to assist the Earth to heal her wounds and in the process heal our own."

That the climate is changing—and that humans are responsible—is not in serious doubt. "Warming of the climate system is unequivocal," according to the most prominent international scientific body of over 1,000 climate scientists for assessing climate change, the Intergovernmental Panel on Climate Change. "Human influence on the climate system is clear."

What is open to question, however, is how we, as a species, can bend the curve of planetary warming before it is too late. That warming curve is illustrated in stylized form on the title page of this book and represents that the world needs to cut emissions by 80% by 2050, and to cut emissions to close to zero soon after. We don't have much time. We have already emitted 2.2 trillion tons of carbon dioxide into the air, and the third trillion will be dumped into the air by 2030. How can we rapidly phase out our dependence on fossil fuels? How can we quicken the pace of technological innovation and create the social, political, and economic impetus to implement those solutions that are already available? How can we do so in a way that helps, not harms, the most disadvantaged people in society?

The industrial era was ushered in with the invention of the improved steam engine by the Scottish engineer James Watt in 1769. The Industrial Revolution that followed benefited humanity immensely with vastly improved health and wealth, but the improvement in the human condition came at a huge and unacceptable cost to the environment. Largely as a result of industrial emissions of carbon dioxide and other greenhouse gases, the planet has already warmed by about 1°C (1.8°F) since preindustrial times. If emissions continue at the present rate, the planetary warming is highly likely to reach 1.5°C (2.7°F) before 2030. The last time the planet was this warm was 130,000 years ago, and it was sufficient to increase sea level by about 6 to 9 meters (20 to 30 feet). With unchecked emissions beyond 2030, the warming could exceed 2°C by 2050, exposing more than 1.5 billion people to extreme heat waves, storms, floods, fires, droughts, and a variety of diseases.

Such projections were thought to be unrealistic or dystopian in the first decade of the twenty-first century, but not anymore. The science linking warming to extreme weather has improved so dramatically in the years following the Paris climate summit (in 2015) that the normally cautious American Meteorological Society declared in 2017: "We are experiencing new weather extremes because we have created a new climate." The prestigious Lancet Commission, consisting of medical experts in Britain, concluded in 2015: "The effects of climate change are being felt today, and future projections represent an unacceptably high and potentially catastrophic risk to human health."

Scientists by and large accept that we have entered the age of humans—the Anthropocene. In other words, we have transitioned from the Holocene epoch with its relatively stable climate to the Anthropocene, a period when climate change has led to climate disruption. Such far-reaching disruptions are no longer being debated among the vast majority (97%) of scientists.

How This Book Is Organized

This book is about solutions. More than 20 leading experts, most at the University of California, share their analyses of how to bend the curve of planetary warming. Taken together, the following chapters tell us that the deep emission cuts that are required are well within our

technical capabilities. This book demonstrates, however, that deploying the technological solutions demands a broad understanding of the multidimensional aspects of the climate change problem.

The book consists of 19 chapters organized by themes into three parts: The first part sets the stage for the entire book by introducing concepts and solutions. The second part consists of 12 chapters that describe in more detail the solutions and their multidimensional nature, which capture aspects of societal transformation, governance, market instruments, technology measures, and ecosystem restoration. The third part focuses on special topics that are vital for developing mitigation solutions.

The first 4 chapters of the book set the stage for the entire book by introducing *concepts and solutions*. Chapter 1, Climate Change, is a broad summary of climate change science that describes what we know, how we know what we know, and the future extreme climates society will inherit this century if we do not bend the curve in time. Chapter 2, Humans, Nature, and the Quest for Climate Justice, gives a broad background on the societal behavior and history that led to the current state of affairs, while Chapter 3, Climate Change and Human Health, describes the impacts of climate change on health—perhaps the most important motivation for urgent action. Chapter 4, Overview of the Ten Solutions for Bending the Curve, introduces readers to ten solutions to bend the curve.

Chapters 5 through 8 together argue that we need to foster a *global culture of climate action* that creates the will to take the measures required. Such a culture can be created by social movements (Chapter 5) and by behavioral changes through changing social norms (Chapter 6). Chapter 7, Religion, Ethics, and Climate Change, brings up a major tool for solving the climate change problem, of forming an alliance with leaders from a range of religious belief systems to effect large-scale societal transformation. Communication is a fundamental requirement for fostering a global culture of climate action, as argued in Chapter 8, which also offers effective communication techniques to persuade those who have difficulty accepting climate change science, the data, and the predictions.

Chapters 9 and 10 deal with *governance solutions* that explore

policymaking at vastly different scales—the local and the global. Locally and regionally, many cities and states in the United States are already well on the road to bending the curve and are acting jointly through coalitions such as C40 Cities; the case of the state of California is analyzed in detail in Chapter 9. But these leaders—city mayors and state governors—need broad-based political support to continue to deepen their efforts, while other leaders need to be pushed into action. At the global level, Chapter 10 shows the promise of new models of international cooperation, and the potential to build on the Paris Agreement.

Solutions related to *market instruments* are explored in two chapters that analyze climate change through an economic lens. Chapters 11 and 12 discuss market-based, regulatory, and policy approaches such as carbon pricing that encourage firms and individuals to switch to cleaner production methods, prioritize energy efficiency, and travel more sustainably. The chapters also highlight how market instruments are working successfully in many parts of the world.

Technological measures are detailed in Chapters 13 to 15, which that introduce you to the tools to solve the problem. New breakthroughs in renewable energy, vehicle electrification, and smart grids, detailed in Chapters 13 and 14, will help to bring down the cost of emission reductions and help us reach zero emissions shortly after 2050. But reductions in carbon emissions of 30% to 40% are already feasible using mature technologies that are available today. Chapter 15 shows that tackling short-lived climate pollutants—such as methane, black carbon, hydrofluorocarbons, and ozone—can bend the curve quickly, giving time for the carbon reduction measures to take effect.

Chapter 16 describes *natural and managed ecosystem solutions* and argues that much of the climate change remedy has already been provided by nature. As this chapter highlights, we can reduce emissions by one-quarter through tackling deforestation, regenerating damaged natural ecosystems, improving the ability of soils to store carbon, and reducing food waste.

The book concludes with three more chapters on *special topics*. Chapter 17, Sea Level Rise from Melting Ice, addresses the impact of the possible disintegration of the massive ice sheets of Antarctica and Greenland. Chapter 18, Atmospheric Carbon Extraction: Scope,

Available Technologies, and Challenges, addresses a major emerging theme in climate solutions, deploying technological measures to extract carbon from the atmosphere. Chapter 19, Local Solutions, describes a local community-scale living laboratory that is attempting societal transformation.

What This Book Does Not Address

This book does not address adaptation to climate change. The world has already passed the point where some adaptation will be needed, such as changing agricultural practices, retreating from or protecting coastlines threatened by rising sea levels, and managing increased heat waves and droughts. But that is not our focus here. Nor do we discuss climate engineering—drastic, and controversial, measures to try to stave off climate change, such as injecting millions of tons of sulfur into the atmosphere. Bending the curve of planetary warming must remain the first priority—reducing emissions enough to allow us time to adapt and avoiding the potentially disastrous unintended consequences of climate engineering.

Who Is This Book For?

This book is written for anyone who cares about the future of the planet and human well-being. The chapters will help you understand how individuals, community groups, businesses, religious leaders, mayors, heads of state—in short, everyone—can work to bend the emissions curve.

What you will learn from the chapters in this book is this: climate change is not a question of political beliefs but a dominant scientific and societal issue, and without the fast actions described here to bend the curve, it can quickly morph into an issue of incalculable human tragedy.

We've designed each chapter as a stand-alone resource that can be read independently, in any order. If you aren't familiar with climate science, though, it will help to start with Chapter 1, which explains how and why the climate is changing, as well as the likely impacts under a "business as usual" scenario. And the solutions that can bend the warming curve are interconnected. To see this, read Chapter 4, which introduces the ten solutions and explains how they fall into a series of

six clusters that involve science, societal transformation, governance, markets, technology, and ecosystems.

Each chapter is written for a generalist audience—nonexpert readers at the level of a second-year undergraduate student—with little assumed in the way of prior knowledge. If you are trained as a microbiologist, you can jump right into the chapters that draw on political science and psychology. If you are an artist or a social scientist, Chapter 1 will introduce you to the physical principles and evidence that demonstrates how and why humans are changing the climate. Key terms, especially those that might be unfamiliar, are **boldfaced** and defined when first used. Given the interconnected nature of the climate challenge, such an interdisciplinary approach is essential. Climate science, economics, and engineering all just have a piece of the puzzle. The learning objectives at the start of each chapter will give you a road map for what you can take away. Discussion questions in the learning companion to this book provide an opportunity to extend your understanding through talking with classmates, friends, or family members. And if you want to delve further, references and in some cases additional readings are given at the end of each chapter.

After you read this book, we hope you are convinced of two things. First, climate change is a major problem for all human beings. Second, the solutions are within reach. But how will that social and economic transformation be brought about? Bending the curve will take a world of climate champions who can innovate and implement climate solutions. This book will help you to join their ranks.

Adam Millard-Ball
University of California, Santa Cruz

V. Ramanathan
University of California, San Diego, Scripps Institution of Oceanography

HOW TO USE THIS BOOK AND THE LEARNING COMPANION

Bending the Curve: Climate Change Solutions brings together leading experts from diverse areas of academia and research to address the multidimensional aspect of climate change. As an interdisciplinary book, it has been written to appeal to a broad audience, including students and instructors in a wide range of educational settings, as well as readers beyond the classroom. The chapters do not assume that the reader has prior knowledge of climate change science.

To help all audiences gain the most from this book, we have also developed a learning companion that includes questions and resources to help readers connect ideas, understand key concepts, and increase their ability to effectively discuss and explain climate change solutions. The learning companion is available for download through the California Digital Library as a PDF in print-ready format.

For Students

Each chapter in the book focuses on a particular aspect of climate change. To support your learning, each chapter includes an overview that highlights the key concepts presented by the author(s). We recommend that you spend some time familiarizing yourself with the focus of each chapter before diving in. For those of you who are interested in learning more about the focus of a particular chapter, please consult the text sources at the end of the chapter as well as a list of additional resources in the learning companion that have been provided on a particular topic.

The organization of the learning companion mirrors that of the book, with a section for each chapter. The companion provides two sets of questions for each chapter: review questions and discussion questions. Review questions are presented in multiple-choice format and are designed to help you gauge how well you have grasped key concepts and information. Discussion questions are open-ended and designed to

help you apply what you read to the world around you. These questions are designed to promote deeper learning through conversation with your fellow students, or others outside the classroom.

For Instructors

Bending the Curve: Climate Change Solutions is meant to address climate change through a wide lens that includes physical and atmospheric science, government and policy, economics, technology, as well as the humanities and social sciences. With that in mind, this digital book is meant to help you bolster your background in fields beyond your specialty.

The learning companion provides review questions that can be used to assess familiarity with key concepts, ensuring all participants are ready to apply what they've learned. These questions can also help instructors identify areas of learning that may require additional explanation. The learning companion also provides discussion questions, which can help facilitate deeper conversations in the classroom, or activities that engage student-to-student discourse. All of the questions provided in the learning companion can be included in live class sessions or through online delivery environments.

For Readers Beyond the Classroom

Bending the Curve: Climate Change Solutions, while written primarily for a higher-education audience, will also appeal to a broader audience of readers. This may include community organizers or climate advocates seeking key arguments, facts, and details. This book is also helpful to everyone interested in expanding their learning about climate change solutions. The book can be helpful to those who are already climate change solution champions interested in expanding their learning, as well as those who are new to the idea of identifying climate change solutions and are curious about learning the basics.

We recognize the importance of public communication and education to promote a broad culture of climate action. Using the companion guide questions can help you to take action and to collaborate with others as a learning community, focused on climate change solutions.

Scott Friese and Alan Roper
University of California, Office of the President

PART ONE

Concepts and Solutions

CHAPTER 1

Climate Change

V. RAMANATHAN

UC San Diego, Scripps Institution of Oceanography

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Learning Objectives

1. **Explain the basic concepts of climate change science.**
   You will learn how some atmospheric gases emitted by human activities spread around the planet like a blanket and how that blanket traps infrared radiation (heat radiation) and warms the planet. Such gases are popularly called **greenhouse gases**. A basic knowledge of climate science will help motivate you to solve the problem of increased greenhouse gases. You will be able to explain the underlying scientific principles of climate change to others, including skeptics.

2. **Discuss the anthropogenic drivers of climate change.**
   Next you will learn how our various activities—driving, flying, cooking, heating and cooling homes, and producing food—contribute to climate change. Because these drivers are related to human activities, we call them **anthropogenic** drivers of climate change (*anthropogenic* is the scientific term for "human-caused").

3. **Explain how and why the climate is changing.**
   By this point, you will know how the greenhouse gases emitted by human activities are expected to change the climate, based on physical principles. The third learning objective is to understand how the climate is changing now and how our observations of the weather are matching predictions from climate models.

4. **Describe the likely climate changes and their projected impacts.**
   The fourth objective is to use the knowledge you have gained thus far to describe the potential impacts of the warming on aspects of climate that affect us all, including heat extremes, droughts, floods, sea level rise, and melting sea ice and glaciers. It is having huge impacts on almost everything we know. Climate change is causing new weather extremes such as floods, heat waves, and droughts, with negative effects on public health. It is better termed as climate disruption. We will track down the various impacts we are already experiencing today and project the impacts that are likely to occur in the future if we continue on our current path of unsustainable greenhouse gas emissions.

Overview

The climate system is dynamic and has undergone major changes in the history of the planet. Over the last 2 million years, the Earth's climate has cycled between cool glacial periods and warm interglacial periods. These cycles have occurred about every 100,000 years over at least the past 800,000 years. Beginning 11,700 years ago, the Earth transitioned to the current interglacial warm epoch called the **Holocene**. Before the nineteenth century, climate change on the planet was mainly a naturally occurring phenomenon caused by changes in the Earth's orbit around the sun, changes in the amount of solar radiation reaching the Earth, volcanic activity, and natural patterns of heat exchange between the land, the ocean, and the atmosphere.

Since the dawn of the industrial era, a new global causal factor has been added to this list: humans. We emit **carbon dioxide** and other pollutant gases when we burn fossil fuels and do many other things, such as refrigerate our food and fertilize our crops. These pollutants have drastically altered the heat-trapping properties of the atmosphere. In the case of carbon dioxide, the changes are irreversible on time scales of thousands of years or more. These pollutant gases now cover the Earth like a blanket, trapping infrared heat and warming the planet. The climate has already warmed by 1°C since the preindustrial era and in another 15 years (from 2018) will reach levels not seen in the past 130,000 years. Climate scientists have concluded that if the current rate of emissions continues, the planet will warm to levels not observed in the last 25 million years or more. Not only is the amount of the warming unprecedented, but the rate of change is also orders of magnitude larger than that of past natural variations.

How do we know this is true? Climate change science is intensely data driven and has undergone the traditional scrutiny and rigor of scientific methods. It has taken thousands of peer-reviewed studies over more than 100 years and large quantities of data collected from ships, surface stations, aircraft, and satellites to arrive at the conclusions described in this chapter. The findings reported here are based on analyses of literally trillions of bytes of data by thousands of scientists from around the world as reported in thousands of peer-reviewed publications. These studies have been reviewed by science academies in the United States

and around the world since the 1970s, culminating in the formation of the Intergovernmental Panel on Climate Change (IPCC) by the United Nations in 1989. Hundreds to thousands of scientists contribute to the IPCC's periodic reports that assess, evaluate, and update the science and the data. References to some of these reports are provided at the end of this chapter.

The most important messages in this chapter are that (1) anthropogenic emissions are causing climate change at a magnitude and rate that are unprecedented over at least the past million years, and (2) this human-caused climate change is likely to have severe impacts on both the natural environment and human society. Finally, it is particularly important to recognize that *we still have time to act to reduce human-caused climate change and moderate or avoid the most serious impacts*—if we start acting now (2019). The purpose of this book is to empower you and give you the tools you will need to act as "climate warriors" innovating and implementing climate solutions.

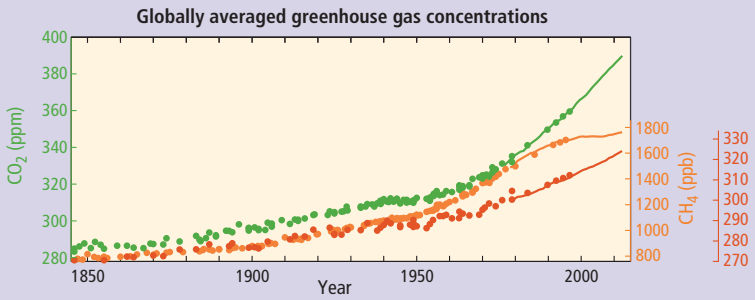
This chapter will also help you address questions that people you know, including climate change skeptics, might ask you. For example, how do you know the climate is changing? Even if it is changing, how do you know the change is caused by human activities? And whom do you believe?

Your answer to the last question should be simple: we do not have to *believe* anyone. We have the data. Thousands of scientists have analyzed and interpreted observed data from peer-reviewed studies, so these are facts, not beliefs. The real issue we want to address is the following: if we continue along the current path of unsustainable pollution, what does the future hold for us? How will the planet look a few decades from now? And what's in store by the end of the century? The projections made by various scientific institutions are summarized in this chapter.

Hopefully these scientifically projected scenarios will give you the reasons, as well as the motivation, to solve the problem in a timely manner. As you already know, this book is about *solving* the climate change problem. A hopeful message comes out of the findings summarized in this chapter: there is still time to solve the problem of climate change and stabilize the climate below dangerous levels of warming.

Box 1.The Intergovernmental Panel on Climate Change

The Intergovernmental Panel on Climate Change (IPCC) is the most prominent international scientific body for assessing climate change. It was formed in 1988 by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP). There are currently 195 member countries in the IPCC, and membership is open to all countries in the WMO and UN. The IPCC is responsible for reviewing and evaluating scientific, technical, and socioeconomic information related to climate change. While the IPCC neither conducts research nor monitors any climate change data directly, it provides policymakers with the most comprehensive picture of the scientific consensus.



Increase in atmospheric concentration of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) with time. Reproduced from IPCC.

The information assessed by the IPCC is synthesized into a major assessment report (AR) every 5 to 7 years. There are currently five multivolume assessment reports, and the latest one, AR5, was finalized in 2014. Each AR has three volumes, each of which is led by a working group. Working Group I (WGI) consists of 258 experts who assess the science behind climate change and how humans are causing it. With 302 experts, Working Group II (WGII) evaluates the impacts of climate change and how living things, such as humans, animals, and plants, can adapt. Working Group III (WGIII) has 271 experts and focuses on mitigating climate change—that is, slowing it down and preventing its worst possible effects.

AR5 has more than 830 lead authors across the three working groups from over 80 different countries. The reports submitted for any AR undergo a rigorous, multistage review process. The IPCC is currently working on AR6, and the contributions from the three working groups will be finalized by 2021.

SOURCE: https://www.ipcc.ch/organization/organization.shtml.

1.1 Entering the Age of Humans

Before diving into the problem of anthropogenic climate change, it's helpful to understand what the planet's climate was like before modern humans (*Homo sapiens*) became a major force.

The history of *Homo sapiens* extends as far back as 160,000 years ago. However, it was only in the last 10,000 years, with the advent of the Agricultural Revolution, that *Homo sapiens* began modifying the land surface for growing food. The Agricultural Revolution roughly coincides with a warm interglacial that began about 11,700 years ago and continues to the present. Scientists call this period of warm and relatively stable climate the **Holocene**. Although there were significant regional climate fluctuations, the stable climate of the Holocene enabled the Agricultural Revolution. During this period humans transitioned from hunting and gathering to agriculture. Cities, writing, and major human civilizations all developed during this time. The last 270 years of the Holocene ushered in the Industrial Revolution, and with that, climate pollution began to increase dramatically.

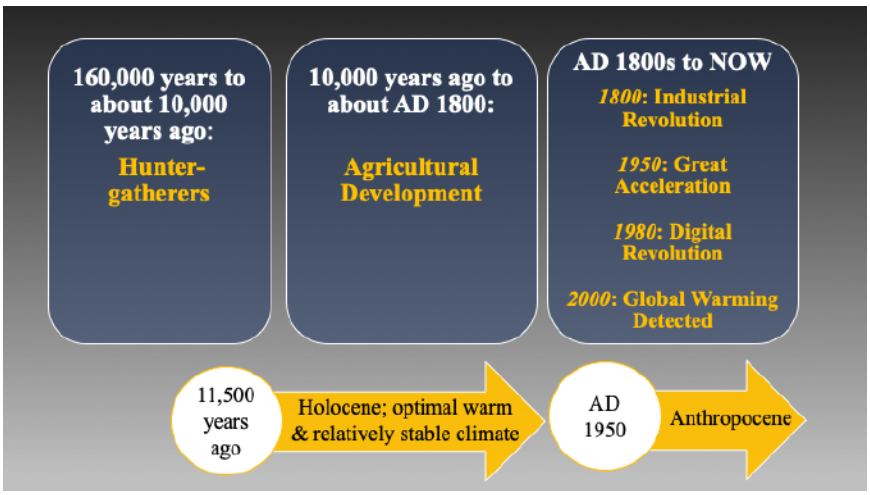


FIGURE 1.1.1 ***Homo sapiens* history.** Image from V. Ramanathan.

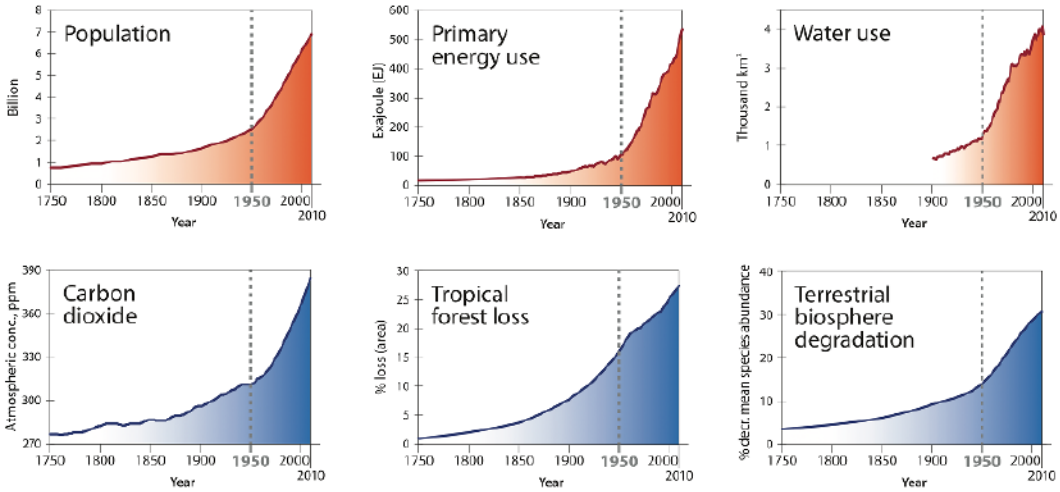


FIGURE 1.1.2 Effects of the Great Acceleration on six different measures. As human population and gross domestic product (GDP) have risen sharply, so have water use, carbon dioxide emissions, deforestation, and species extinctions. Adapted from Steffen et al. 2015.

The "Great Acceleration"

The Industrial Revolution, which started in Britain and evolved during AD 1750–1850, was powered by fossil fuels. Now nearly all nations in the world consume them. Beginning around 1950, after World War II, the production and consumption of goods increased dramatically, leading to accelerated burning of fossil fuels. This acceleration is illustrated in every measure we can think of: population, gross domestic product (GDP), water use, fertilizer consumption, the number of motor vehicles in circulation, and many more. Because of this, scientists call the period from 1950 to the present the **Great Acceleration**.

Not only did the Great Acceleration increase production, consumption, and population, it also left a huge imprint on the ecosystem. For example, the rate of change in carbon dioxide concentration, which was already steadily increasing, accelerated in 1950. By the 1980s, this increase in carbon dioxide had already led to a significant rise in global temperatures, which in turn brought huge ecological impacts. Depletion of the ozone layer again became a major factor in the 1980s. After 1950, the biodiversity of species started decreasing and the extinction of species accelerated.

Figure 1.1.2 shows a few examples of the rapid increase in human activity and its ecological impacts during the Great Acceleration. Notice that nearly every measure—population, total real GDP, water use, biosphere degradation (species extinctions), and the loss of tropical rain forests—takes off dramatically beginning around 1950.

No part of the planet remains unaffected by the Great Acceleration. The planet we see today is vastly different from the planet our ancestors inherited a century ago.

The Anthropocene

We are still in the Holocene climatologically, but the impacts of the Industrial Revolution and Great Acceleration, combined with a massive population increase, have caused many scientists and other thinkers to argue that we have entered a new period called the **Anthropocene**, or age of humans. Humans have emerged as a major force modifying the environment. The activities of all humans combined are comparable to geological forces, such as earthquakes and volcanoes, that modify the Earth's surface and atmosphere on large scales and in visible ways.

Scientists have not yet agreed on the time period that marks the beginning of the Anthropocene. Many propose the period started sometime during the Industrial Revolution. Others argue that it began with the advent of the Agricultural Revolution about 10,000 years ago. Still others suggest that its start date should be set to 1945, the date of the first atomic explosions. Irrespective of how scientists settle the starting date of the Anthropocene, it's the Great Acceleration that began in the 1950s that marks the beginning of *Homo sapiens*' truly massive global imprint on the planet. The climate has already warmed by 1°C since 1900. If we continue with business-as-usual consumption of fossil fuels, the warming between 1900 and 2100 could exceed 4°C.

Why worry about a warming of 4°C?

We know that the planet has been both significantly warmer and significantly cooler in the past. Why bother about a human-induced warming of 4°C? How do we judge whether this amount of warming is large or small? One way is by looking at the glacial to interglacial cycles the planet has undergone many times over the last 2.5 million years. The

difference in global average temperature between a glacial and an interglacial period is only about 4°C to 5°C, but this difference results in a dramatically different climate. At the coldest point of the last glacial period (the Ice Age, about 20,000 years ago), an ice sheet covered most of what is now Canada and the northern United States. This ice sheet was about 1 kilometer thick over the current location of New York City. In contrast, during the previous warm interglacial period about 120,000 years ago, called the Eemian interglacial, there was substantially less ice in Greenland and Antarctica than at present, and global sea levels were at least 6 meters higher. The temperature at that time was only about 1°C warmer than the preindustrial average of the early 1800s. It's clear that a 4°C increase in the global temperature is, in fact, a big deal.

It's also important to understand that the planet is *already* in its warm state (interglacial period), having warmed by about 4°C from the glacial temperatures of about 20,000 years ago. Warming it by another 4°C would push the planet, along with all of its ecosystems and glaciers, beyond any temperature experienced in the last 25 million years. In short, more than just the 4°C warming, the fact that this warming is happening on top of the current warm interglacial period is the bigger concern.

Finally, past changes in global temperature by as much as 4°C occurred over periods of thousands of years or more. Compare that to the projected Anthropocene warming, which will happen within a single century. This rate of warming is at least 100 times faster than naturally occurring changes—and far too rapid for social systems, natural species, and ecosystems to adapt.

1.2 The Atmospheric Blanket and Its Warming Effect

The Earth's atmosphere is an extremely thin shell compared with the size of our planet. The primary gases in the atmosphere by volume are nitrogen (78.1%), oxygen (20.9%), and argon (0.9%). These figures don't include water vapor, which varies significantly with location and altitude but averages about 0.4% of the atmosphere globally. Other naturally occurring gases include carbon dioxide (designated by chemists as CO_2), ozone, and methane, which all occur in trace amounts. Although CO_2, methane, and ozone occur naturally, human activities are increasing their concentrations.

This blanket of atmosphere sustains life in many fundamental ways. First, it is vital to the cycle of plant and animal life. Plants grow by taking carbon dioxide from the atmosphere. In the process of photosynthesis, they use energy from the sun to synthesize carbon dioxide with water and release oxygen to the atmosphere. Plants incorporate the carbon into sugars that store energy and into structural materials such as cellulose, while they release the oxygen back into the atmosphere. When animals, including human beings, consume plant material (or other animals), they digest it: that is, they take in oxygen, which reacts with the food to release its stored energy. In the process, animals and humans convert some of the carbon back into carbon dioxide and re-exhale it into the atmosphere.

Water vapor is a crucial part of the atmospheric composition. Water vapor is produced primarily from evaporation from the oceans, surface soils, and subsurface aquifers and then spreads around the planet. It is the water vapor in the atmosphere that forms clouds and rain, thus creating rivers, lakes, glaciers, and ski slopes.

Most important for our purposes, the atmosphere plays a crucial role in determining the temperature of our planet, as we will see in our discussion of the greenhouse effect. Water vapor, carbon dioxide, and

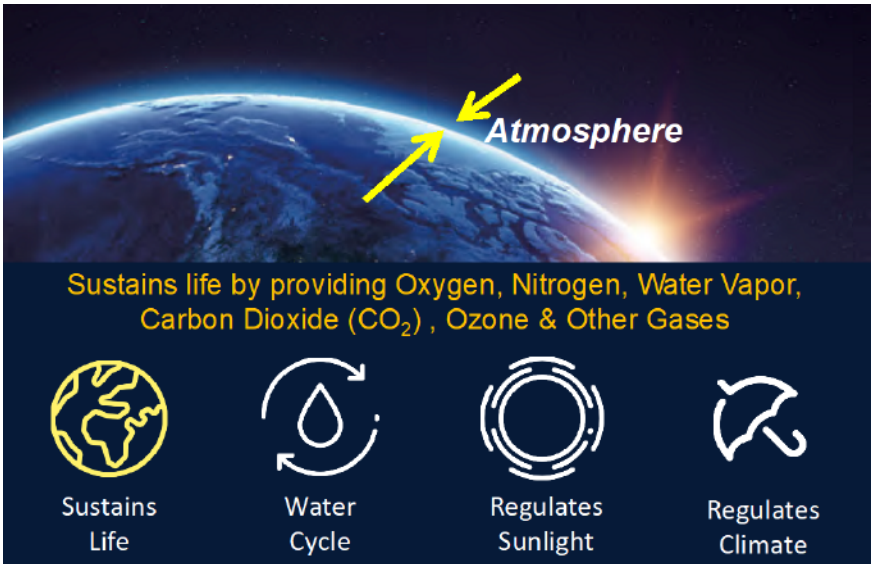


FIGURE 1.2.1 **Atmosphere: a thin, fragile shell. The various ways the atmosphere sustains life on the planet.** Image by V. Ramanathan. Icons designed by Freepik from Flaticon.com.

other greenhouse gases warm our planet. Without these greenhouse gases, our planet would be about as cold as Mars—far too cold to support liquid water and life. At the other extreme, without clouds, ice, and snow to reflect sunlight, the planet would be so hot that it would be unlivable.

Thus, the composition of the atmosphere keeps the Earth's temperature at just the right level for water to be present in the planet in all three phases: gaseous water vapor, liquid water, and solid ice and snow crystals. The presence of all three forms of the water molecule is essential for the survival of *Homo sapiens* and most other species on Earth. The atmosphere thus protects life.

The natural greenhouse effect

Our planet's fundamental energy source is incoming radiation from the sun, which we will refer to as **incoming solar energy**. Not all of this solar energy is absorbed by the planet. About 29% of it is reflected back into space by the atmosphere, the land surface, and the sea surface. The percentage of solar radiation reflected back into space is called the

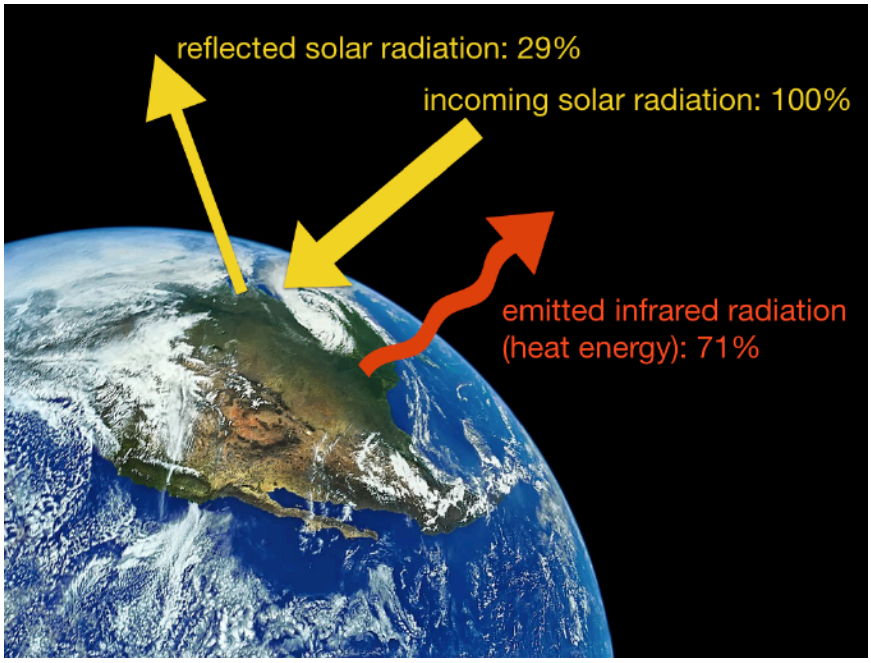


FIGURE 1.2.2 **The greenhouse effect.** Adapted from NASA.

albedo. The primary climate variables responsible for the Earth's 29% albedo are clouds, snow cover, ice sheets, sea ice, glaciers, and oxygen and nitrogen in the atmosphere. In general, whiter substances (clouds, ice, and snow) reflect more solar radiation. The scattering of sunlight by oxygen and nitrogen gives the sky its blue color.

After 29% of the incoming solar radiation is reflected back to space, the Earth absorbs the remaining 71%, which heats the land, ocean surface, and atmosphere. In response, the surface and the atmosphere radiate (i.e., give off) this heat by emitting **infrared radiation**. This infrared radiation is commonly referred to as **heat energy** because the infrared radiation emitted by any substance depends on its temperature. The higher an object's temperature, the more heat energy it emits.

However, not all of the emitted heat energy can escape to space. The greenhouse gases in the intervening atmosphere absorb (trap) some of this heat energy. As a result, the heat energy leaving the planet is reduced by the intervening atmosphere. It is this trapping of heat energy that otherwise would have escaped to space through the atmosphere that is referred to as the **greenhouse effect**.

Now, let's see how this trapping effect warms the surface. The greenhouse gases in the atmosphere trap heat energy and reradiate some of it back to the surface. The surface absorbs this reradiated heat energy, causing it to warm some more. The Earth will continue to warm until it reaches a temperature at which the net incoming solar energy equals the heat energy emitted to space by the warmer surface and the atmosphere.

Thus, the surface temperature of a planet is primarily determined by two factors: the net amount of incoming solar energy it receives, and the heat-trapping properties of any greenhouse gases in its atmosphere. Increasing the concentration of greenhouse gases shifts the balance between incoming solar energy and outgoing heat energy, requiring the planet to become warmer and emit more heat energy to restore equilibrium.

"Blanket" is a better metaphor

The trapping of heat by the Earth's atmosphere is typically referred to as the "greenhouse effect." This metaphor compares the heat-trapping gases in the atmosphere to the glass panes of a greenhouse, which allow solar radiation to enter but slow down outgoing infrared heat radiation. Although this name has become standard, it's not the best metaphor for understanding the effects of climate pollutants. In fact, the main reason it's warmer inside a real greenhouse is not because it traps radiated heat energy, but because its walls and roof keep warm air from escaping and colder outside air from entering.

FIGURE 1.2.3 Blanket metaphor. Photograph by Matthew Henry on Unsplash.

A more scientifically accurate metaphor for the warming effect of the atmosphere is the **blanket effect**. On a cold night, a blanket (the atmosphere) warms us by trapping some of the heat energy radiated by the body (the planet's surface) and thus prevents some of it from escaping to the rest of the room (space). However, following well-established tradition, we will retain the terms *greenhouse effect* and *greenhouse gases* throughout this book.

What are the natural greenhouse gases?

So, what are the gases responsible for this natural heat-trapping effect? Most of the Earth's atmosphere is made up of gases, primarily nitrogen and oxygen, that do not trap heat energy and do not contribute to the greenhouse effect. The term **greenhouse gases** refers to the small fraction of gases that do have the ability to trap infrared heat energy.

The dominant greenhouse gas in the Earth's atmosphere is water vapor. Next is carbon dioxide. Other naturally occurring greenhouse gases in the atmosphere include methane, ozone, and nitrous oxide. Concentrations of these gases are extremely small when compared with oxygen and nitrogen, but they play a crucial role in regulating climate and climate change. They have a much larger role in determining the Earth's climate than their tiny concentrations would suggest.

As we noted earlier, water exists in the atmosphere not only in the form of gaseous water vapor, but also in the form of clouds (liquid water droplets and ice crystals). Clouds also provide a large greenhouse effect, almost comparable to that of CO_2. However, clouds also reflect solar energy. The reflective effect of clouds is about twice as large as their greenhouse effect. Thus clouds, in spite of trapping significant amounts of heat, have a large net *cooling* effect on the planet.

Experimental validation of the atmospheric greenhouse effect

How do we know the greenhouse effect is real? One way is to look at the energy absorbed and emitted by the Earth. Satellites routinely measure the incoming solar energy and the outgoing heat energy from the planet. Independently, the heat energy emitted by the surface has been estimated using observed surface temperatures on land and sea.

A note about units: scientists measure energy in units called joules. To describe incoming and outgoing energy for the Earth, scientists use **watts**. A watt is a unit describing the *rate* at which energy is emitted or absorbed; 1 watt is equal to a rate of 1 joule per second. To give a familiar example, a 60-watt lightbulb, when lit, emits 60 joules of heat and light energy per second. Scientists measure the rate of incoming solar energy and emitted heat energy for a planet in terms of the energy

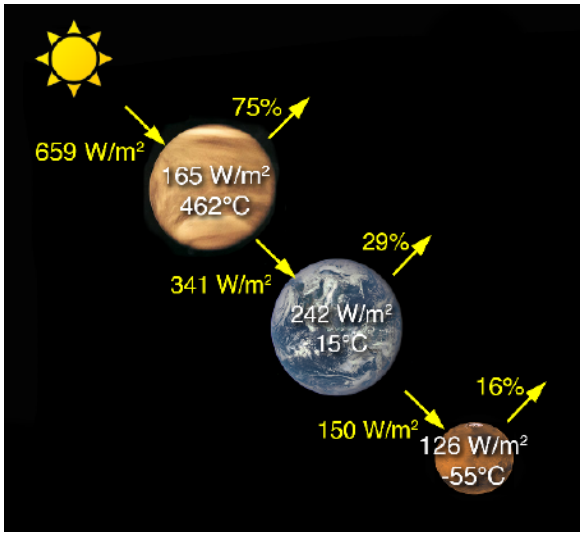


FIGURE 1.2.4
Comparative statistics of the incoming solar energy and surface temperatures of Venus, Earth, and Mars. Adapted from NASA.

rate per unit of its surface area. This is expressed as **watts per square meter** of the planet's surface, denoted in short form as **W/m²** (where the slash means "per").

Globally, measurements show that the Earth's surface emits heat energy at 390 W/m². However, satellite measurements during the 1980s showed that the heat energy escaping to space through the atmosphere was only 260 W/m². Thus, the atmosphere traps about one-third of the surface-emitted heat energy. Clouds decrease the energy that escapes by an additional 25 W/m²; thus, the net heat energy escaping to space (with clouds) is 235 W/m².

We can use another, more whole-system approach to validate the greenhouse effect: comparing planet Earth with its neighbors, Venus and Mars. On one hand, the average surface temperature of Earth is 15°C. The Venusian surface, on the other hand, is searing hot at 462°C—well above the melting point of lead. Why is this the case? The first obvious suggestion would be that Venus is hot because it is so close to the sun. Indeed, Venus is close to the sun, and its incoming solar energy is 659 W/m², compared with 341 W/m² for Earth.

But there is a second factor to consider: Venus is completely cloud covered and as a result reflects as much as 75% of its incoming solar energy (that is, the albedo of Venus is 75%). Taking this into account, we find that Venus actually absorbs solar energy of 165 W/m², slightly *less*

than the amount of solar energy that Earth absorbs (242 W/m^2). On that basis, we would expect Venus to be *cooler* than the Earth.

The only remaining explanation for Venus's searing hot surface temperature is the greenhouse effect of the CO_2 in its atmosphere. It turns out that the concentration of CO_2 on Venus is about 200,000 times more than that on Earth, creating a superstrong CO_2 greenhouse effect, which maintains Venus's hot temperature.

Mars, on the other hand, is much farther from the sun and receives less than half the solar energy that Earth receives. Mars is nearly cloud-free (except for some dust clouds), and its albedo is only 18%. The net effect is that the solar energy that Mars absorbs (125 W/m^2) is only half of that absorbed by Earth. This is the primary reason for the frigid average temperature on Mars (−55°C). Mars's atmosphere is mostly CO_2, and the amount of CO_2 on Mars is actually about 15 times larger than that on Earth, but the stronger greenhouse effect is not enough to compensate for the lower incoming solar energy.

Earth in the Goldilocks zone

The above exercise illustrates an important message about the optimal climate on Earth. The surface temperature is determined by a delicate balance between the amount of incoming solar energy, the reflected solar energy, and the greenhouse gases in the atmosphere.

As we saw earlier, water vapor has the strongest warming effect of the naturally occurring greenhouse gases. At the same time, clouds made up of condensed water vapor have a net cooling effect. If water vapor plays such a significant role in our climate, why do discussions of climate change mostly focus on emissions of carbon dioxide? Where does the water vapor greenhouse effect fit in this picture?

While carbon dioxide is emitted by geological processes (and more recently, human activities), the concentration of water vapor is primarily governed by surface and atmospheric temperatures. The warmer the atmosphere, the higher the concentration of water vapor, assuming there is an abundant source (such as oceans or water "cooked out" from minerals deep in the Earth's interior).

Because the concentration of water vapor depends on temperature,

climate scientists refer to it as a **climate feedback** that amplifies warming, rather than a direct cause of warming. If there were no carbon dioxide in the Earth's atmosphere, temperatures would fall to the point that most of the water vapor would condense or crystallize out of the Earth's atmosphere as well. Without carbon dioxide, there would be very little water vapor greenhouse effect and the Earth would be much cooler, if not frozen.

FIGURE 1.2.5 Goldilocks principle. Reproduced from NOAA.

Thus, the Earth seems to have just the right amount of incoming solar radiation, clouds, and CO_2 to maintain an equitable climate. Among the three planets, Earth is the only one whose temperature is not too hot, not too cold, but "just right" for Goldilocks's porridge—and for life.

CO_2 increased by human activities

While the natural greenhouse effect is vital for maintaining life on Earth, humans have added an enormous amount of carbon dioxide to the thin shell of the atmosphere since the dawn of the Industrial Revolution. As of 2017, we have dumped 2,200,000,000,000 (2.2 *trillion*) tons of carbon dioxide into the atmosphere over the past 240 years. About 45% of that carbon dioxide still remains in the air today. That leaves a blanket of human-generated carbon dioxide in our thin atmospheric shell whose sheer weight is astounding—990 billion tons. That's equivalent to the weight of about 490 billion cars circling the planet all the time.

How do we know the weight of the human-made CO_2? From direct measurements initiated by Charles David Keeling of the Scripps Institution of Oceanography (UC San Diego). This wiggly curve (Figure 1.2.6) is called the Keeling Curve and shows the concentration of carbon dioxide in the atmosphere. When Keeling first started making measurements in 1958, the atmospheric carbon dioxide concentration was 313 **parts per million** (abbreviated as 313 **ppm**). That is, out of every million molecules in the atmosphere, 313 were carbon dioxide molecules in 1958.

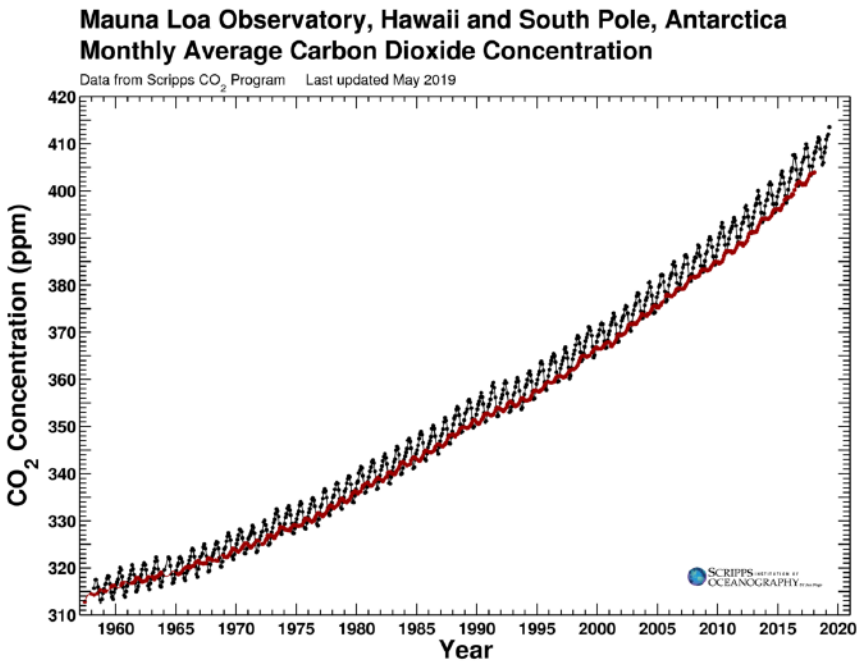


FIGURE 1.2.6 The Keeling Curve shows the increase in CO_2 from 1958 to 2017. Reproduced from the Scripps CO_2 Program from the Scripps Institution of Oceanography.

Passing a major threshold

In the year 2016, we passed a major threshold—one that we should not be passing. Based on measurements of ancient air bubbles trapped in ice and other data, scientists estimate that the concentration of CO_2 before 1850 was 275 ppm. That concentration has since increased steadily, shooting past 300 ppm by 1950, 369 ppm by 2000, and 400 ppm by 2016. Carbon dioxide concentration was about 410 ppm in 2018, meaning that humans have now increased the overall concentration of carbon dioxide by nearly 50% since the preindustrial era. Crossing the threshold of 400 parts per million signifies that the planet could be transitioning into an era of major climate changes.

The increase is seen everywhere on the planet: the ocean surface, mountaintops, and deserts. Whether the data are collected in Hawaii, the Arctic, or the Antarctic, the findings are the same. Basically, the additional CO_2 has covered the planet like a blanket.

How did that happen? Air travels fast. Pollution from North America travels to Europe in days; pollution from Asia travels to North America in a week; and pollution from South America travels to the Antarctic in a few weeks. Air takes a few years to travel from the Arctic to the Antarctic. Travel times for pollution are much shorter than the lifetime of the CO_2 molecule in the air, which is 100 to 1,000 years. That's why the CO_2 increase is found everywhere on the planet. Carbon dioxide is what scientists refer to as a **well-mixed gas**—one that remains in the atmosphere much longer than the time it takes to spread around the world.

What is the take-home message?

The atmosphere connects every part of the world with every other part in a matter of days or weeks. Therefore, we can only solve the climate change problem through global cooperation.

Greenhouse gases as pollutants

Why do we call carbon dioxide and other anthropogenic greenhouse gases "pollutants"? *Pollute* means "contaminate something with a harmful or toxic substance." Carbon dioxide is a natural component of the atmosphere and a vital part of the respiration cycle that sustains life, so how can it be a pollutant? Although carbon dioxide and most other greenhouse gases exist naturally in the atmosphere, human emissions are increasing their concentrations, causing warming that will most definitely have harmful impacts, as we will see later in this chapter. The harmful impacts of these emissions make it appropriate to refer to greenhouse gases as "pollutants."

What are the sources for the observed increase in CO_2?

Many human activities that address our basic needs, development, and well-being are sources of greenhouse gases. Most of the energy used by society since the Industrial Revolution has come from **fossil fuels**: coal, oil, and natural gas. Burning fossil fuels emits the largest amount of CO_2 by far, contributing an estimated 34 billion tons in 2016.

Major anthropogenic sources of carbon dioxide include the following:

- Using fossil fuels to produce electricity: In 2016, 65% of electricity worldwide was generated by burning fossil fuels, including 38% from coal and 23% from natural gas. Coal emits roughly twice as much CO_2 per unit of electricity generated as natural gas, so burning coal to generate electricity is particularly concerning.
- Transportation: There are about 1 billion motor vehicles in use around the world, the vast majority of which use oil-based fuels. Aviation and commercial shipping are also major emitters of carbon dioxide.

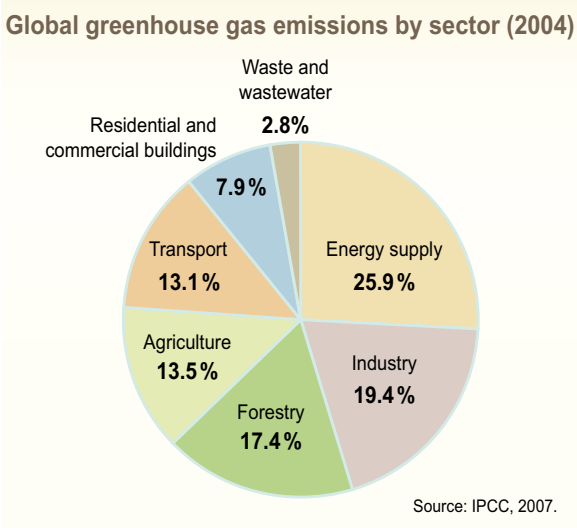


FIGURE 1.2.7 Sources of greenhouse gas emissions. Reproduced from UNEP/GRID-Arendal.

- Residential and commercial buildings and activities: In addition to indirect emissions from electricity use, buildings can be a direct source of CO_2 emissions, primarily through heating. In developed countries, natural gas is frequently used for space heating, water heating, and cooking. The least affluent 3 billion, with limited access to fossil fuels, frequently burn wood or animal dung for heating and cooking, which also release CO_2.
- Industrial processes: A range of industrial processes, in particular cement and steel production, emit significant amounts of CO_2. Cement production alone is estimated to have been responsible for 2 billion tons of CO_2 emissions in 2016.
- Land use: Changes in land use, in particular burning forests to clear land for farming, grazing, or housing, also emit significant amounts of carbon dioxide. Over the decade 2007–2016, CO_2 emissions from land use averaged about 5 billion tons per year.

How much additional heat energy is trapped by the 990-billion-ton CO_2 blanket?

As of 2010, the heat-trapping effect of human-emitted carbon dioxide was about 860 **terawatts** (1 terawatt equals 1,000 billion watts—that's a 1 followed by 12 zeros). This represents about 50 times our total global rate of energy consumption! To understand the enormity of 860 terawatts, let's look at another statistic. The heat energy trapped by our human-made blanket is equivalent to burning 40 trillion 60-watt light-bulbs every second, every day, every month, every year. We are trapping an enormous amount of heat in the land, oceans, and atmosphere. Based on fundamental physics, the temperature of the planet and the atmosphere will be forced to increase until the extra 860 terawatts are radiated away into space. If we continue to increase the concentration of CO_2 in the atmosphere, even more heat will be trapped, forcing the planet to warm even further. This, in a nutshell, is the cause of global warming.

Is CO_2 the only important anthropogenic greenhouse gas?

Until 1975, we thought that CO_2 was the only source of anthropogenic warming. Then the greenhouse effect of **chlorofluorocarbons** (**CFCs**)—a group of artificially produced molecules used as refrigerants, solvents, and propellants—was discovered in 1975. Soon after, a host of other anthropogenic gases (more than 20) were added to the list of climate-warming gases. The most important of these, in terms of their warming impact, are **methane**, **ozone**, **nitrous oxide**, and another group of refrigerants known as **hydrofluorocarbons** (**HFCs**). The sources of these pollutants are the following:

- Methane is the main natural gas that we use for power generation, heating, and cooking. Natural gas leaks (called "fugitive emissions") at production and processing facilities and through distribution pipes are a significant source of methane emissions. Another major source is methane produced by bacteria in the guts of cattle, sheep, and goats. Wet rice agriculture (rice paddy fields), wood burning, landfills, and sewage water treatment plants are among the other significant sources.

- CFCs (chlorofluorocarbons) and HFCs (hydrofluorocarbons) are artificially produced for refrigeration and air conditioning. CFCs have been phased out by international treaty since the late 1980s, but work to phase out HFCs is just beginning.
- Ozone is not directly emitted by human activities, but fossil-fuel power plants and automobile engines emit gases known as ozone precursors (methane, nitrogen oxides, and volatile organic compounds) that react with sunlight to produce ozone in the lower atmosphere.
- Nitrous oxide is released by bacteria in the soil. Nitrogen-based fertilizers used in agriculture increase the activity of soil bacteria and their nitrous oxide emissions.

The IPCC estimates that as of 2010 (the IPCC data is available for only up to 2010), CO_2 has trapped 1.8 W/m^2 of heat, which is 860 terawatts when integrated over the surface area of the whole planet. All of the anthropogenic non-CO_2 gases have added another 1.2 W/m^2, bringing the total heat trapped by all anthropogenic greenhouse gases to 3 W/m^2 (about 1,500 terawatts).

Is the climate responding to this added heat?

Undoubtedly, the climate is responding to this added heat, according to data that scientists have collected at the surface, in the atmosphere using aircraft and balloons, and from space using satellites. The entire atmosphere, most of the land surface, and the oceans to depths of as much as a kilometer have warmed to unprecedented levels compared with the temperatures of the last 100,000 years. In the following section, we will review the vast amount of past climate data that provide quantitative answers about the magnitude of the climate's response.

1.3 Why and How Is Climate Changing?

You have so far learned how certain pollutant gases behave like a blanket, trapping heat and causing global warming. In this section, we will document the evidence that these gases are changing our climate and do a deep dive into why and how the climate is changing.

Distinguishing between weather and climate

Weather is what is happening at any given time or on a short time scale of a few weeks or less. For example, there may be rain today, sunshine tomorrow, and a storm a few days later. These kinds of day-to-day short-term changes are what we call weather. **Climate** describes conditions over a longer term. For example, in many regions winter is colder and drier than summer. Summer might bring monsoons to some regions. These are descriptions of climate, which is essentially a longer-term average of weather. The greenhouse effect causes warming and other changes to climate on time scales of seasons or longer. A warmer climate in turn leads to other changes, such as extreme weather events (heat waves, droughts, extreme storm events). It's in this context that we talk about **climate change**.

Distinguishing between global warming and climate change

Until about two decades ago, scientists used to refer to the increase in temperature due to increases in CO_2 as **global warming.** However, this term does not describe all of the impacts that go along with warming, such as extreme weather and rising sea levels. Moreover, in the 1990s and early 2000s, "global warming" became a politicized phrase and issue, particularly in the United States. Scientists have responded by avoiding the phrase *global warming* and replacing it with the phrase *climate change*. Both terms are used in this text because global warming and climate change are distinct processes. By definition, global warming

FIGURE 1.3.1 Human activities that lead to climate pollution. Top left image by Alan Kiniry from Pexels. Top right image reproduced from Pixabay. Bottom left image by V. Ramanathan. Bottom right image reproduced from Pixabay.

refers specifically to the warming effect of anthropogenic gases on the planet. This global warming in turn leads to broader climate change, which includes changes in winds, storms, rainfall, and humidity.

Why is the planet warming?

As briefly described in the earlier sections, the Earth has been warming since the 1850s. The warming has not been constant or steady, however. As we will see, the evidence indicates that most of this warming is caused by human activities that release pollutant greenhouse gases into the atmosphere, thickening the natural greenhouse blanket. The gases began increasing in the 1850s, but the Great Acceleration in consumption that began in the 1950s (Section 1.1 and Figure 1.1.2) contributed

to a steeper increase in the concentration of many gases during the last half of the twentieth century.

The four images in Figure 1.3.1 reveal the interconnectedness of the climate change problem. The woman cooking with firewood (that was my grandmother's kitchen in south India) could lose her source of food because of changes in climate, such as droughts, caused by CO_2 emitted for the most part in developed countries. Likewise, the smoke coming from that woman's kitchen in south India—as well as from cars in the US and power plants in China—could melt glaciers thousands of kilometers away. It is imperative to keep in mind that pointing fingers at each other will not solve the climate change problem. We are all in this together and together we must solve this problem.

We have already identified carbon dioxide as a major anthropogenic greenhouse gas. Carbon dioxide is a significant concern in part because of its long lifetime in the atmosphere. Roughly half the emitted CO_2 will be taken out of the atmosphere in less than a decade by the land biosphere (trees, plants, and soil) and by the ocean, but the remaining half will stay in the air for at least 100 years, and about 20% of the CO_2 will stay in the atmosphere for *1,000* years or more. You, your children, your grandchildren, and future generations yet to be born will still be inhaling the carbon dioxide emitted by your car today.

The impact of aerosols

One important point to note from Figure 1.3.1 is that the visible smoke and smog shown in the images is made up in part of tiny particles called **aerosols**; carbon dioxide and other greenhouse gases cannot be seen by the human eye. Most of these aerosols reflect sunlight and have a cooling effect, but **black carbon aerosols** (a major component of soot) absorb solar radiation entering the atmosphere and have a warming effect. This trapping of incoming solar radiation should not be confused with the trapping of outgoing infrared radiation emitted by the surface. Often black carbon is referred to as a greenhouse gas. This is wrong on two counts: black carbon is not a gas, and black carbon warms the climate by absorbing solar energy rather than infrared energy from the planet. Black carbon is mainly produced by incomplete combustion. Major anthropogenic sources include internal combustion

engines in vehicles (particularly diesel-powered vehicles) and the burning of solid coal, firewood, crop residues, and animal dung (for heating and cooking).

Fertilizing agricultural fields and burning fossil fuels and biomass fuels (for example, wood) also contribute to other types of aerosol particles, such as sulfates, nitrates, and organics. Unlike black carbon, these other aerosol particles primarily reflect sunlight and have a cooling effect. Although some of this cooling is offset by black carbon's warming, the net effect of all aerosols combined is one of cooling. This cooling has been estimated to offset about a third of the warming caused by anthropogenic greenhouse gases, but the net impact of human emissions still warms the planet.

Super pollutants

As of 2010, non-CO_2 pollutants (non-CO_2 greenhouse gases and black carbon) contribute about 45% of the total anthropogenic warming effect. These non-CO_2 greenhouse gases and black carbon particles are also called **super pollutants**. This is because, per molecule, their warming effects are much larger than that of CO_2. For example, methane is 25 times more potent than CO_2 at warming the planet; nitrous oxide is 300 times more potent; HFCs and CFCs are a few thousand to 10,000 times more potent; and black carbon is 2,000 times more potent (also Box 1.3.1). These non-CO_2 pollutants have powerful warming effects, but methane, ozone, HFCs, and black carbon are also called **short-lived climate pollutants** (**SLCPs**) because their lifetimes in the air range from less than a week (black carbon), to a month (ozone), to a decade or two (methane and HFCs), compared with the century to millennial time scales of CO_2. These relatively short atmospheric lifetimes will be an important factor when we begin to look at climate solutions.

Warming trends

Signs of warming can be seen on the land and sea surface as well as in the atmosphere and the deeper oceans. The globally averaged surface temperature shown in Figure 1.3.2 reveals a persistent warming that began in 1900 and continues until the present (2018), with some ups and downs. Most of the 1°C warming experienced since the beginning

Box 1.3.1 Global Warming Potential of Greenhouse Gases

Each greenhouse gas has a different capacity to trap heat in the atmosphere. One way we can measure this is through **global warming potential** (**GWP**), which compares the heat-trapping effect of a gas to the effect of an equal mass of carbon dioxide.

Different gases stay in the atmosphere for different time periods; scientists call the time a particular gas remains its **lifetime**. Since the warming effect of a gas depends in part on how long it stays in the atmosphere, global warming potential must be defined for a specific time period, usually 20 years or 100 years.

The table below lists the 100-year global warming potential (GWP100) for three of the most important greenhouse gases. For example, the 100-year GWP of methane is given as 30 (with a range of 28 to 36). This means that if we were to emit equal masses of methane and carbon dioxide into the atmosphere at the same time, the methane would trap 30 times as much heat energy as the carbon dioxide over a period of 100 years.

Greenhouse gas	*Chemical Formula*	*Lifetime in the Atmosphere (years)*	*GWP (100 years)*
Methane	CH_4	12	30
Nitrous Oxide	N_2O	114	298
HFC-134a*	CH_2FCF_3	14	1,430

* HFC-134a is a commonly used refrigerant and is given as an example of a hydrofluorocarbon (HFC). There are dozens of different HFCs in use, with GWP values ranging from a few hundred to several thousand.

We can use global warming potentials to define "equivalent emissions" in terms of CO_2. Scientists call this the **CO_2 equivalent**, typically written as "CO_2e" or "CO_2eq." For example, since methane has a GWP of 25, the release of 1 ton of methane would have a warming effect comparable to 25 tons of CO_2. This might be described as the addition of 25 tons of CO_2e. When looking at greenhouse gas emission numbers, it's important to note whether they're expressed in tons CO_2 or tons CO_2e.

You may have noticed that carbon dioxide is not included in the table; its GWP is 1 by definition. Also, as we will see, carbon dioxide is removed from the atmosphere by a variety of different processes, so it's not possible to define a single lifetime for CO_2.

Also notice that two important greenhouse gases, water vapor and ozone, are not included in the table. That's because their lifetimes in the atmosphere are extremely short, only a few days or weeks, so it's not meaningful to define a 100-year global warming potential for them.

SOURCES: Climate Change 2013: *The Physical Science Basis*. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T. F., et al. (eds.)]. Lifetimes, Radiative Efficiencies and Metric Values, Table 8.A.1 Cambridge University Press, New York, NY.; UNEP. 2012. *The Emissions Gap Report 2012*. United Nations Environment Programme, Nairobi, Kenya.

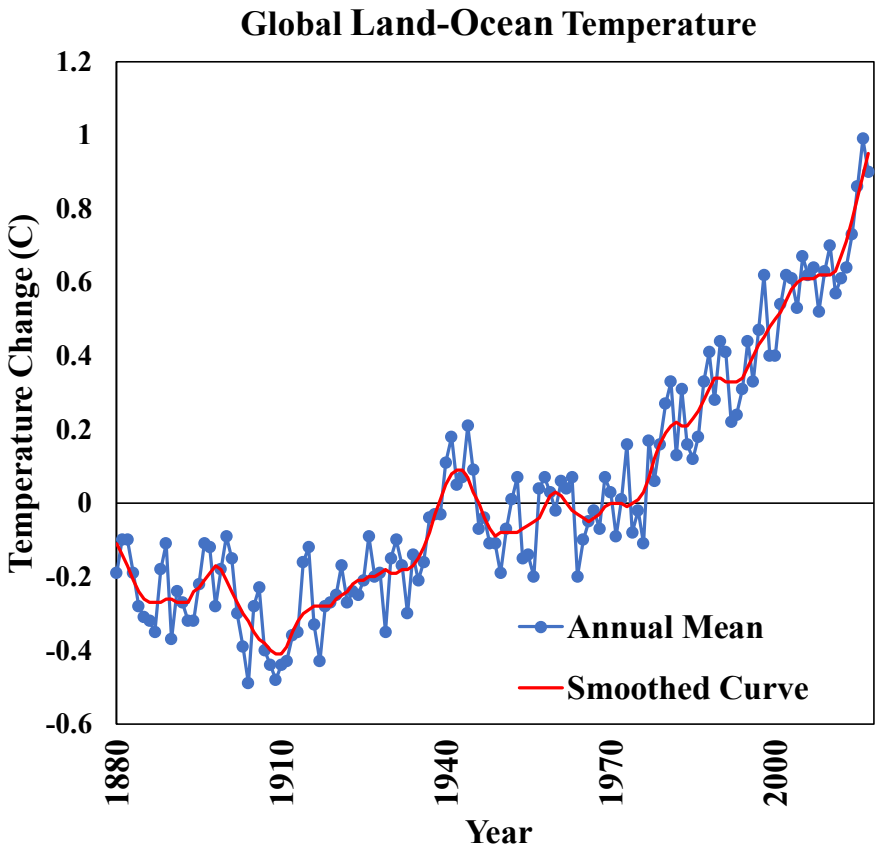


FIGURE 1.3.2 **Changes in global averaged land and sea surface temperatures since 1880, relative to 1951–1980 average.** Adapted from NASA/GISS.

of the twentieth century happened after the Great Acceleration began in the 1950s.

A similar pattern is observed in the ocean to a depth of at least 700 meters. The warming can be seen over the whole globe with very few exceptions. Most every region has experienced the warming, but it is not uniform. For example, the land surfaces have warmed more than the sea surface. This is expected since the land surface has less thermal inertia than the sea and hence warms more rapidly than the ocean. The Northern Hemisphere has warmed more than the Southern Hemisphere, again largely because of the ocean's influence: the spatial extent of the ocean is not as great in the Northern Hemisphere. The northern polar regions have warmed twice as much as the global average: more than 2°C compared with the global average of 1°C.

If we keep adding climate pollutants at the present rate, global temperatures will continue to increase to more than 2°C by 2050, and to a catastrophic 3°C to 7°C by end of this century.

How do we know the warming is due to human activities?

A large amount of evidence and many lines of evidence-based reasoning have led scientists to conclude unequivocally that the warming is caused by the increase in the thickness of the greenhouse blanket of CO_2, methane, CFCs, ozone, and nitrous oxide. There are two primary grounds for this conclusion:

1. Natural changes are much too small to produce the observed warming. There are three main ways that natural changes can contribute to climate change. First, changes in processes within the sun can cause variations in incoming solar energy. However, incoming solar energy has been regularly monitored by satellites since the late 1970s, and the observed variations in incoming solar energy are about a factor of 10 lower than the 3 W/m^2 increase caused by anthropogenic thickening of the greenhouse gas blanket. Even more significantly, changes in solar output over the last couple of decades have been in the *opposite* direction. That is, the sun's energy output has *decreased* slightly, which would tend to cause cooling, not warming.

A second natural factor that can affect climate is variation in the Earth's orbit around the sun. These orbital changes play a significant role in climate changes on time scales of 10,000 years or more (for example, the cycles between glacial and interglacial periods), but they have negligible effects on time scales of a century or so. They are simply too slow to be responsible for the warming observed over the past few decades.

The third natural factor that can cause climate changes is volcanic eruptions. Volcanoes put out sulfur gases that get converted into reflective aerosol particles in the atmosphere. By reflecting solar energy back into space, these particles cool the climate. Volcano-induced cooling is real but lasts for less than 5 years. The change in reflected solar radiation due to volcanoes and the resulting temperature changes have been measured

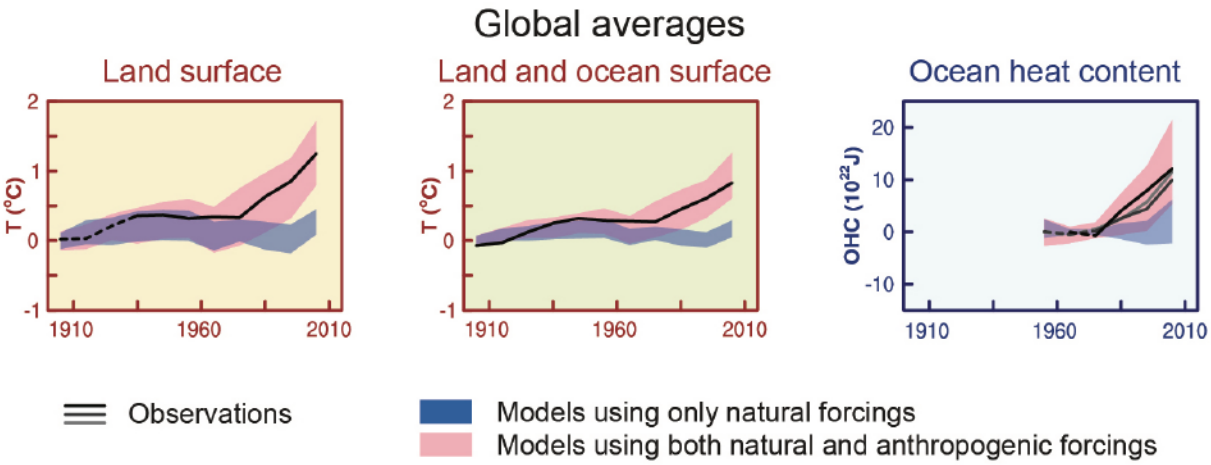


FIGURE 1.3.3 Observed temperatures compared with those from models using only natural factors and with those from models using both natural and anthropogenic factors. Reproduced from IPCC.

from both surface instruments and satellites. For example, the eruption of Mount Pinatubo in the Philippines in 1991 produced a measurable drop in global temperatures for at least 2 years. As the sulfate particles are gradually removed from the atmosphere, temperatures tend to return to previous levels. Although volcanoes do emit carbon dioxide, these emissions are less than 1% of human-generated CO_2. Scientists have concluded that apart from temporary cooling, volcanoes have had very little effect on the rapid warming trend observed since the 1980s.

2. Models can simulate the observed warming only if they include human activities. The most sophisticated climate models to date account for both natural variations and the human-caused increase in greenhouse gases. Model runs that include only natural variations show year-to-year fluctuations in temperatures, but they completely fail to reproduce the current warming trend. Only when models include the anthropogenic thickening of the greenhouse blanket do they reproduce the observed warming of the planet. We can see this in Figure 1.3.3. The black lines represent observations, the blue regions represent the range of predicted temperatures from models that include only natural

factors, and the pink regions indicate the range of projections from models that include both natural and anthropogenic factors. The observed warming is far outside the range of projections that include only natural factors, but it is well within the range of projections that include anthropogenic factors as well. This leads climate scientists to conclude that anthropogenic changes are the dominant factor in recent warming.

Why trust the models?

This leads us to a question: Why should we trust the models? After all, they are just computer calculations. How do we know they accurately reflect the real world?

Scientists trust the models in attributing the observed warming to human activities because, in general, the model projections are consistent with the observed changes. Models have successfully predicted many changes that were later observed, a few of which are listed below:

- In 1980, models were used to predict that CO_2-induced warming would be detected by the year 2000. Indeed, in 2001 the comprehensive report written by over 1,000 scientists for the IPCC was the first to formally conclude that there was a discernible warming in the observed records.
- Models predicted that warming induced by greenhouse gases would penetrate to the deeper oceans. Scientists have deployed thousands of underwater probes in every major ocean basin, and their measurements show that warming temperatures have penetrated to at least 700 meters below the surface.
- Models predicted that the greenhouse-gas-induced warming would extend to the entire lower atmosphere (from the surface up to above 12 kilometers). This has been confirmed by balloon and satellite data.

The predictions suggested that a warmer atmosphere would become more humid and that the increase in water vapor would in turn amplify the warming because water vapor is a powerful greenhouse gas. Humidity data collected by weather balloons and microwave instruments

on satellites confirmed that water vapor has increased with the increase in temperature since the 1980s.

In the late 1960s, a Russian meteorologist predicted that as the planet warmed, sea ice and snow would retreat, making the surface less reflective and exposing the darker ocean below to solar energy. This reduced reflectivity would increase the solar energy absorbed by the Arctic Ocean, amplifying the warming. Indeed, satellite data have shown that the Arctic sea ice has retreated significantly since the late 1970s, followed by an increase in solar energy absorption by the Arctic Ocean and amplified warming. The Arctic region has warmed by almost 2.5°C, compared with the global average warming of 1°C.

But models are tested not just by their ability to successfully forecast changes in climate that are later observed. A typical test for modern climate models is their ability to reproduce *past* climate observations, such as the temperature record for the twentieth century. This process is called hindcasting. The ability of models to pass such tests increases scientists' confidence that they include the factors necessary to determine the causes of observed climate change, as well as to project changes likely to occur in the future.

Based on the results from models and other observations and analyses, the most recent report of the US Global Change Research Program, composed of 13 federal departments and agencies, concluded in 2017 that "it is extremely likely that human activities, especially emissions of greenhouse gases, are the dominant cause of the observed warming since the mid-20th century. For the warming over the last century, there is no convincing alternative explanation supported by the extent of the observational evidence."

Projecting future warming: climate feedbacks

As we have seen, we have a good scientific understanding of temperature increases over the past century. Warming is driven primarily by increases in concentrations of greenhouse gases. This warming has been partially offset by the net cooling effect of aerosols.

Past and future warming is governed by **climate feedbacks**, which happen when the climate system responds to temperature increases in ways that can either amplify or moderate warming. Three of the most

Box 1.3.2 Climate Change: Is the Science Settled?

Media coverage of climate issues sometimes gives the impression that there is significant scientific debate about climate change. In reality, the scientific community largely agrees about climate change—both the fact that it is occurring and *why* it is occurring. This understanding of the mechanics of climate change is based on fundamental physics and well-established scientific principles. We address some of the most common questions about the scientific consensus on climate change here.

What fraction of the warming is due to human activities?

My best estimate: 80% or more. How did I arrive at such a number? The science tells us that the variations in natural climate forcing (that is, solar and volcanic activities) are too small to account for the observed warming trends and at times contrary to them. Further, both pedagogical and complex climate models are able to simulate the observed warming magnitude (0.9°C to 1°C) only if they include the observed buildup of greenhouse gases since 1900. See Box 1.3.3 for details of these calculations.

So, is the science settled?

The answer depends on what aspect of climate change science you ask about. Some of the most important questions have been answered with a high degree of confidence, as summarized in Table 1.3.1.

What aspect of the science is not settled?

Predictions of *future* warming are less certain. In the first place, we do not know how much climate pollution humans will emit over the coming decades. Even for a particular emissions scenario, however, climate models give a wide range of estimates. Some of the major reasons for this range include varying assessments of factors such as aerosols, cloud feedbacks, and other feedbacks due to the response of soils and plants to warming temperatures.

With sufficient warming, there is also the possibility of abrupt and irreversible changes if global temperatures cross "tipping points" that can push the climate into new states. Examples of tipping points include significant methane releases from melting permafrost or large-scale changes in ocean circulation. Unfortunately, the temperature thresholds for these tipping points are not well understood.

These feedbacks and dynamic processes mean that we must present any conclusion regarding the Earth's future warming as a probable range rather than a single value.

TABLE 1.3.1 Summary of scientific consensus

Question	*Reply*
Is the atmosphere getting more polluted?	Yes
Are the greenhouse gases CO_2, methane, and others increasing?	Yes
Are the increases due to human activities?	Yes
Is the climate warming?	Yes
Is the warming in part due to human activities?	Yes
What fraction of the warming is due to human activities?	50%–90%
What human activities are responsible for the warming?	Increase in CO_2, other greenhouse gases, and black carbon particles due to human activities
Can we make precise predictions of future temperatures?	No. We can only provide probabilistic values.

important feedbacks we need to consider in relation to climate change in the twentieth and twenty-first centuries are the following:

1. Water vapor feedback: We have already discussed this feedback earlier in the chapter. When the temperature of the atmosphere increases, it holds more water vapor. Since water vapor is a greenhouse gas, this feedback acts to amplify warming, resulting in temperature changes that are roughly twice as large as would be expected from the increase in greenhouse gases alone.
2. Ice-albedo feedback: As described in the previous section, increasing temperatures reduce snow and sea ice cover, which decreases albedo and amplifies warming. This feedback has its strongest effect in the Arctic, which is why this region has warmed substantially more than the global average.
3. Cloud feedbacks: Clouds can affect temperatures in two different ways. Clouds reflect sunlight, which tends to cool the Earth. However, the liquid water or ice crystals in clouds also trap infrared radiation, causing warming. It turns out that low, thick clouds have a net cooling effect, while high cirrus clouds have a net warming effect. Thus, the overall feedback from clouds depends on whether a warmer world would have more low,

Box 1.3.3 Can Climate Science Account for the Observed Warming Trends?

Certainly—let me walk you through a little bit of math. We've already mentioned that scientists measure incoming solar radiation and outgoing heat in units of watts per square meter (W/m^2). The physics behind the heat-trapping effect of greenhouse gases is well understood, so we can calculate the imbalance they create in outgoing versus incoming radiation. Scientists call this imbalance *greenhouse gas forcing*. For the amount of greenhouse gases in the atmosphere in 2005, we find that the forcing is about 3 W/m^2.

How much warming would that 3 W/m^2 forcing be expected to cause? To calculate this, we divide the greenhouse gas forcing by a number called the *climate feedback parameter*. Our best estimate of this number is 1.3 $W/(m^2\ °C)$, read as "1.3 watts per square meter per degree Celsius." This means that a forcing of 1.3 W/m^2 would be expected to raise the global temperature by 1°C. Thus we are able to derive the theoretical warming that we should have seen from greenhouse gases alone by dividing 3 W/m^2 by 1.3 $W/(m^2\ °C)$, resulting in an expected warming of 2.3°C. However, we have only observed 1°C. Where is this difference coming from?

First, not all of the warming appears at the Earth's surface; approximately 0.5°C is stored by the oceans. Also, greenhouse gas forcing is not the whole story. About 0.7°C of the expected warming is reversed by aerosol cooling, and 0.2°C is reversed by changes in surface albedo, mainly due to clearing of forests for agriculture and grazing. When we subtract out warming that was stored by the oceans or reversed (2.3 − 0.5 − 0.7 − 0.2), we arrive at 0.9°C expected warming for the surface (Table 1.3.2). This is a good match for the 1°C warming that has been observed.

What about natural factors, such as changes in the energy radiated by the sun, volcanic eruptions, or natural variability due to heat exchanges between the oceans, atmosphere, and land? These factors have been examined carefully, and the conclusion is that they could cause the global temperature to vary up or down by as much as 0.2°C. In short, natural factors alone are far too small to account for the observed 1°C warming. We can only account for the observed warming by including the effects of anthropogenic greenhouse gas emissions.

SOURCE: Myhre, G., et al. 2013. Anthropogenic and natural radiative forcing. In *Climate Change 2013: The Physical Science Basis*. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T. F., et al. (eds.)]. Cambridge University Press, New York, NY. https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter08_FINAL.pdf.

TABLE 1.3.2 Theoretical warming breakdown

Factor	*Warming*
Greenhouse gas forcing (2005)	3 Wm^{-2}
Climate feedback parameter	1.3 Wm^{-2} °C^{-1}
Theoretical warming we should have seen with just greenhouse gas forcing (= greenhouse gas forcing divided by the climate feedback parameter = 3/1.3)	2.3°C
Observed warming	1°C
Ocean heat storage. This is the heat energy stored in the ocean, and it will be released as surface warming in a few decades.	−0.5°C
Masking by aerosol cooling	−0.7°C
Surface albedo changes	−0.2°C

thick clouds or more high cirrus clouds. Including cloud effects in computer models is difficult because of their relatively small size and complex formation processes. The current scientific consensus is that, overall, cloud feedbacks are likely to have a small amplifying effect on warming. However, cloud feedbacks continue to be one of the largest sources of uncertainty in computer projections of future temperatures.

1.4 Impacts of Climate Change

Climate change affects all aspects of life on the planet, including ecosystems, social systems, economics, public health, urban systems, and rural systems. The observed warming of 1°C is already having an impact on these systems. With unchecked emissions, warming could reach unmanageable levels this century. It may be better to call it *climate disruption* rather than climate change.

As shown in Figure 1.4.1, the Earth's climate has varied significantly over the last 1,000 years. Global records for this period are not available, but proxy records such as tree rings and pollen suggest that the northern half of the Northern Hemisphere experienced significant warming (0.5°C) during the **Medieval Warm Period** from AD 950 to 1250. While Europe enjoyed the warmth and Vikings traveled westward to found settlements in Greenland, other regions, including the American Southwest, suffered from megadroughts and heat waves. The unlucky regions included North America, Central and South America, and northern China. The legendary city and massive temple complex of Angkor Wat in Cambodia were abandoned largely because of decades-long megadroughts interrupted by occasional episodes of intense rainfall and flooding. The Medieval Warm Period was followed by the **Little Ice Age** from about the mid-1600s to the mid-1800s, which saw widespread cooling over the North Atlantic and Europe, with global temperatures on the order of 0.5°C cooler than in the mid-twentieth century. The Thames River in London froze over multiple times during this period.

These climate events serve to illustrate the strong vulnerability of civilizations to climate change. However, the large climate changes experienced during the past 1,000 years cannot be assumed to be a reliable guide for expected climate changes in the coming decades, in part because the Medieval Warm Period was neither global nor widespread, even over the Northern Hemisphere. We will begin with the

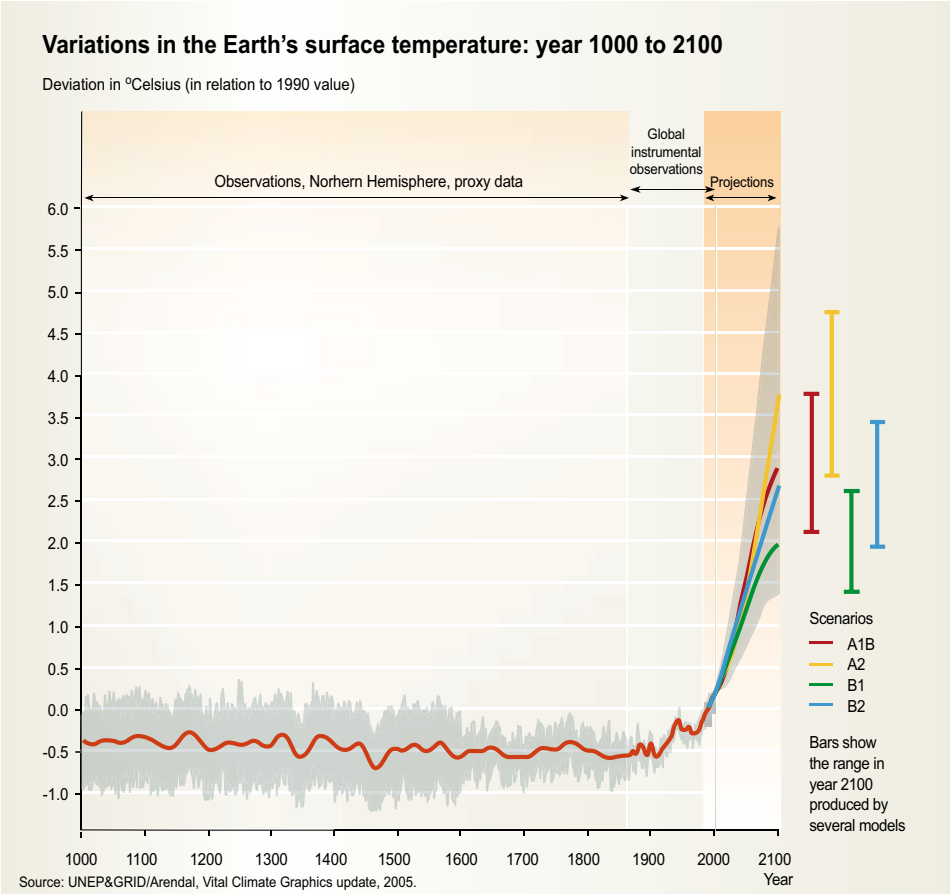


FIGURE 1.4.1 Observed temperature changes during the last 1,000 years compared with the predicted changes from 2018 to 2100. Reproduced from UNEP/GRID-Arendal.

documented impacts of twentieth-century warming on a global scale. As we will see, temperature changes during the twentieth and twenty-first centuries have been larger than those of either the Medieval Warm Period or the Little Ice Age, with significant climate impacts. After that, we will look at the projected impacts of continued warming during the twenty-first century.

Current impacts: twentieth and early twenty-first centuries

About two-thirds of the 1°C warming recorded since the beginning of the twentieth century has occurred in the past four decades, starting

around 1980. As of this writing (2019), 2009 to 2018 has been the hottest 10-year period on record.

As previously discussed, a warmer atmosphere holds more water vapor, so as the planet warms, it becomes more humid. Warmer temperatures also increase the overall cycle of water evaporation and precipitation, making drier regions even drier and wetter regions wetter. Dry areas worldwide have increased from about 15% of the Earth's land surface during the mid-twentieth century to about 30% by the first decade of the twenty-first century.

The last two decades have also witnessed record increases in extreme weather events. The incidence of very strong hurricanes (category 4 and 5) has increased at the rate of about 25% per degree of global averaged warming. The number of disastrous floods has increased from less than 50 per year during the mid-twentieth century to more than 150 per year during the first decade of the twenty-first century.

How do we know the increase in extreme weather is due to anthropogenic global warming? The science of attributing individual extreme events to climate change has improved significantly. Multiple factors are involved in any extreme event, so it's not possible to say that a specific weather event was "caused" by global warming, but we can determine how much more *likely* that kind of event is, given the increased temperatures. For example, the record Russian heat wave of 2010, which claimed 15,000 lives, as well as many of the major storms and droughts witnessed in 2016, have all been statistically attributed to global warming with about 80% certainty. That is, there is a four in five (80%) chance that the Russian heat wave would not have occurred in the absence of human-induced climate change. It's estimated that widespread warming and rising humidity increased the probability of extreme weather, particularly heat waves, by a factor of 10 or more from 2011 to 2015. An analysis of 170 reports on 190 extreme weather events from 2004 to mid-2018 suggests that about two-thirds of these extreme weather events were made more likely, or more severe, by anthropogenic climate change.

The impacts of global warming can also be seen in its effects on ice and sea levels around the planet. Since 1980, the summer extent of Arctic sea ice has decreased by as much as 10% to 15%. Glaciers

Box 1.4.1 Observed Impacts of Global Warming (Late Twentieth and Early Twenty-First Centuries)

Impacts on ecosystems

- As we saw earlier in this chapter, trees and other plants absorb and store carbon dioxide from the atmosphere. Prior to the twenty-first century, tropical forests acted as a net absorber (sink) of carbon dioxide. For example, a young growing tree would absorb carbon in carbon dioxide, while a dying tree would release that carbon back to the air. However, during the first decade of the twenty-first century, tropical forests became a net source of CO_2 because of degradation from drought and warming.
- Corals get most of their energy from single-cell, photosynthetic organisms that live in their tissues. However, if water temperatures are too warm, the corals expel these photosynthesizing organisms and are left as white skeletons. This is called coral bleaching. If warm conditions persist for weeks or months, the coral may die. Coral bleaching due to warming is happening in most coral reefs; the most severe global bleaching event in recorded history occurred from 2015 to 2017. During this period, it is estimated, as much as half of the coral in Australia's Great Barrier Reef was killed.

Impacts on human societies and human health

- Warming and droughts have increased water demand over 86% of cropping area by about 2.3% to 3.6% per decade since 1981, contributing to significant reductions in wheat yield and increase in plant diseases.
- Adverse health impacts of climate change, such as heat stress, have been documented extensively. The Lancet Commissions, which consists of international experts in public health, air pollution, and climate change, concluded in 2015 that the "effects of climate change are being felt today, and future projections represent an unacceptably high and potentially catastrophic risk to human health."
- Threats to health, both physical and mental, also arise from decreases in food security and water availability. These threats include increases in waterborne diseases such as childhood gastrointestinal diseases caused by floods. Due to worldwide increases in temperature and humidity, insect-borne diseases, such as malaria, dengue fever, Lyme disease, and chikungunya, are migrating outside the tropics and to higher altitudes.
- The number of people displaced because of weather extremes has increased to 21 million people.

are melting worldwide. Major ice sheets, particularly in Greenland and West Antarctica, are losing mass at a significant rate. Sea levels are rising at a rate of about 3 millimeters per year because of the melting of glaciers and ice sheets and the expansion of seawater as the ocean warms. The ocean is also becoming more acidic because of absorption of CO_2, which produces carbonic acid.

The changes described above have had significant impacts on natural ecosystems as well as human society and human health. A few of the observed impacts are detailed in Box 1.4.1.

Climate change to climate disruption

For the first time, the statistical barrier against identification of climate change as causal factor for extreme weather events was overcome. The scientifically cautious American Meteorological Association (AMS) issued the remarkable statement:

> For years scientists have known humans are changing the risk of some extremes. But finding multiple extreme events that weren't even possible without human influence makes clear that we're experiencing new weather, because we've made a new climate.

The United Nations Office for Disaster Risk Reduction estimates that from 1995 to 2015, weather-related disasters have claimed 606,000 lives; furthermore 4.1 billion people have been injured, made homeless, or required emergency assistance. In addition, the UN agency estimates the number of disasters during the latter half of the 20-year period was double that of the first 10-year period. Climate change is thus bringing new weather extremes and fatal catastrophes—meaning that *climate change* is better termed *climate disruption*. Unchecked climate change is likely to become unmanageable. That could happen in a matter of few to several decades as discussed next.

The next three decades: impacts of 2°C warming

As of 2010, we have already emitted 2 trillion tons of carbon dioxide. As discussed earlier in this chapter, nearly half of that amount is still in the atmosphere—990 billion tons of CO_2, trapping 860 terawatts of heat energy. Since 2010, we have added another 200 billion tons, bringing the

total to 2.2 trillion tons as of 2018. Even if we were to stop emissions immediately, the Earth would warm by another 0.5°C by 2030 to compensate for the heat energy trapped by the already emitted CO_2, along with non-CO_2 pollutants. Emissions to date have already committed us to this 0.5°C rise in temperature, which would bring the total warming since 1850 to 1.5°C. For comparison, even the 1°C of warming experienced during the Eemian interglacial 130,000 years ago was sufficient to increase sea level by 6 to 9 meters.

At current emission growth levels, under a "business as usual" scenario, we will add another *trillion* tons of carbon dioxide to the atmosphere within the next 15 years, by about 2030. This additional carbon dioxide is likely (with a probability of at least 50%) to mean that total warming will exceed 2°C before 2050. At that point, the decadal rate of climate change will be *three times* faster than the pace experienced until now. Most climate scientists and ecologists concur that 1.5°C to 2°C represents the warming threshold for dangerous climate impacts.

The impacts of 2°C warming would be quite severe. Rising temperatures will result in an increase in the frequency and duration of severe heat waves. It's estimated that with 2°C warming, well over 3 billion people—about 40% of the human population by 2050—would experience summer mean temperatures hotter than the current *record hottest* summers in one out of every two years. Moreover, about 1.8 billion people would be exposed to lethal heat for more than 20 days a year. Increasing temperatures will also lead to more droughts and wildfires, as well as increases in severe storms and flooding.

One impact with truly global consequences is sea level rise. Even in the unlikely event that warming is stabilized at 1.5°C, sea level rise will continue for centuries because of ongoing melting of the Greenland and West Antarctic ice sheets. Studies of data for the past million years suggest that a 1°C warming (equivalent to the Eemian warming) is sufficient to lead to an eventual sea level rise of 6 to 9 meters over several centuries, and a 2°C warming could lead to a rise of 6 to 13 meters. Since more than 75% of the population will be living in coastal cities by the end of this century, sea level rise of such magnitudes has enormous negative implications for displacement and mass migration

Box 1.4.2 Impacts of 2°C Warming

- Highly populated regions, such as the eastern and western United States, Middle East, South Asia, and China, could experience heat waves worse than the most severe Russian heat wave of 2010, when temperatures reached 55°C (131°F).
- About 600 million additional people will be exposed to dengue, chikungunya, and many other viruses because of the expanded range of disease-carrying mosquitoes.
- Moderate to severe widespread droughts and fires will occur worldwide. Both rural and urban populations will be affected by air pollution, loss of property, and land degradation that reduces food production and contributes to volatile food prices.
- Floods and storms will become more frequent and/or intense. Scientists are still debating whether the frequency of hurricanes will increase, but the storms that do occur are expected to be stronger, meaning an increase in the strongest (category 4 and 5) hurricanes.
- The climate could reach a tipping point when forest recovery time increases to more than 55 months and the intervals between droughts decrease to *less* than 55 months. If that happens, forests may not recover from droughts and fires.

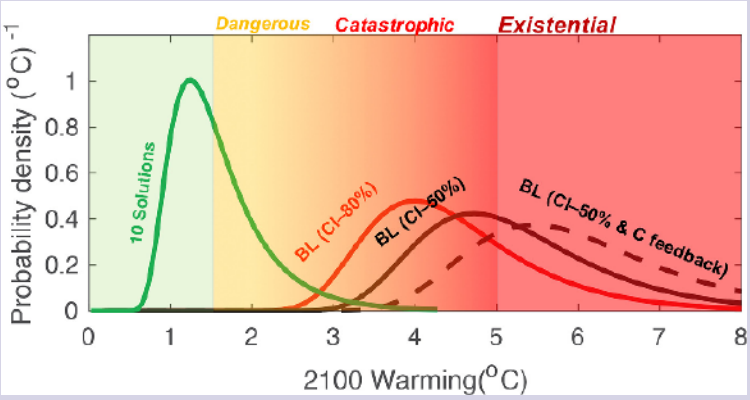
of people, disruption of social systems, and exacerbation or creation of international conflicts.

Box 1.4.2 provides some additional examples of the impacts of 2°C warming.

The late twenty-first century: warming of 4°C or more

By the end of this century, a business-as-usual path with unchecked emissions will lead to warming that could exceed 4°C. As we discussed in Section 1.3, projections by models give a range of possible future temperatures because of differing model treatments of climate feedbacks that can either amplify the warming or moderate it. These feedbacks, as discussed earlier, include increasing water vapor in the atmosphere and the melting of Arctic sea ice, replacing the reflective ice surface with open ocean waters that absorb additional solar radiation and amplify

Box 1.4.3 Dangerous to Existential Risk: Categories of Projected 2100 Warming



The green curve on the left labeled "10 Solutions" represents a scenario in which emissions are curtailed or phased out completely, employing the ten solutions described in Chapter 4. The other three curves in red and brown represent scenarios with unchecked emissions.

For the red and brown curves, BL = baseline, meaning no significant mitigation efforts. CI = carbon intensity, referring to the amount of carbon dioxide emitted per unit of the global economy. Because of shifts in the economy and increasing costs of fossil fuels, it's expected that the carbon intensity of the economy will decrease even without significant mitigation efforts. However, because the world economy will continue to grow, actual carbon emissions are expected to increase. For example, if the carbon intensity of the world economy were to decrease by half while the economy grew to four times its present size, total emissions would double.

There are specific scenarios shown: BL (CI–80%), the lowest-emission scenario of the three, in which carbon intensity decreases 80% by 2100; BL (CI–0%) in which carbon intensity decreases 50% by 2100; and BL (CI–50% & C feedback), which is the same as the second scenario except that it also accounts for feedbacks such as a decrease in carbon dioxide uptake by soils as temperatures increase, meaning that more carbon dioxide would stay in the atmosphere.

SOURCE: Ramanathan, V., et al. *Well Under 2 Degrees Celsius: Fast Action Policies to Protect People and the Planet from Extreme Climate Change, 2017.* Image from Figure 1. http://www.igsd.org/wp-content/uploads/2017/09/Well-Under-2-Degrees-Celsius-Report-2017.pdf.

Box 1.4.4 Impacts of 4°C Warming or Greater

- Warming of 4°C would likely expose over 70% of the population (this would be about 7.5 billion people by 2100) to lethal heat waves. More than 2.5 billion people could be exposed to diseases carried by mosquitoes and other pests.
- Warming of 4°C would likely expose about 20% of natural species to extinction. This is in addition to the roughly 50% or more of species that will be exposed to extinction through habitat destruction by the 11 billion humans populating the planet by 2100. An extinction rate of 70% or more is considered to be a **mass extinction** similar to what happened during the Cretaceous period when dinosaurs disappeared from the planet.
- Over several centuries, warming greater than 5°C could result in an ice-free Earth, with a rise in sea level of more than 90 meters. Widespread droughts are likely the most serious outcome, threatening food and water for most of the 11 billion people expected to be on the planet by 2100 (Figure 1.4.2).
- These impacts will be in addition to worsening droughts, floods, fires, storms, hurricanes, and dying forests. Widespread droughts are likely the most serious outcome, threatening food and water security for most of the 11 billion people expected to be on the planet by 2100.
- These weather extremes, sea level rise, and the spread of vector-borne viral diseases will likely lead to the mass migration of millions of human beings.

warming. We also saw that one of the largest sources for the temperature range projected by climate models is differing projections of how the amount and distribution of clouds will change in a warming world. Because of this, scientists express projections of future temperature in terms of a range of *probabilities* rather than a single temperature.

The curves in Box 1.4.3 show the probability of various levels of warming for different scenarios of emissions growth. The three curves in red and brown to the right side of the curve are for scenarios in which emissions growth is essentially unchecked.

The key point is that continued growth in emissions would result in

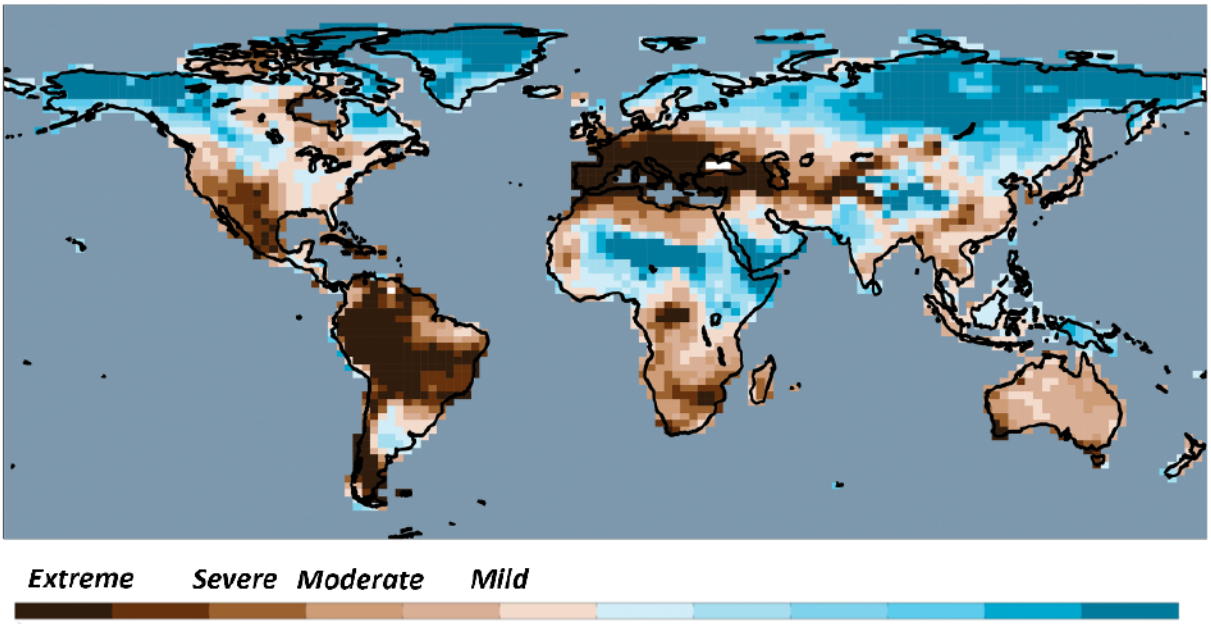


FIGURE 1.4.2 Soil moisture conditions in 2080–2099 with unchecked emissions as simulated by the Princeton University climate model. Adapted from Cook et al. 2015.

temperatures that expose human society and natural ecosystems to very severe threats. In these scenarios, the likely warming by 2100 ranges from less than 3°C to more than 7°C. There is less than 10% probability that the warming will be less than 3°C, and less than 10% probability that it will be greater than 7°C.

Warming in excess of 4°C would produce catastrophic changes, while warming of 5°C or more would have impacts so severe that it could pose an **existential threat** to society, as illustrated by the findings in Box 1.4.4.

One type of high-impact consequence that is of major concern is the possibility of **runaway feedbacks**. For example, large temperature increases could result in methane release by warming permafrost and wetlands and the disappearance of sea ice and glaciers. This could start a feedback loop in which higher temperatures cause more methane to be released, in turn causing further warming. Such a feedback loop would be outside human control and could undo much of the benefit of any reductions in anthropogenic emissions.

Extreme temperature increases of 6°C or greater are an example of **low-probability, high-impact events**. While the chance that these events will occur may be comparatively low, their consequences would be so severe that significant efforts to avoid them are warranted. One way to think about this is to consider the question, Would you get on a plane if you knew there was a 10% chance it would crash? While there is a high probability (90%) that you would survive the flight, the severe consequences of the "low-probability" crash might make you rethink your plans.

However, the green curve in Box 1.4.3, labeled "10 Solutions," represents the warming probability if the ten climate solutions presented in Chapter 4 are implemented. Note that this curve gives a high probability of remaining below the 2°C threshold for dangerous climate change. The green curve shows us there is real hope that if we act now, we will be able to avoid the most serious negative consequences of climate change.

1.5 Summary: What Have We Learned So Far?

- Many scientists propose that the current era be called the Anthropocene in view of the fact that human beings have emerged as a major force transforming the planet, comparable to major geological events.
- Human impacts on climate began gradually with the Agricultural Revolution that started 10,000 years ago; the rate of transformation picked up with the Industrial Revolution that started around 1750. Two hundred years later, there was a quantum jump in the pace of transformation with the Great Acceleration beginning in 1950.
- The post-1950 period witnessed massive changes in the composition of the atmosphere due primarily to the use of coal and petroleum for power generation, transportation, and industries.
- Climate change caused by emissions of greenhouse gases and black carbon has emerged as one of the iconic impacts of the Anthropocene.
- The primary sources for anthropogenic CO_2 emissions are fossil fuel combustion, biomass burning, cement manufacturing, and deforestation and other land use changes. Methane sources include natural gas leaks during production, processing, and transmission; wood burning; cattle and other livestock; rice paddy agriculture; and landfills and sewage water treatment plants. Sources for CFCs and HFCs are refrigeration and air conditioning. Ozone is not directly emitted by human activities, but the emissions of ozone precursor gases (methane, nitrogen oxides, volatile organics) produce ozone in the lower atmosphere. Nitrous oxide is released by agriculture as a result of fertilization. Black carbon is produced by diesel combustion; burning of solid coal; and burning of firewood, crop residues, and dung for cooking.

- The emitted greenhouse gases cover the planet like a blanket and trap the heat energy (infrared radiation) emitted by the surface. This trapped heat energy warms the planet. Carbon dioxide is the most important warming pollutant, contributing as much as 55% of the present-day warming. Other greenhouse gases and black carbon particles contribute the remaining 45%. The planet has already warmed by about 1°C because of this added heat. All parts of the Earth system, including the atmosphere, land, oceans, glaciers, and sea ice, are warming. The warming has extended down to 700 meters below the ocean surface and up to about 12 kilometers in the atmosphere—just as predicted by climate science and climate models. The last time the planet was this warm was during the Eemian interglacial period of 130,000 to 115,000 years ago. Impacts of this warming include heat waves, severe storms, droughts, and sea level rise.
- Climate change science is intensely data driven. The changes in the planetary climate have been documented by thousands of instruments at the surface and aboard ships, aircraft, balloons, and satellites. These data have been integrated into sophisticated climate models run by the world's fastest computers to determine the causes and impacts of climate change.
- The validity and veracity of models have been assessed by simulating climate changes during the twentieth century and so far in the twenty-first century, and then comparing the models' predictions against observations. Predictions that have been verified include when human-induced warming would be detected above the background natural variations; amplifying feedbacks involving water vapor, sea ice, and sea level rise; and the depth of penetration of the warming in the oceans and the atmosphere.
- The observed 1°C warming has already led to a substantial retreat of sea ice, an increase in hurricane intensity, an increase in the intensity of precipitation worldwide, large-scale droughts and more frequent fires, and a tenfold increase in extreme temperatures and lethal heat waves. Major health impacts have also been documented.
- The planet is currently on a path to warm to 1.5°C (from preindustrial

levels) within 15 years, most likely by the year 2030. If we keep adding climate pollutants at the present rate, it will continue to warm to 2°C by 2050, and to a catastrophic 3°C to 7°C (95% confidence range) by the end of this century. The potential impacts on human health, ecosystem health, and species extinction lead to the conclusion that warming in excess of 5°C would pose existential threats to *Homo sapiens* (all 11 billion of us) and numerous other species.

As we have seen in this chapter, the science of global warming is clear, and the potential impacts of continuing emissions for human society and natural ecosystems are severe. There is still time to act, but we have only about 20 years to bring all of the solutions described in this book up to full speed.

Fortunately, a range of climate solutions that offer real hope are available and will be explored in detail in the remainder of this book. These solutions will help provide you, climate warriors, with the tools to avoid such a catastrophic future.

Supplementary Readings

Check out the following resources for more information and discussion topics:

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Intergovernmental Panel on Climate Change. *Climate Change 2013. The Physical Science Basis: Frequently Asked Questions*. https://www.ipcc.ch/report/ar5/wg1/.

For more comprehensive and detailed scientific reports, see these sources:

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The Intergovernmental Panel on Climate Change. http://www.ipcc.ch.

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Figure 1.2.1: Ramanathan, V. Bending the Curve: Lecture 1, Module 2. Icons designed by Freepik from http://www.flaticon.com/packs/ecology-enviroment-2.

Figure 1.2.2: Earth image from Apollo 16 in 1972. https://nssdc.gsfc.nasa.gov/imgcat/html/object_page/a16_h_118_18873.html.

Figure 1.2.3: Photograph by Matthew Henry on Unsplash.

Figure 1.2.4: All images from NASA. Venus image: https://nssdc.gsfc.nasa.gov/image/planetary/venus/pvo_uv_790205.jpg. Earth image: https://www.nasa.gov/image-feature/nasa-captures-epic-earth-image. Mars image: https://www.jpl.nasa.gov/news/news.php?feature=5473.

Figure 1.2.5: Image from NOAA. https://sos.noaa.gov/datasets/earth-our-goldilocks-planet/.

Figure 1.2.6: Image from the Scripps CO_2 Program from the Scripps Institution of Oceanography. http://scrippsCO2.ucsd.edu/graphics_gallery/mauna_loa_and_south_pole/mauna_loa_and_south_pole.

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Figure 1.3.1: Top left photograph by Alan Kiniry, reproduced from https://www.pexels.com/. Top right image reproduced from https://pixabay.com/. Bottom left photograph by V. Ramanathan. Bottom right image reproduced from https://pixabay.com/.

Figure 1.3.2: Repurposed image obtained from NASA's Goddard Institute for Space Studies (GISS). https://climate.nasa.gov/vital-signs/global-temperature/.

Figure 1.3.3: Image from IPCC. 2013. Figure SPM.6. Page 18. https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_all_final.pdf.

Figure 1.4.1: Variations in the Earth's surface temperature: year 1000 to 2100. UNEP/GRID-Arendal, Vital Climate Graphics update, 2005. Page 26. https://www.uncclearn.org/sites/default/files/inventory/unep125.pdf.

Figure 1.4.2: Cook, B. I., et al. 2015. *Global Warming and 21st Century Drying*. Drought Index for 2080–2099: NOAA-Princeton Univ Model Study. https://www.ldeo.columbia.edu/~bc9z/cook_pdsi_clidyn_REV_v01.pdf.

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CHAPTER 2

Humans, Nature, and the Quest for Climate Justice

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Learning Objectives

This chapter will teach you how to do the following:

1. Recognize the disproportionate impact of climate change on the world's most vulnerable people.
2. Understand the difference between climate mitigation and climate adaptation and why vulnerable populations are less capable of both.
3. Understand the difference between the intergenerational and intragenerational impacts of climate change.
4. Be familiar with a variety of perspectives about the relationship between humans and nature, as well as with the negative environmental and human consequences of asserting human dominion over the natural world.
5. Appreciate the urgency of climate justice.
6. Understand global and local trends associated with climate injustice.
7. Discuss major climate policy frameworks.
8. Be familiar with core climate justice movement ideas, actions, and visions of change.

Overview

This chapter will address the impact of climate change on human populations and the ecologies that sustain human life. "Climate justice" is a set of global responsibilities toward those who are least responsible for causing climate change but most negatively affected by it. This chapter will emphasize the urgency of climate justice in our world today, and it will hopefully stimulate thinking about what you, as a climate champion, can do to address it.

Section 2.1 defines climate justice and climate injustice, focusing on how climate change affects the bottom 3 billion—that is, the poorest people in the world. Here, we will explore the environmental and human harms of climate change, emphasizing the disproportionate

impacts of climate change on the world's most vulnerable populations. Climate change and poverty are inextricably linked. In this section, we will also consider the difference between the *intergenerational* and *intragenerational* harms of climate change—harms both to those now living, and to those yet to be born.

Section 2.2 will reflect on the historical relationship between humans and the natural world. We will encounter a variety of religious and secular views, past and present, about the relationship between humans and nature, ranging from justifications for human *dominion* to perspectives that advocate a more *harmonious* relationship. This section is mindful of the devastating real-world consequences of human dominion over nature both for the environment and for people, especially the most vulnerable. We will stress the need for a more harmonious perspective.

In Section 2.3, we will explore the disproportionate impacts of climate change on vulnerable people around the world and the resulting ethical imperatives for us as a global community. This section will introduce the difference between adaptation and mitigation; we will explore why poorer communities are less capable of both adapting to a warming climate and participating in global mitigation strategies to reduce greenhouse gas emissions. We will examine cases of climate injustice and the effects of climate change on women, Indigenous peoples, and African Americans, among others.

Section 2.4 outlines key global climate policy frameworks, from the 1990s to today. It also surveys climate justice advocates' criticism of such policy frameworks and explores some of their unintended consequences. We aim to illustrate what both climate justice and climate injustice are by examining real cases where people and ecosystems are affected by climate change. Such cases will help us to think about solutions to these problems from a global policy perspective as well as how we might implement solutions on the ground.

Finally, Section 2.5 explores alternative principle and policy approaches proposed by community-based social movements and climate justice activists. We ask, What might climate justice look like?

2.1 Defining Climate Justice and Injustice

> We are faced not with two separate crises, one environmental and the other social, but rather with one complex crisis, which is both social and environmental. Strategies for a solution demand an integrated approach to combating poverty, restoring dignity to the excluded, and at the same time protecting nature.
>
> His Holiness Pope Francis, *Laudato Si'*, ch. 4: 139

Climate change and the bottom 3 billion

Climate change is caused disproportionately by the energy consumption and production habits of the world's richest populations. The richest 1 billion people on the planet are responsible for about 50% of greenhouse gas emissions, while the poorest 3 billion, without access to affordable fossil fuels, are responsible for about 5%, as P. Dasgupta and V. Ramanathan have found.

A crowd-sourced image of the world at night, Figure 2.1.1 demonstrates the disproportionate energy usage among the world's richest and poorest populations. This image reveals that *dark* does not always mean "unpopulated." Dark, densely populated areas are distributed across the world. They tend to be the most vulnerable zones on our planet, concentrated in the global South, among populations who don't have access to fossil fuels. However, those in the dark typically suffer the greatest harms associated with climate change and will continue to be most affected by climate change into the future.

In other words, those who contribute the least to the greenhouse gas emissions that cause climate change are now, and will continue to be, the most severely affected by it. This phenomenon is called climate injustice. These same vulnerable populations are also less capable of adapting to a warming climate, because they have less access to financial and other resources that might allow them to avoid harm. Climate

FIGURE 2.1.1 ***In Plain Sight*. Installation designed for Dimensions of Citizenship, the US Pavilion at the 16th International Architecture Exhibition of La Biennale di Venezia, commissioned by the School of the Art Institute of Chicago and the University of Chicago.** Installation by Diller Scofidio + Renfro, Laura Kurgan, and Robert Gerard Pietrusko with the Center for Spatial Research.

justice, as a philosophy and a set of social movements, demands that we recognize the imbalances between responsibilities and harms and that we intervene to correct them.

While contributing the least of anyone to the causes of climate change, people of color, women, Indigenous communities, and global South nations often bear the brunt of climate disruption. Climate disruption is another term for climate change, one that emphasizes the way global warming disrupts climate systems and, along with them, environments, economies, and human health. Marginalized communities are among the first to experience the effects of climate disruption, which can include rising levels of respiratory illness and infectious disease, heat-related deaths, large increases in energy costs, and so-called natural disasters that climate change makes more frequent or severe. These communities also bear the burdens created by ill-conceived policies designed to prevent climate disruption.

The effects of climate injustice have been evident for years. Flooding from severe storms, rising sea levels, and melting glaciers affect millions

FIGURE 2.1.2 People's Climate March, Seattle, Washington, October 14, 2015. Photograph by John Duffy from Flickr.

in Asia and Latin America, while sub-Saharan Africa is experiencing sustained droughts. Scholars collectively call these areas of the world the global South in order to distinguish them from the global North, which includes Europe and the United States. Unlike older terms such as *third-world* versus *first-world*, or *developing* versus *developed* countries, these terms point to the historical colonization of much of the global South by nations in the global North.

Consider that nearly 75% the world's annual carbon dioxide emissions come from the global North, where only 15% of the global population resides. If historic responsibility for climate change is taken into account, global North nations have emitted more than three times their share of the total greenhouse gases that we can safely put into the global atmosphere, while the poorest 10% of the world's population has contributed less than 1% of emissions. Thus the struggle for racial, gender, and economic justice is inseparable from any effort to combat climate disruption.

Climate justice is a vision aimed at dissolving and alleviating the unequal burdens created by climate change (Figure 2.1.2). The topic of climate justice is a major point of contention in both US and international

policy efforts to address climate disruption, because it would require wealthy nations that have contributed the most to the problem to take greater responsibility for solutions. For many observers, the path is clear: for humanity's survival, for justice, and for sustainability, they maintain, we in the global North must reduce our emissions and consumption.

Why is justice so important?

Justice is a core principle of democracy and is tightly linked with environmental and climate protection. How so? Those communities, states, and nations with stronger protections for women and other marginalized communities also tend to have stronger *environmental* protections. In other words, those societies with healthier indicators of social equality, democracy, and justice tend to protect their environments better as well. If we want ecological sustainability and climate protection, we must work to strengthen our democracies, and that means strengthening social systems that facilitate justice for all. Let's consider these claims in more detail.

Social scientists such as Liam Downey and Susan Strife have demonstrated that general measures of social and political inequality are strongly correlated with and contribute to greater levels of ecological harm. In addition, James Boyce finds that the level of egalitarianism in a society strongly predicts the degree of environmental harm it causes. That is, societies with higher levels of economic and political inequality are characterized by higher overall ecological harm, and the reverse is true for societies with more egalitarian structures. How does this relationship unfold? Richard Wilkinson and Kate Pickett conclude that rising levels of social inequality contribute to heightened competitive consumption among a given society's citizens. This rising consumption, in turn, causes an increase in industrial activity that contributes to climate change in particular and to environmental harm in general.

Scholars have discovered that there are strong correlations between gender inequality and environmental harm as well. For example, Christina Ergas and Richard York find that carbon emissions are lower in nations where women have high political status. Thus efforts to improve gender equality and gender justice will likely be more effective if they work synergistically with campaigns to address climate change.

Ergas and York also find that nations with greater military spending have higher carbon emissions than other nations, supporting the work of ecofeminist scholars, such as Greta Gaard, who have long argued that militaristic policymaking is linked to ecological harm.

Research on climate justice reveals that socially marginalized communities face the greatest threats from climate change but contribute the least to the problem. Going further, however, with respect to the causes of this crisis, we find that the contemporary "wicked problem" of global climate disruption has its roots in European conquests of Indigenous peoples and lands in the Americas, the enslavement and forced labor of vast swaths of people across the global South, and the Industrial Revolution. These major social, economic, and technological upheavals also ushered in the Anthropocene—the age in which human activity has begun to affect the planet so much that it is leaving marks in the geological record (Chapter 1).

Finally, while researchers have shown that marginalized populations tend to live in places that experience severe environmental harm, the driving forces behind this environmental violence require more investigation. Traci Brynne Voyles's concept of "wastelanding" is immensely useful here. She shows how the concept of "wasteland" has been used to define certain human populations and landscapes as pollutable and expendable.

All the research summarized in this section sends a clear message: ideologies, policies, and practices that produce and enable human inequalities not only harm the people whom they target directly, but also drive climate change and environmental damage.

Climate justice: redistributing harms and responsibilities

In 2011, United Nations Secretary-General Ban Ki-moon delivered an address to the General Assembly of the United Nations in which he voiced the same integral message:

> Saving our planet, lifting people out of poverty, advancing economic growth—these are one and the same fight. We must connect the dots between climate change, water scarcity, energy shortages, global health, food scarcity, and women's empowerment. Solutions to one problem must be solutions to all.

In 2013, Pope Francis launched his papacy with a similar commitment to tackling these urgencies together. In his inaugural Mass, he declared: "Let us be protectors of creation, protectors of God's plan inscribed in nature, protectors of one another, and of the environment." Soon after, in his 2015 encyclical *Laudato Si'*, he issued perhaps the most integral and robust plea for climate justice the world had ever seen.* He linked the global fights against poverty and for tolerance and human dignity with the fight against climate change. For him, these urgent concerns go hand in hand:

> Today we have to realize that a true ecological approach always becomes a social approach. It must integrate questions of justice and debates on the environment so as to hear both the cry of the earth and the cry of the poor.

When Mary Robinson, former president of Ireland, was the UN High Commissioner of Human Rights from 1997 to 2002, she made climate change central in her human rights agenda. She argued that many of the human rights we value as a global community—women's rights, children's rights, immigrants' rights, and the rights of all people to health and well-being, food and water, shelter, and education—are being undermined by climate change. After she left the United Nations, she founded the Mary Robinson Foundation–Climate Justice, a center for thought leadership, education, and advocacy on the struggle to secure justice for those who are vulnerable to the impacts of climate change. Though such marginalized communities are disempowered and usually forgotten, they have a right to low-carbon development.

We need to consider both the *intra*generational and *inter*generational harms caused by the wealthy global minority through its energy consumption and production habits. Intragenerational harm refers to the disproportionate impact of climate change on vulnerable people within our own generation; it is the kind of harm discussed in the previous section. Climate justice means that we have an urgent ethical responsibility to help those who are suffering right now from the impacts of climate

*Encyclical Letter, *Laudato Si'* of the Holy Father Francis, on Care for Our Common Home, 2015. http://w2.vatican.va/content/francesco/en/encyclicals/documents/papa-francesco_20150524_enciclica-laudato-si.html.

change. But we also have to think about intergenerational harm—that is, the harm that climate change will do to those who are not yet born, the populations of the future, who cannot consent to the planet that we are preparing for them. As a matter of climate justice, we need to reduce warming for our own grandchildren and for the grandchildren of all.

Viewed through the lens of human suffering, climate change becomes not only an environmental problem but also an urgent ethical one. Climate justice demands that those who cause harm, and especially those who benefit from that harm, bear primary responsibility for remedying it and for preventing further harm in the future.

In other words, climate justice is both backward looking and forward looking. The wealthy polluting population has an ethical responsibility to alleviate present-day human suffering caused by past acts and omissions, in part by providing aid to populations struggling to adapt. But the polluting population also has an ethical responsibility to mitigate future harm by doing everything we now know is necessary to mobilize a low-carbon global economy. This includes both helping people in developing countries to leapfrog a carbon-based economy and tempering the promotion of our own wasteful lifestyles as the epitome of human happiness.

It could be said that climate justice redistributes responsibilities and harms for the common good. The Mary Robinson Foundation–Climate Justice, the first international organization that committed to climate justice as a human right, frames this as "sharing benefits and burdens equitably":

> The benefits and burdens associated with climate change and its resolution must be fairly allocated. . . . In addition, those who have benefited and still benefit from emissions in the form of on-going economic development and increased wealth, mainly in industrialised countries, have an ethical obligation to share benefits with those who are today suffering from the effects of these emissions, mainly vulnerable people in developing countries. People in low income countries must have access to opportunities to adapt to the impacts of climate change and embrace low carbon development to avoid future environmental damage.

FIGURE 2.1.3 The co-author's son "Marching for Science" in San Diego, California, April 22, 2017. Photograph by Fonna Forman.

There is no time to wait. Your generation will be most affected by the changes that are taking place—particularly the most vulnerable among your generation. Because of the climate disruption you will witness in your lifetimes, you have a valuable perspective on the intergenerational harms caused by climate change. Each of us needs to play our role and find creative ways to intervene in the crisis (Figure 2.1.3). Reading this book is a very good first start.

2.2 Humans and Nature

How we think about nature has long influenced our actions toward it, as well as our actions toward each other as fellow human beings. Has the relationship between humans and the natural world been understood primarily as one of harmony and care, or as one of dominion? This section will stress that traditions of dominion have produced devastating environmental and human consequences over time. A more harmonious and caring relationship between humans and nature will be essential to solving the integral challenge of climate change, which is presently not only destroying our environmental ecologies, but also threatening to destroy our human ecologies as well. Already vulnerable human communities across the globe are struggling to adapt to a warming climate, raising urgent issues of climate justice—but we and our children and grandchildren will all be affected by climate change.

Dominion over nature

In some religious traditions, the environment seems to exist to satisfy human need and pleasure. Exercising mastery over nature and extracting what nature provides for human ends is thus considered by these traditions a mandate of divine law or natural law. A foundational claim in the Judeo-Christian tradition, for example, is that God has given the Earth to humans for their own sustenance, use, and pleasure. The most well-known biblical statement of human dominion over nature can be found in Genesis 1:28:

> Be fruitful, multiply, fill the earth, and subdue it. Have dominion over the fish of the sea, over the birds of the sky, and over every living thing that moves on the earth.

Here, humans are acting in accordance with God's will when they subdue the natural world and appropriate the bounty of nature for human purposes (Figure 2.2.1). In Western history, this religious way of

FIGURE 2.2.1 ***The Garden of Eden***. Painting by Lucas Cranach the Elder (German, 1472–1553).

thinking about human dominion over nature evolved into a full-blown secular culture of private property. The religious orientation to dominion in the Judeo-Christian tradition became secularized in the modern period and was encoded in modern property law.

The seventeenth-century English philosopher John Locke is an important figure in this theoretical evolution. Locke is best known today for articulating the modern foundations of private property and for his theory of moderate government designed primarily to protect "human life, liberty, and property." His theory of property is important to us here, since it was a deliberate secularization of the Judeo-Christian idea of dominion. Consider this passage, drawn from Locke's 1690 work, the *Second Treatise of Government*:

> God, who hath given the world to men in common, hath also given them reason to make use of it to the best advantage of life, and convenience. The earth, and all that is therein, is given to men for

> the support and comfort of their being. . . . Though the earth, and all inferior creatures, be common to all men, yet every man has a property in his own person. . . . Whatsoever then he removes out of the state that nature hath provided, and left it in, he hath mixed his labour with, and joined to it something that is his own, and thereby makes it his property . . . that excludes the common right of other men.

This passage is instructive. God gives the world to humankind in common, but through the use of one's body and mixing one's labor with what is common, an individual can remove something from nature, privatize the commons, and make it his own. This, for Locke, is the origin of private property. According to Locke, extracting property from the commons is God's plan for humankind: God endowed us all with reason so that we could do this. Through the exercise of our reason, individuals can conceive of the best ways to use and expropriate nature for the betterment of human life. The environment is there for us to use.

Locke's theory of property is rooted in the ancient idea of terra nullius. Terra nullius, an old Latin term, refers to land that is empty and belongs to nobody. According to Locke's theory, an individual can rightfully take land that is not being used by another person or group, because such land is not fulfilling God's purpose. An individual can enclose the commons, cultivate it, make it his own, and fulfill God's wishes for humankind on Earth.

Locke did set an ethical limit on how much an individual can take. He said that we cannot appropriate more than we can *use*. According to divine law, we are not permitted to allow nature to spoil in our possession and thus deprive others of its usage. We cannot enclose more of the commons than we can cultivate. We cannot gather so many apples or fish that they rot. However, Locke quickly observed that human societies had invented *money* to bypass the spoilage limitation. An individual thus exchanges his property for something that symbolizes its value—money—and can accumulate unlimited sums of money since money does not spoil. As human societies developed further and money became the main method of human exchange, an individual could enclose large tracts of the commons and pay people to cultivate it for him, either with money or the land's produce. This, for Locke, was the birth of agriculture.

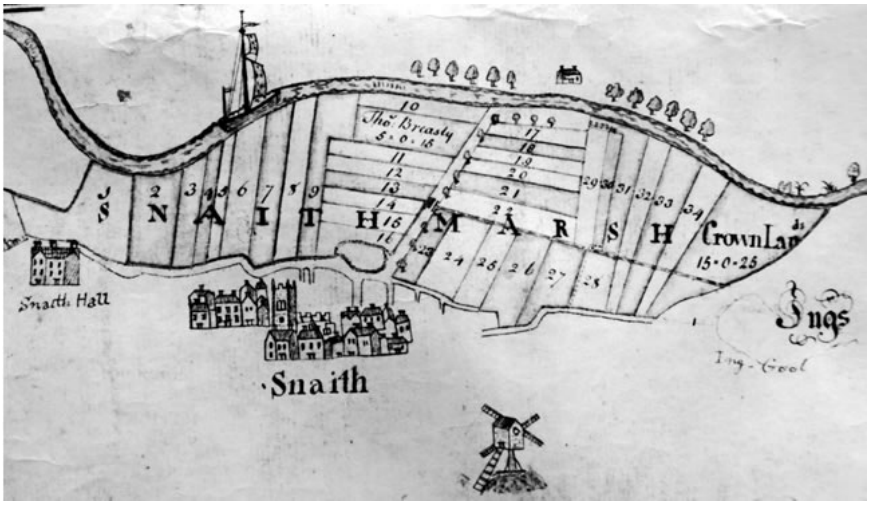

FIGURE 2.2.2 This is an eighteenth-century English enclosure map, depicting the town of Snaith. *Enclosure of the Commons*, *Yorkshire 1754*. Reproduced from Howdenshire History.

Enclosure and subdivision

Terra nullius, understood as a divine or natural justification for privatizing the commons, was useful to the British aristocracy at the time that Locke was writing. For example, it gave convenient validation to the enclosure movement, which first began in England in the twelfth century but accelerated in the eighteenth and nineteenth centuries. The commons were lands held in common by a given community; people who did not own land could pasture animals, gather wood, or grow vegetables or crops for their own use there. Enclosure referred to dividing up the commons into parcels of private property for more intense agricultural usage, a process that was nearly complete across England by the close of the nineteenth century (Figures 2.2.2 and 2.2.3).

While enclosure advanced agricultural productivity in England and other European nations through the eighteenth and nineteenth centuries, agriculture would not be the sole motivation for enclosing and subdividing the commons throughout the twentieth century and into the twenty-first (Figures 2.2.4–2.2.8).

For those seeking profit, terra nullius has been a convenient justification for enclosing the commons, encroaching on and subdividing empty or allegedly underutilized spaces, and expropriating natural resources.

FIGURE 2.2.3 This is what the enclosure of farmlands looks like today when you fly over the United Kingdom—small plots of private land divided by trees, shrubs, rocks, and so forth. This aerial photo is of farmland east of Great Massingham, 2018. Reproduced from Geograph.

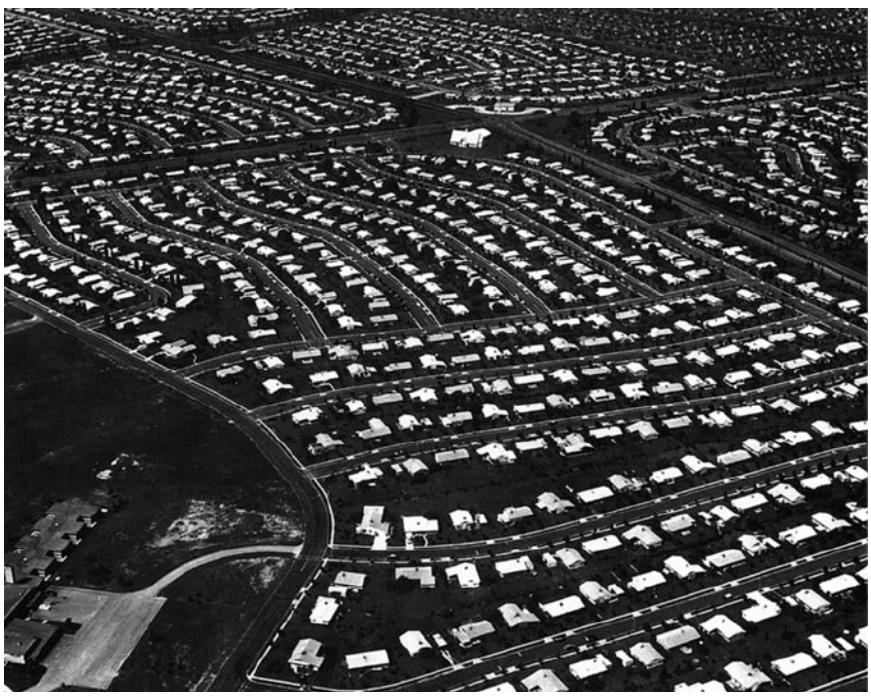

FIGURE 2.2.4 Levittown, Pennsylvania, was the first master-planned development in the United States, built in the 1950s. Its 17,000 identical houses inaugurated a new symbol of American happiness—the single-family home in the suburbs—that also required freeway infrastructure and an oil-hungry automobile industry. Reproduced from Wikimedia Commons.

FIGURE 2.2.5 This is what suburban sprawl looks like today, in this case outside Las Vegas, Nevada. Photograph by Jan Buchholtz from Flickr.

FIGURE 2.2.6 Unsustainable American sprawl has been an infectious pattern around the world, in both developed and developing cities, from Dubai to Nairobi. Here, for example, is a master-planned community in Huaxi, China. Photograph by ImmerQi, May 6, 2009, from Flickr.

FIGURE 2.2.7 Sometimes these master-planned developments abut against precious environmental zones, encroaching into wetlands and into forests. Here, for example, is a development in Kendale Lakes, Florida, encroaching on the Everglades National Park. Photograph by Fred Ward from Wikimedia Commons.

FIGURE 2.2.8 Sometimes master-planned developments abut on entirely unsustainable environments, like this desert in Rio Rancho, New Mexico. Reproduced from Wikimedia Commons.

FIGURE 2.2.9 ***The Plumb-Pudding in Danger*** **(1805).** Cartoon by James Gillray.

Terra nullius also became a powerful justification for European colonization around the world.

Colonization

John Locke's theory of property, grounded in terra nullius, or empty land, had important implications for global dynamics in early modernity. Take a look, for example, at this famous cartoon by James Gillray, *The Plumb-Pudding in Danger*, from 1805 (Figure 2.2.9). The French Emperor Napoleon, on the right, sits with the British Prime Minister William Pitt, on the left, as they carve up the Earth, distributing terra nullius for their own national agendas. Extractions from these colonies—gold and silver, foodstuffs, wood, raw materials, and so forth—would enrich the mother country.

Of course, when Europeans landed in terra nullius, these lands weren't empty at all. They were richly inhabited by ancient societies with forms of life that were foreign and often surprising to Europeans. Enslaving these inhabitants allowed the conquering nation to extract resources to ship back to the mother country. Centuries of such extractive

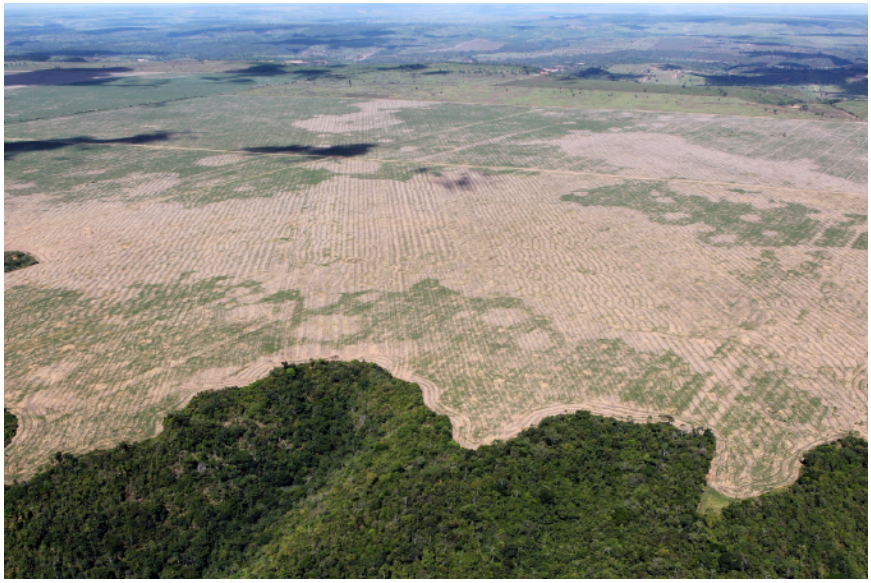

FIGURE 2.2.10 Here we see the environmental scars of mining and of deforestation, devastating the integral ecologies of northern Brazil, the lungs of our planet. Photograph by Operação Hymenaea, 2016, from Wikipedia.

practices destroyed Indigenous cultures as well as the environmental ecologies that situated their ways of life. From Spain's infamous Potosí silver mines in Peru and sugarcane plantations in the British Caribbean to diamond and gold mining in South Africa and the rubber boom in the Congo, modernity has been a brutal story of dominion over land and peoples and of slavery, extraction, and environmental mutilation across the world (Figure 2.2.10).

Harmony with nature: protecting the environment, protecting each other

One hundred years before we were thinking about climate change, Gandhi declared, "Earth provides enough to satisfy every man's needs but not every man's greed." In contrast with traditions, histories, and practices of dominion over the centuries, there are alternative religious and secular traditions that have cautioned us to respect the Earth and to find ways to live in *harmony with* it. These include Koranic, Buddhist, and Hindu traditions, a vast range of Indigenous traditions and practices, and strands within Judeo-Christian tradition itself. Most often these

traditions recognize the inherent interdependence of natural and social systems—what Pope Francis calls our "integral ecology." They stress that irresponsible human dominion over nature causes not only environmental harm, but human harm as well. It violates not only the integrity of nature, but also the well-being of humans.

The great variety of religious and cultural traditions that emphasize our harmony with nature, as well as our ethical responsibility toward each other, can be very helpful to us today as we tackle the urgent challenge of climate change. For example, the Koranic *ayah* 24:45 instructs that we are "stewards of the Earth":

> The Earth is green and beautiful, and Allah has appointed you his stewards over it. The whole Earth has been created a place of worship, pure and clean. Whoever plants a tree and diligently looks after it until it matures and bears fruit is rewarded. If a Muslim plants a tree or sows a field and humans and beasts and birds eat from it, all of it is love on his part.

The Buddhist Za Choeje Rinpoche teaches:

> By injuring any part of the world's system, you injure yourself. Think of life on this planet in terms of systems and not detached elements. See that the environment does not belong to any single country to exploit and then disregard.

Laguna Pueblo poet Paula Gunn Allen describes a Native American orientation to the Earth as inherently part of the self, and explicitly rejects a relation of dominion:

> We are the land . . . that is the fundamental idea embedded in Native American life and culture in the Southwest . . . the Earth is the mind of the people as we are the mind of the Earth. The land is not really the place (separate from ourselves) where we act out the drama of our isolate destinies. It is not a means of survival, a setting for our affairs. . . . It is rather a part of our being, dynamic, significant, real. It is ourself.

There are countless examples of belief systems and practices that embrace harmonious views of the human relationship with the natural world.

FIGURE 2.2.11 Rise for Climate march in San Francisco, September 8, 2018. 350.org. Photograph by Xanh Tran, Survival Media Agency, from Flickr.

An important strategy for climate action today is to identify common views among otherwise diverse cultural, religious, and political groups to summon agreement, coordinate action, and assert political pressure to protect the planet from destructive human behavior (Figure 2.2.11). Too often commonalities are buried beneath political contestation over other issues—and this can be detrimental to building coalitions around urgent environmental and human challenges like climate change.

As an example of finding commonalities, a new and fruitful conversation has opened in recent years between climate scientists and members of the American evangelical community. Evangelical and atmospheric scientist Katharine Hayhoe gives voice to a position, rooted in scriptural commitments, that is attracting increasing support among some evangelicals:

> If I say that I respect God, that I love God, and God has given us this incredible life-giving planet, then if I strip every resource at the expense of my poor sisters and brothers—one in six of whom die because of pollution-related issues, who are suffering and dying today—then I'm not somebody who takes the Bible seriously.

Along these lines, the recent "Climate Change: An Evangelical Call to Action" asserts that "love of God, love of neighbor, and the demands of stewardship are more than enough reason for evangelical Christians to respond to the climate change problem with moral passion and concrete action." This document proceeds to cite relevant scripture to substantiate its claims:

- Christians must care about climate change because we love God the Creator and Jesus our Lord, through whom and for whom the creation was made. This is God's world, and any damage that we do to God's world is an offense against God himself (Gen. 1; Ps. 24; Col. 1:16).
- Christians must care about climate change because we are called to love our neighbors, to do unto others as we would have them do unto us, and to protect and care for the least of these as though each was Jesus Christ himself (Mt. 22:34–40; Mt. 7:12; Mt. 25:31–46).
- Christians, noting the fact that most of the climate change problem is human induced, are reminded that when God made humanity he commissioned us to exercise stewardship over the earth and its creatures. Climate change is the latest evidence of our failure to exercise proper stewardship and constitutes a critical opportunity for us to do better (Gen. 1:26–28).

The ethical stand against climate change today, emerging from both religious and secular positions, typically combines care for the environment itself with care for our fellow humans, particularly those who are most vulnerable. In the next section, we turn to the human impacts of climate change, emphasizing what we call the "disproportionate impacts" on the global poor.

2.3 Disproportionate Impacts: Global and Local Trends

In this section, we turn to the impacts of climate change on human life. Here we acknowledge that all of us are vulnerable to climate change but that those who are young, elderly, poor, and sick are most vulnerable to—and least capable of adapting to—the impacts of climate change.

Climate change is projected to cause widespread and serious harm to human settlements on the planet, threatening to unravel many of the development gains of the last century. The effects of climate change cluster and bear down hard on the global poor, those who are both least responsible for the causes and least capable of adapting. The health impacts of climate change are predicted to become catastrophic by the middle of this century if significant reductions in greenhouse gas emissions do not occur.

Several years ago, the Lancet Commissions documented the public health impacts of climate change and presented predictions for the future. The commissions found that climate change poses unacceptable risks to global public health. The United Nations Children's Fund (UNICEF) similarly predicted that there may be "no greater growing threat facing the world's children and their children than climate change. This mounting global crisis has the potential to undermine many of the gains we have made in child survival and development and poses even greater dangers ahead."

We look around us and we can see that our world is changing. We are witnessing the effects of warming through our own senses: more extreme weather events, more damaging wildfires, rising sea levels, more frequent and severe floods, and so forth. But these effects do not affect everyone in the same way. This section is about the disproportionate impacts of climate change on the most vulnerable people around the world and in our own regions, cities, and villages. The vulnerable lose more when these kinds of disasters strike.

Adaptation and mitigation

To appreciate the disproportionate impacts of climate change, we begin by distinguishing a few concepts. The language of "adaptation" and "mitigation" is often used in discussions about climate impacts. Let's define each of these terms and explore why vulnerable communities are less capable of both adaptation and mitigation.

Adaptation refers to the capacity of a community or a demographic group to accommodate to changes in climate or extreme weather events related to climate change. Does climate change disrupt someone's livelihood? Does it displace someone from her home? Does it threaten her life or affect her health, and does she have adequate health care to treat these health impacts? Does it force her to move, and does she have the resources and social capital to relocate if she needs to? Does she have access to government services or other social or humanitarian aid resources to assist her? Wealthier individuals and communities have more capacity to adapt, and poorer individuals and communities, including those who rely on the natural world for subsistence, have less. Thus we refer to an "adaptation gap" between the rich and the poor across the world.

While *adaptation* refers to the capacity to accommodate to a changing climate, mitigation refers to activities that reduce the production of carbon dioxide and other greenhouse gases. Poorer individuals and communities have fewer resources for participating in mitigation activities and climate action—in other words, for contributing to a low-carbon economy. Poorer communities have less capacity to adapt to a warming climate, and they also have less capacity to participate in mitigation strategies. Vulnerable communities produce proportionately far less carbon than wealthier populations. But as these societies "develop," it is essential that they do so in greener ways, not by mimicking the carbon-hungry development patterns of wealthier societies. The problem is that it is costly to invest in sustainable development and green technologies. For this reason, global resources must flow toward vulnerable communities to help them leapfrog over the oil-based development patterns of wealthy nations that have already gotten us into so much trouble.

With the concepts of adaptation and mitigation in mind, we are now better prepared to make sense of the risks of climate change and

to appreciate what's at stake for the poorest societies across the world. Let's consider some cases of climate injustice and what they can tell us about how best to address this challenge.

Climate migration

The adaptation gap is evident in the acceleration of climate-related human displacement across the world in recent years. Social scientists are still figuring out how to accurately measure the rate of climate migration. In 2009, António Guterres, then the United Nations high commissioner for refugees, predicted that climate change would become the largest driver of population displacements both inside and across national borders. His prediction seems to be bearing out. The global rate of displacement has more than doubled since 1970, from fewer than 2,000 persons per million to more than 4,000 persons per million in 2014.

The most commonly cited estimate is that climate change will force 200 million people to move by 2050. These displacements, even if temporary, have a profound impact on individuals' lives, often involving the loss of a home or crops. Such relocations disproportionately harm individuals at the very bottom, who lack the resources to adapt and are increasingly susceptible to the perils of human trafficking and forced labor.

In their recent paper on climate migration, Fonna Forman and V. Ramanathan focus on the slower progressive impacts of climate change, such as drought, soil erosion, forest loss, and sea level rise. While extreme weather events often cause sudden mass displacements and are increasing in frequency, slower processes seem to have a stronger predictive effect on the likelihood of climate migration. Those living in rural or low-lying coastal areas, whose livelihoods are linked with climate-sensitive sectors like agriculture and fishing, are the most vulnerable and at highest risk, as they are typically the least capable of either adapting or migrating. After all, the capacity to leave one's home requires financial and social capital, such as education, language skills, and support networks.

In 1991, the Intergovernmental Panel on Climate Change (IPCC) predicted that climate change would accelerate urbanization in developing

countries, with populations migrating from coastal lowlands (particularly densely inhabited deltas) to inland areas. The world is now urbanizing at a rate of roughly 32 million people each year, exerting unmanageable demands on urban services and increasing political pressure on nation-states.

The 30-year drought in Syria, for example, is inevitably linked with the tragic political turbulence we've witnessed there in recent years. Drought destroyed rural economies and drove farmers into the cities. Cities couldn't handle the dramatic influx of population, which contributed to greater civil unrest. It would be inaccurate to say that climate change was the "cause" of the geopolitical dynamics that have rocked Syria and the global community. But it undoubtedly served as a "threat multiplier," exacerbating existing conditions of instability and institutional weakness and accelerating the dramatic political outcomes that ensued.

In the developing world, rapid urbanization in recent decades has also produced dramatic "asymmetrical" growth patterns. The poorest populations have amassed by the millions in precarious informal settlements, often peri-urban and frequently along rivers and lagoons, uniquely exposing them to the effects of climate change—floods, drought, food and water shortages, and disease. The explosion of slums at the periphery of cities across the planet is a humanitarian crisis of gargantuan proportions that cities in the developing world today are proving unprepared to confront.

Latinx communities in California

For generations, electricity for California's Central Coast region has been produced by polluting gas-fired power plants concentrated in Oxnard, a working-class community that is 85% people of color and 75% Latinx. Oxnard already has three power plant smokestacks along its shoreline, more than any other city on the coast of California. Recently, Oxnard faced a proposal for a fourth power plant that would produce more greenhouse gases and expose local residents to more particulate matter pollution while generating electricity for other cities. In other words, Oxnard would shoulder the cost and receive few of the benefits of this development. Many neighborhoods in Oxnard are already above the

FIGURE 2.3.1 Puente protest. Photograph by Central Coast Alliance United for a Sustainable Economy (CAUSE).

ninetieth percentile for asthma rates in the state of California—their residents are literally gasping for air.

But local residents, grassroots organizations, and college students stood up to oppose this power plant and called for an end to dangerous and polluting fossil fuel projects that threaten human and environmental health. They simultaneously took action to promote positive practices and policies, such as the restoration and protection of critical habitat and the expansion of safe, well-paying jobs. This is an example of a community fighting against climate injustice and demanding climate justice, and they succeeded in stopping the proposed plant in its tracks (Figure 2.3.1)

Africa and climate disruption

Western nations are responsible for the great majority of greenhouse gas emissions globally. The European Union, the United States, Canada, Australia, and Russia are responsible for 68% of global emissions while sub-Saharan Africa is responsible for only 2%. The African continent's economies are largely dependent on farming and natural resource extraction and export. These are two of the industries that scientists expect to be hit hardest by climate disruption in the coming years.

In fact, according to the IPCC, Africa is the continent most at risk from climate disruption. These threats include reduced agricultural productivity as a result of rising temperatures, which may lead to rising food insecurity, hunger, and political conflict. The output of rainfed agriculture is expected to drop by as much as 50% in some African nations by 2020. Increasing drought conditions in some parts of the continent and rising sea levels near coastal areas may contribute to social and economic problems as well. Generally, African nations can expect to see increased desertification, more floods and droughts, intensified water shortages, and massive increases in climate refugees. In 2009, the Climate Change Vulnerability Index of the conservation group NatureServe concluded that of the 28 nations around the world facing "extreme risk" due to climate change, 22 of those countries were in Africa. Issues that we define as "environmental" or "climate-change related" cannot be cordoned off—they intersect with a host of other problems and concerns.

African societies are far less responsible for climate disruption than other nations because they have far lower per-capita energy consumption and greenhouse gas emissions. Sub-Saharan Africa is the poorest region on Earth in strict economic terms. However, it is also the world's most profitable investment site because of its abundance of ecological wealth critical to the functioning of the global economy. As journalist Naomi Klein puts it, "Africa is poor because its investors and its creditors are so unspeakably rich." Many leaders of nongovernmental organizations in the global South believe that the struggle for climate justice in Africa has to be a part of the broader struggle against inequalities that reflect the continuing legacies of colonialism.

African Americans

The story of Africa and climate disruption in many ways mirrors the story of African American communities. African Americans make up roughly 12% of the US population and emit far fewer greenhouse gases than white Americans. In fact, African Americans produce only 9% of carbon dioxide emissions, while whites, who comprise 62% of the population, produce 76% of emissions.

African Americans are less responsible for emissions but experience

a disproportionate burden of the costs of climate change. For example, African Americans are more likely to live in close proximity to coal-fired power plants and suffer from greater vulnerability to asthma, heat waves, "natural" disasters, food insecurity, and high energy prices—all of which are correlated with intensifying climate disruption. In fact, African Americans experience climate injustice at nearly every point in the process that causes climate change. They are exposed to health risks from living near or working in sites of fossil-fuel extraction, refinement, processing, combustion, and waste dumping. African Americans are also more vulnerable to hurricanes, heat waves, and other so-called natural disasters linked to climate disruption. These pressures are intertwined and amplified by historic and contemporary racial inequalities with respect to income and wealth, energy expenditures, urban sprawl and transportation design, housing, food security, and disaster relief and recovery policies.

Climate disruptions are indelibly marked on the bodies and communities of African Americans. The significant public health effects associated with climate disruption include more deaths from heat waves, increases in asthma and other respiratory illnesses, and developmental abnormalities, just to name a few. These health effects harm African Americans at higher rates than whites, as Robert Bullard and Beverly Wright have shown.

Heat waves and other extreme weather events have devastating and unequal effects on African Americans. As a result of historical internal migrations and the urbanization of the US, most African Americans live in cities, which tend to be several degrees warmer than surrounding areas. People living in urban centers suffer the most from heat waves. Research has shown that people of color are twice as likely as whites to die in a heat wave and also suffer more from heat-related stress and illness. African Americans are also more likely to suffer during heat waves because they have less access to heat-adaptive technologies like home insulation and air conditioning, as a result of lower levels of income and wealth.

Considering these factors, it is no wonder that we see so much tragedy in cities across the US facing heat waves. In the 1995 Chicago heat wave, for example, African Americans died at a rate 50% higher

FIGURE 2.3.2 Indigenous block at Rise for Climate march, San Francisco, September 8, 2018. 350.org. Photograph by Brooke Anderson, Survival Media Agency, from Flickr.

than whites did. Climate disruption is expected to increase the number of heat waves and related deaths in urban areas in the coming years.

Indigenous rights

Indigenous peoples, in particular, face a range of threats from climate disruption.

Leaders of Indigenous communities around the globe have been clear about the need to recognize Aboriginal peoples' rights under international law, their roles as stewards of ecosystems, the inherent value of traditional ecological knowledge, and their positions on the front lines both of climate change's impacts and of forging solutions (Figure 2.3.2). These leaders demand that the United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP) be fully recognized and respected in all decision-making processes and activities related to climate change policy at the UN Framework Convention on Climate Change (UNFCCC). This includes rights to Indigenous lands, territories, environment, and natural resources, as outlined in Articles 25–30 of UNDRIP.

In 2009, the National Aeronautics and Space Administration (NASA)

and various tribal college partners held a workshop on climate change, Native peoples, and Native homelands in Anchorage, Alaska. The collective statement that emerged from this gathering—the Anchorage Declaration—included the following:

> In order to provide the resources necessary for our collective survival in response to the climate crisis, we declare our communities, waters, air, forests, oceans, sea ice, traditional lands and territories to be "*Food Sovereignty Areas*," defined and directed by Indigenous Peoples according to customary laws, free from extractive industries, deforestation and chemical-based industrial food production systems (i.e. contaminants, agro-fuels, genetically modified organisms).

Workshop organizers stated that climate change affects Indigenous peoples first and foremost and that solutions must include "shifting the energy paradigm so that we develop efficiency and produce our own clean energy, and it means growing our own traditional varieties of food. It means returning to self-sufficiency by creating energy and food sovereignty that can provide a bright future for the generation yet to come."

The programmatic exploitation of conventional energy resources has run a long and often deadly course in Native communities. It also has a distinctly colonial flavor: tribes have supplied energy companies with access to abundant ecological resources at low prices in contracts promoted by the federal government, yet these communities themselves are often unserved or underserved by the benefits of such projects. Even the most recent federal energy legislation and incentives are still designed to encourage the development of tribal resources by outside corporate interests without ownership by or financial benefit to the host tribes. The fact that the US has yet to sign on to UNDRIP compounds this situation.

Gender and climate

Gender inequality has major implications for how people are affected by climate disruption, and scholars have discovered important linkages among gender, power, and environmental outcomes. According to Joane Nagel, the differing social roles that men and women occupy

"position them differently in terms of their vulnerability to the impacts of climate change, access to resources associated with recovery from climate-related disasters, and participation in the political processes that shape mitigation and adaptation policies."

Researchers report that vulnerability to disasters—including those associated with climate disruption—is strongly correlated with demographic factors such as gender. Exposure to heat, hypothermia, and waterborne diseases during extreme weather events disproportionately affects women. According to United Nations WomenWatch, studies predicting population displacements due to climate change anticipate uneven and disproportionate effects on women as a result of their social position as people who are primary caregivers for children and the elderly, have limited land rights and lower social status, depend on subsistence agriculture, and work for low or no wages. In addition, women frequently face a heightened risk of sexual and domestic violence when social norms and networks break down in the aftermath of natural disasters.

Not only are women frequently affected more severely by climate disruption, but they are also routinely excluded from policy discussions on disaster planning, mitigation, and response. This exclusion is especially troubling because the many women who are small farmers in the global South have experience and knowledge that could be of great value in shaping climate policy. Social scientists Kari Norgaard and Richard York have demonstrated that nation-states in which women hold a larger share of parliamentary seats are more likely to ratify international environmental treaties. As noted earlier, those nations where women enjoy higher political status also tend to have lower per-capita carbon emissions on average. This all adds up to the conclusion that gender equality and climate justice are tightly interwoven, so any effort to secure one of these aims will likely be more transformative if it is tied to the other.

2.4 Major Policy Frameworks

The UN Framework Convention on Climate Change (UNFCCC) of 1992 is "the law of the land" in most countries, including the United States. All signatories to the treaty agreed to stabilize greenhouse gas emissions to prevent dangerous climate change. The UNFCCC is based on the principle of equity and common but differentiated responsibilities. Under the treaty, global North, or "Annex 1," nations have committed to taking the lead on reducing their own greenhouse gas emissions, assisting global South nations with technology transfer to pursue sustainability goals there, and supporting climate change adaptation in the global South through funding, with the additional goal of poverty reduction.

In the view of many global South community leaders, the UNFCCC has been problematic because it relies primarily on market-based approaches, which present many challenges for achieving carbon emissions reductions and climate justice. These policies are rooted in a framework that embraces economic growth and social inequality, though these are some of the primary driving forces of the climate crisis in the first place.

Another reason these efforts have fallen short is because Indigenous peoples, people of color, women, family farmers, fisherfolk, forest-dependent communities, youth, and other marginalized communities have been systematically excluded from the negotiations. Moreover, despite UNFCCC and IPCC goals, there is, thus far, no meaningful momentum in the global North toward reducing emissions by the targeted amounts. In fact, emissions have actually increased in global North nations; large portions of any claimed reductions have been made through offsets in the global South rather than through real action in the North. While these last two trends are part of the system's design, many global South environmental advocates argue that this is unacceptable.

The Kyoto Protocol supplements the UNFCCC and puts forth legally binding measures for reducing emissions in global North nations. Kyoto created a number of flexible procedures for meeting emissions targets,

two of which are an international emissions trading (IET) scheme for Annex 1 nations and the clean development mechanism (CDM). The IET is a carbon cap-and-trade scheme on a global scale, but it has not achieved success, according to many critics, because it encourages "business as usual" practices in many industries that profit most from the use of fossil fuels. Numerous leading global South activists have concluded that *no* cap-and-trade scheme can achieve climate justice.

The clean development mechanism was proposed during Kyoto negotiations in 1997 as a less painful method of capping greenhouse gas emissions and assisting nations in their efforts to adapt to new carbon constraints. The CDM has two primary goals: to promote sustainable development in global South countries and to allow industrialized countries to earn emissions credits from their investments in emission-reducing projects in the South. The CDM specifically allows global North countries to purchase credits from southern nations that reduce carbon emissions. Those northern countries can then use or sell those credits in the global North. This program has also been the target of criticism for numerous reasons. For example, major emitters in the global North generally treat buying CDM offsets as a far cheaper alternative to actually reducing their own emissions or making large capital investments in renewable energy technology. In addition, methane recovery from industrial agriculture, large hydropower projects, and coal-fired power plants can receive credits under the CDM. Emissions reductions credits have also been used to expand polluting industries in the global South.

Finally, CDM includes agrofuel or biofuel crop projects that rely on industrial-scale agriculture, which has long relied on deforestation and cheap fossil fuels, thus threatening biodiversity and food security for Indigenous communities in various regions. While the US and European governments have embraced agrofuels as a "green" alternative to fossil fuels for automobiles, in many global South nations rain forests are threatened in order to make way for agrofuel plantations. Deforestation disrupts the regulation of climate systems, as do the nitrous oxide emissions from chemical fertilizers used in plantation agriculture. The biofuels market has also led to an increase in the cost of staple foods like corn, sugar, and soy for people in the global South, leading to popular unrest in Indonesia, Mexico, and many African nations. In Tanzania,

thousands of people have been evicted for the development of agrofuel plantations.

Critics claim that the problems with the CDM are insurmountable because it seeks to reduce emissions in the South and not in the North, while we need such reductions in both places. Many observers view the CDM's strategy as unjust, given the historic responsibility on the part of the North for the vast majority of carbon emissions. Furthermore, CDM projects often create problems in global South communities, such as displacing populations from their land, and lock nations into high-carbon pathways.

Reducing emissions from deforestation and degradation (REDD) is another offsetting mechanism. Devised by the World Bank, it is slated to be a key component of any post-Kyoto climate treaty. REDD is intended to help global South countries protect their remaining rain forests and reduce the greenhouse gas emissions caused by deforestation, forest degradation, and peatland destruction. Countries that reduce net REDD emissions below a preset baseline would receive credits that could be sold in carbon markets and used by purchasing nations to meet their international mitigation obligations.

The definition of *forests* used by the UNFCCC includes clear-cuts, which are euphemistically referred to as "temporarily unstocked areas," and monoculture tree plantations—that is, plantations of one species of tree, which are much less biodiverse than forests and less useful in taking up carbon dioxide. Therefore, a government or logging company could hypothetically evict an Indigenous community, clear-cut or burn down the forest, impose a monoculture plantation, and still receive REDD money, since that would not count as deforestation. The Climate Justice Now! network stated in 2010, "These plantations destroy ecosystems and subsistence agriculture, cause rural unemployment and depopulation, deplete soils and water resources and violate Indigenous Peoples' rights." The International Indigenous Peoples' Forum on Climate Change opposes such carbon markets and calls them a new form of colonialism, declaring that "under REDD, States and Carbon Traders will take more control over our forests." Other global South activist groups, like La Via Campesina, representing activists from more than 36 nations, view REDD as a way of privatizing forests.

FIGURE 2.4.1 Activists pressure universities and other institutions to divest from fossil fuels out of a conviction that we cannot wait for national and international leaders to address climate change. Fossil-free UC action at the Regents of the University of California meeting in Sacramento, May 16, 2014. 350.org. Photograph by Mauricio D. Castillo from Flickr.

Global South activists argue that we need to reduce both deforestation and fossil fuel emissions, not trade between them. Hundreds of REDD-type projects already exist and have resulted in human rights violations and violence against Indigenous peoples.

The Paris Agreement (Accord de Paris) is a global agreement that came into force in 2016 and builds on the UNFCCC with the aim of limiting global temperature rise to less than 2°C above preindustrial levels. All parties to this agreement are to report regularly on their emissions and implementation efforts. One major limitation of the Paris Agreement is that it is voluntary and thus has little in the way of an enforcement mechanism.

Perhaps even more exciting is the growth of a number of subnational agreements to achieve climate stability. One example is the Under2 Coalition, a diverse group of 177 jurisdictions, 37 nations, and 6 continents that represents 1.2 billion people and nearly 40% of the global economy. Their aim is to achieve the goal of limiting global temperature rise to less than 2°C through subnational government action. In other words,

they are not waiting on heads of state or world leaders to reach consensus—they're going ahead regardless of what national governments do (Figure 2.4.1).

REDD case study: the Ogiek people

A Mau Forest conservation project in Kenya, funded by the United Nations Environment Programme (UNEP), provides an example of a carbon offset project that has resulted in serious human rights violations. In 2009, the Mau Forest was "prepared" for this carbon offset reforestation project by the forceful and often violent eviction of its inhabitants, including the Indigenous Ogiek people, who had lived on their ancestral lands in the region for centuries. Prime Minister Raila Odinga argued that in order to preserve the forests, the Indigenous inhabitants had to be removed; he represented them as a threat to the stability of the ecosystem. Following up on the prime minister's declaration, Kenyan President Mwai Kibaki stated, "The government shall take action against people who destroy forests. Such people should not be spared at all, they should be arrested and charged with immediate effect." The prime minister and the Kenyan Forest Service evicted more than 20,000 Ogiek people from their ancestral lands.

The Ogiek have confronted eviction and displacement in the past, extending back to the colonial era when, in the 1930s, British authorities similarly claimed that they were depleting forest resources needed by others. At that time, the Ogiek were forcibly removed to "native reserves" while their lands were logged and replaced with pine plantations. In the 1990s, the Kenyan government allotted large areas of the Mau Forest to friends and associates of elected officials. In 2009, the same week that evictions were announced, the government made allotments in the region to 49 companies and individuals, and one such company has strong ties with former president Daniel Moi. Underscoring this observation, Ogiek leaders argued that the displacement order seemed to ignore the activities of logging corporations and non-Indigenous settlers moving into the region. Large tracts of the Mau Forest continued to be destroyed by corporations turning trees into plywood, doors, and other products for export. Survival International condemned the eviction of the Ogiek in a statement that read in part, "If evicted from

their ancestral land in the misplaced name of conservation, the Ogiek will become the world's next 'conservation refugees.'"

But UNEP, which has its headquarters in Nairobi, supported the government's plans for the Mau Forest. In September 2009, well after the threats of evictions had started, UNEP's executive director, Achim Steiner, was clear in his embrace of the project: "The Mau Complex is of critical importance for sustaining current and future ecological, social and economic development in Kenya. The rehabilitation of the ecosystem will require substantial resources and political goodwill. UNEP is privileged to work in partnership with the Government of Kenya towards the implementation of this vital project."

In 2017, the Ogiek won a victory: an international court ruled that the Kenyan government had violated their ancestral land rights by evicting them from the forest. There is still fear, however, that the government may not abide by the ruling. While many observers agree that the Mau Forest must be restored, UNEP's failure to focus on corporate-led deforestation there while ignoring the eviction of thousands of people to make way for a carbon offset project is troubling for the future of REDD programs and the prospects for millions of Indigenous peoples and forest-dwelling communities of the world.

As much as the above issues and cases are cause for concern, there are success stories as well. For example, The International Small Group and Tree Planting Program (TIST) project is a global effort that seeks to empower subsistence farmers in East Africa, South Asia, and Latin America to reverse the effects of deforestation, drought, and famine. Through the sale of greenhouse gas credits, TIST generates revenue for farmers and supports sustainable agriculture, tree planting, and improvements in public health and education. TIST has over 70,000 participants organized across numerous small groups of farmers and has achieved impressive results (see www.tist.org). Perhaps the lessons from this project can be studied and multiplied many times over.

The evidence strongly suggests that major climate policy frameworks have failed to deliver, as emissions continue to rise while deforestation, evictions, and land grabs intensify. These agreements also suffer from a logical and ideological problem: they are premised on the idea that market-based, pro-growth solutions are workable, when in fact it was

exactly those kinds of approaches that produced the problem of climate change in the first place. More fundamentally, the vision of infinite economic growth in a finite ecological system is a physical impossibility. Perhaps part of the problem is that many of the most affected populations and their visions of climate justice have been excluded from or marginalized in debates. Given all of these challenges, what are some alternatives?

Addressing climate debt and ecological debt

According to an Ecuadorian nongovernmental organization, Acción Ecológica, ecological debt is "the debt accumulated by Northern, industrial countries toward Third World countries on account of resource plundering, environmental damages, and the free occupation of environmental space to deposit wastes, such as greenhouse gases, from the industrial countries." One of the leading scholars in the field of ecological debt studies, Joan Martinez-Alier, calculates ecological debt by drawing on many variables, such as

> nutrients in exports including virtual water, the oil and minerals no longer available, the biodiversity destroyed, sulfur dioxide emitted by copper smelters, the mine tailings, the harms to health from flower exports, the pollution of water by mining, the commercial use of information and knowledge on genetic resources, when they have been appropriated gratis ("biopiracy"), and agricultural genetic resources.

While each of these examples involves the withdrawal of key ecological resources from the global South to the global North, Martinez-Alier shows that wealthy nations and corporations have also brought numerous threats into local environments in the South, including tons of hazardous chemical wastes.

About a study of global ecological debt that he led, economist Richard Norgaard said, "At least to some extent, the rich nations have developed at the expense of the poor, and, in effect, there is a debt to the poor." Nongovernmental organizations across Africa and the global South—including Jubilee South, the Pan African Climate Justice Alliance, the African Peoples Movement on Climate Change, the World Council of Churches, Action Aid, Africa Action, and the Third World

Network—endorse repayment of ecological debt. Moreover, the World Bank acknowledges the problem of ecological debt and its continuing and highly unequal effects on the gross domestic product of various nations.

Climate debt is a specific type of ecological debt and is best summed up in the UNFCCC's own words: "The largest share of historical and current global emissions of greenhouse gases has originated in developed countries . . . [and should be redressed] on the basis of equity and in accordance with their common but differentiated responsibilities." Many scholars and observers believe that addressing climate debt through global North nations' allocation of funds to the South is a path far superior to carbon trading.

Progressive financing of climate debt would involve transferring considerable resources to the South to account for the historic excessive harm that wealthy nations have visited upon the global climate and for future ecological-social crises that will likely unfold in the South. Coalitions like La Via Campesina have demanded of the UNFCCC that 6% of Annex 1 nations' gross domestic product be allocated to finance actions to mitigate the climate crisis in global South countries. On this topic, Pablo Solón, the Bolivian ambassador to the United Nations, stated, "We are not assigning guilt, merely responsibility. As they say in the US, if you break it, you buy it."

The debate over market-based solutions

For many global South activists, the explicit commitment to economic growth in major policy debates around climate disruption is not useful. Growth of the global economy means the production and consumption of an ever-increasing amount of goods, using an ever-increasing amount of energy, mineral, agricultural, and forest resources. For these critics, replacing "growth" as the main objective of the economy is a fundamental change that must be made to address climate disruption. The challenge ahead is to build a new paradigm rooted in meeting human needs equitably and sustainably.

Regarding the growth imperative in climate policy, Tom Goldtooth, director of the Indigenous Environmental Network, said:

> The climate crisis is rooted in a political and cultural system dedicated to economic growth at any cost. Ideas and actions around the climate crisis must include a complete transformation away from the dominant economic model of incessant and unsustainable growth, and social oppression and injustice. . . . Indigenous peoples' cosmovision and our worldview are concerned of a world that privatizes the air, water and commodifies the sacredness of Mother Earth. We must de-colonize the atmosphere.

After the UN Climate Change Conference (COP 16) in Cancun in 2010, the global coalition La Via Campesina declared, "Stop the tendency to convert the grave problems of the climate crisis into business opportunities. . . . Earth cannot be sold!"

There's another way to think about this. To meet the challenges of the climate crisis, we must make consistent, dramatic, and immediate reductions in carbon dioxide and other greenhouse gas emissions. If those needs are clear, then why would we put so much of our effort into a system that is inherently volatile and has never produced consistent, sustainable, and dramatic gains over time?

For some global South communities, the market-based approach is a significant obstacle to achieving solutions to the climate crisis. These groups oppose the dominant policy and cultural framework for addressing climate change, which suggests that the best way to save the planet from ecological peril is to ensure that someone can make a profit while doing it. This logic views ecosystems as commodities and assumes that we will truly value things only if they have a price tag on them. On one hand, that means that everything can be sold, even if it has great cultural, intrinsic, and ecological value to someone who does not want it to be sold. On the other hand, it means that places and things with rich cultural value can be ignored or destroyed if they do not also enjoy high market value.

Many activists in the global South see this kind of unsustainable thinking at the core of market logic. If everything only has a value in terms of global markets, then what is most important and dear to local communities matters much less. This is one of the many problems with cap and trade, CDM, and REDD. These policies are implemented by officials, corporations, and governments that care not about what local

people value, but only about national and international emissions targets appearing to be achieved. These policies run the risk of disempowering local communities and devaluing their ecosystems because they ignore local peoples' needs.

Speaking to some of these concerns, the US Environmental Protection Agency's Acid Rain Program, established under the 1990 Clean Air Act amendments, demonstrates how a market-based cap-and-trade program might achieve significant results. According to the Office of Management and Budget, this project has produced significant reductions in sulfur dioxide and nitrogen oxide emissions from coal-fired power plants in the United States. Nationally prominent advocacy organizations like the Environmental Defense Fund support this particular project and the general market-based approach as well. Despite this project's admirable success, it is fair to say that carbon is a far more complex substance to regulate than sulfur.

Many global South leaders believe that we sorely need to focus on protecting the various *commons* that we all depend on—the land, water, air, and climate systems that we share. Activists and organizations across the global South call for a post-petroleum and post-fossil fuel global economy and society that will produce dramatic, immediate, and sustainable reductions in carbon emissions.

Community-based social movement responses

Community-based leaders across the global South insist that we focus on the root causes—social, environmental, political, and economic—of the climate crisis in order to move toward a total systemic transformation of our societies. There are numerous exciting proposals and visions for how to move toward climate justice from scholars and advocates from around the world. The following are just a select few:

- We need to redefine economic growth. A new paradigm is needed, one that is rooted in meeting human needs equitably and sustainably.
- The long-standing and dominant commitment to infinite economic growth in major climate policy debates is downright destructive.
- We need to shift from export-led development policies and practices in the global South to supporting locally sustainable economies everywhere.

FIGURE 2.5.1 These posters reflect the struggle for climate justice, underscoring links between social equality and environmental protection. 350.org, UC Davis, 2017. Reproduced from Flickr.

- Wealthy nations of the global North must also learn to consume less and achieve dramatic reductions in carbon emissions without offsetting schemes.
- We should reexamine global trade and investment rules that encourage energy-intensive industries that have been proven harmful to ecosystems and the climate.
- Many observers believe that the United States should launch a Green New Deal that would feature a carbon tax on the biggest industrial polluters, phase out subsidies to high-emissions industries, and promote increases in public funding for clean technology, renewable energy, public transport, and energy efficiency. All of this would improve job creation (Figure 2.5.1).

Those are some examples of proposals for climate justice. The following are some instances of actual documents that leaders from the climate justice movement and governments have authored to inspire people, organizations, and policymakers to implement these kinds of changes.

The Bali Principles

In 2002, an international coalition of nongovernmental organizations drafted and released the Bali Principles of Climate Justice, which seek to redefine climate change from a human rights and environmental justice perspective. While covering an ambitious range of topics, these principles make clear that, for many people, the climate issue is a matter of life and death and that perhaps its gravest injustice is that those who suffer the greatest harm are the least responsible for contributing to the problem. The principles consider the causes of climate change and offer a far-reaching vision for solutions.

For example, Principle 24 states: "Climate Justice opposes military action, occupation, repression and exploitation of lands, water, oceans, peoples and cultures, and other life forms, especially as it relates to the fossil fuel industry's role in this respect." It is well known but rarely stated publicly that military organizations and practices require massive fossil fuel production and constitute one of the greatest global threats to ecological sustainability.

The Bali Principles suggest that any move forward in global climate policy must be inclusive of all peoples, especially persons from those communities most affected by climate disruption. Principle 12, for example, states: "Climate Justice affirms the right of all people, including the poor, women, rural and indigenous peoples, to have access to affordable and sustainable energy." According to Principle 20, "Climate Justice recognizes the right to self-determination of Indigenous Peoples, and their right to control their lands, including sub-surface land, territories and resources and the right to the protection against any action or conduct that may result in the destruction or degradation of their territories and cultural way of life."

Finally, Principle 11 calls for new ways of producing energy that are sustainable and fair: "Climate Justice calls for clean, renewable, locally controlled and low-impact energy resources in the interest of a sustainable planet for all living things."

Grassroots global South networks have argued that successes *are* occurring in the struggle for climate justice in local communities around the globe where activists are building movements and power for broader democratic change. Such efforts have prevented major new industrial

carbon emissions by stopping incineration projects, hydropower projects, coal-fired power plants, oil refineries, and offshore drilling expansion plans. These groups have also embraced efforts to decommission carbon markets and promote massive investments in renewable energy, public transportation, urban agriculture, and green jobs.

The rights of Mother Earth

Indigenous rights and environmental justice activists argue that we need to expand the concept of rights to include nonhuman nature. Their central premise is that ecosystems have inherent value and worth—like humans, they have a right to exist. These emerging concepts of environmental citizenship decenter human beings and expand the categories of "person" and "citizen" themselves.

The draft Universal Declaration of the Rights of Mother Earth, developed at the World People's Conference on Climate Change and the Rights of Mother Earth in April 2010 in Cochabamba, Bolivia, is an international framework to ensure a mechanism for the recognition of human rights and for the rights of Mother Earth, or Pachamama. An estimated 35,000 participants from all over the world attended this gathering to urge governments to grant enduring and permanent rights to the Earth, while claiming that such a practice will improve efforts to ensure the rights of the globe's most vulnerable peoples.

In 2008, Ecuador announced a revised constitution that affords the Earth and nature constitutional rights. One passage states that nature "has the right to exist, persist, maintain and regenerate its vital cycles, structure, functions and its processes in evolution." The Pennsylvania-based Community Environmental Legal Defense Fund assisted Ecuador with the revisions to its constitution and has helped draft similar laws in several states in the US as well. Its aim in this regard is to create legal systems "that change the status of ecosystems from being regarded as property under the law to being recognized as rights-bearing entities."

Taking all of the above ideas into account, we can return to the question, What might climate justice look like?

- Any effort at achieving climate justice will have to focus on the root social, ecological, political, and economic causes of the climate crisis.

- Systemic transformations are needed—hence the slogan "System change not climate change."
- Solutions rooted in practices that produced the problem make little sense. In particular, market-based solutions must be reevaluated since pro-growth policies led us down the path toward climate disruption in the first place.
- Community action at the local level works to build political power, to reduce and prevent carbon emissions, and to promote sustainability.

2.6 Conclusion

While climate disruption is a global reality, it affects various populations and nations in significantly disproportionate and uneven ways. The movement for climate justice is inseparable from the debate over solutions to the climate crisis. From global South communities in Africa to African American communities, individuals and organizations have demonstrated against climate injustices and have offered visions for ways to mitigate and reverse this problem. The question on many people's minds is whether those nations and institutions most responsible for contributing to the climate crisis are willing to take these communities and their ideas seriously.

This chapter is intended to raise questions that might inform the policy debate and action around climate disruption and climate justice. Toward that end, we urge you to consider the following questions:

- How can we work with and empower community-based social movements to change the discourse and policymaking around climate disruption?
- How can we bring a deeper understanding of social inequalities and social justice to climate change debates?
- What are some alternatives to market-based solutions in the climate change debate, and how can we promote them?
- What might climate justice look like?

To sum up, climate justice and climate injustice are key concepts that every informed person should be familiar with because they are at the core of both how the problem of climate change developed and how we must address this challenge.

In short, we cannot understand and confront climate change without attention to social inequality. Profits derived from stolen Indigenous lands and the labor of enslaved African people powered the Industrial

Revolution, which set the world on a course toward today's intensive use of fossil fuels. That is, racism and the conquest of people and ecosystems led to climate disruption in the first place. Justice is not a side issue.

Finally, grassroots social change movements are critical for pushing dialogue and action forward in order to imagine and realize climate justice. How do we build those kinds of movements? Luckily, they're all around us, and they are filled with everyday people like you and me. If you're already involved in that kind of work, keep it up, step it up, and do so in ways that are peaceful, respectful, and nonviolent. And if you're not yet involved in that kind of work, the door is wide open and the climate justice movement welcomes you. But we also encourage you to devise *new* and even more creative ways of thinking about and acting to solve our climate challenges. Thank you for reading this chapter, and all the best of luck.

Sources for the Figures

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CHAPTER 3

Climate Change and Human Health

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Learning Objectives

1. Identify the direct and indirect ways that climate change can affect health.
2. Describe how fossil fuels can cause injury, disease, and death.
3. Discuss solutions that protect health, and address both fossil fuels and climate change.
4. Assess your local community's vulnerability to climate change.

Overview

Climate change will cause widespread harm to public health, unraveling many of the health gains of the last century. Climate change will affect everyone, and it will increasingly manifest as violent extremes, ranging from heat waves to fires, storms, and floods. Climate-related events will have direct effects on human health but will also result in a cascade of indirect health effects through population displacement, increased conflict over resources, and mental health problems (Figure 3.1.1). All people will be affected, but the burden of harm will fall disproportionately on the poorest communities, the disabled, the very young, and the elderly, both in the US and globally. Climate change is a threat multiplier, in that it worsens preexisting individual and societal vulnerabilities. Building resilience to climate change requires strengthening our public health system, our physical infrastructure, and our social support systems. Rapid action to reduce greenhouse gases by reducing our dependence on fossil fuels has the potential to improve the quality of life for everyone.

3.1 Climate Change, Health, and Vulnerable Populations

The health effects of climate change are already occurring globally and are predicted to become devastating by midcentury if significant greenhouse gas reductions do not occur. Illnesses and deaths from climate change will vary widely across the globe based on geographic, economic, and individual factors. The *Lancet* Countdown: Tracking Progress on Health and Climate Change has summarized the health effects of climate change and is tracking them over time. In order to save lives, it is critical to understand the general relationships between climate change and health and to learn to predict how these general relationships will play out in a local community. The burning of fossil fuels causes climate change and also causes other direct human health consequences, so there can be direct and immediate health benefits from taking action today to stop and reverse climate change.

The most direct effect from climate change is from heat. Average temperatures are rising globally, and dangerous extreme heat events—"heat waves"—will become increasingly common. Extremes of heat have increased significantly since 1990 in every region of the world, with 157 million more people exposed to heat wave events in 2017 than in 2000. Increased heat increases energy and turbulence in the Earth's atmosphere. This energy can manifest as dramatic weather fluctuations, including extreme droughts and violent storms. In 2017, a total of 712 extreme weather events resulted in $326 billion in economic losses, almost triple the total losses of 2016.

Most of the health effects from climate change are a direct or indirect result of high heat and weather extremes. For example, oscillation from extremely wet to extremely hot and dry increases the risk of fire. This is because vegetation grows rapidly in unusually wet periods and dies in subsequent drought. If hot, windy conditions follow, the dead brush ignites easily and fuels large firestorms. As another example, heat increases the risk of infectious disease outbreaks, both because certain

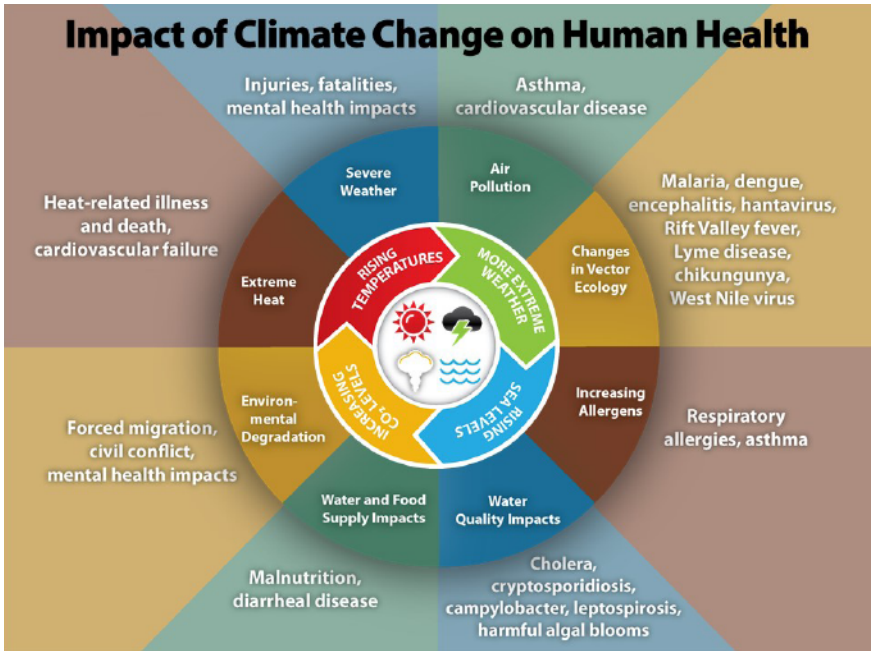

FIGURE 3.1.1 Health effects of climate change. Reproduced from Centers for Disease Control and Prevention.

species of mosquitoes and ticks can survive warmer winters and become established in areas where they could not previously live, and because warmer temperatures encourage bacteria and parasites to proliferate, resulting in outbreaks of food-borne and waterborne illness. Storms, floods, and droughts all contribute indirectly or directly to food and water scarcity, population displacement, conflict, and mental health issues (Table 3.1.1).

Ultimately, some areas will be inundated because of sea level rise; other areas will face increasing challenges from drought-associated food and water shortages; still other areas will encounter river flooding, outbreaks of vector-borne disease, and increased agricultural pest pressures, resulting in more intensive pesticide use and higher crop losses. In some countries, these events will lead to increased conflicts over remaining resources, population displacement and migration, an overstrained public health system, and general social disruption. Even politically stable countries will be stressed by internally displaced populations and an influx of refugees and migrants. Experience from such events,

TABLE 3.1.1 Summary of health effects from climate change

Climate-Related Stressor	*Climate-Related Causes*	*Secondary Effects*	*Health Effects*
Heat	Overall warming	Extreme heat days Ozone smog pollution Reduced work capacity	Heat-related illness Respiratory illnesses Economic stress
Drought	Shifts in rainfall patterns	Reduced agricultural yield Food scarcity	Malnutrition Population displacement
Fire	Shifts in rainfall patterns	Smoke (particulate matter) Property damage	Death Respiratory illnesses Cardiovascular illnesses Population displacement Mental health effects
Increased weed pollen	Higher CO_2 levels Overall warming	More weeds and invasive plant species	Worsened allergies and asthma
Sea level rise	Melting of Antarctic and Greenland ice	Coastal flooding Property damage	Population displacement Drownings Mental health effects
Extreme weather events	Increased atmospheric energy Warming of oceans	Coastal and river flooding Property damage Drinking water contamination Mold growth	Population displacement Drownings Diarrheal disease Respiratory and skin disease Chemical contamination Mental health effects
Vector-borne disease	Overall warming Shifts in rainfall patterns	Mosquito- and tick-borne illnesses shifting north and to higher elevations	Malaria, dengue fever, Zika, chikungunya, Lyme disease, and emerging illnesses
Algal blooms	Overall warming Runoff from heavy rains	Marine mammal and bird die-offs Fishery contamination and loss	Diarrheal disease Neurological disease Economic stress Malnutrition

SOURCE: Watts, N., et al. 2018. The 2018 report of the *Lancet* Countdown on health and climate change: shaping the health of nations for centuries to come. *Lancet* 392(10163), 2479–2514. https://doi.org/10.1016/S0140-6736(18)32594-7; Mora, C., et al. 2018. Broad threat to humanity from cumulative climate hazards intensified by greenhouse gas emissions. *Nature Climate Change* 8, 1062–1071. https://doi.org/10.1038/s41558-018-0315-6.

both in the United States and globally, has shown that the people most likely to suffer and die include the poorest segments of society, the very young, the elderly, and the disabled. The health effects in general will be more severe in poorer countries, placing the worst health burdens on those who contributed least to creating the problem.

Health effects of heat

Extreme heat, the most direct effect of global warming, causes large numbers of deaths and severe illnesses, depending on the intensity and duration of the heat event. Extreme heat events are projected to continue to increase significantly in the United States and worldwide (Figure 3.1.2). Those most likely to die or require emergency hospitalization include the elderly, infants, pregnant women, outdoor workers, and people with a range of underlying health conditions. Major increases in deaths, hospitalizations, and emergency room visits always occur during heat waves, but even during a non-heat-wave period there are clearly documented associations between increased temperatures and a range of health problems. It has been documented in many countries that hospital and emergency room visits increase with increased heat, including from respiratory disease, emphysema, heart disease, heart attack, stroke, diabetes, renal failure, intestinal infections, heat stroke, dehydration, hypertension, and asthma. Studies have also shown that for every increase of temperature by 10°F there is a nearly 9% increase in preterm births.

People exposed to heat can sometimes cool off and rehydrate at night, but if the nights remain hot, there is no opportunity for recovery. Urban areas with extensive paved surfaces are also high-risk zones. Dark pavement and roofing absorbs heat and results in temperatures that are several degrees hotter than nearby tree-shaded or grassy areas. This phenomenon, known as the urban heat island effect, can be mitigated by lighter-colored roofing material, street trees, and parks. Unfortunately many inner-city communities lack natural cooling resources such as trees and parks. A national analysis in the US found significant racial and ethnic disparities in heat-risk-related land cover of neighborhoods, even after adjusting for other factors that influence tree growth. Lack of access to air conditioning is also correlated with risks of heat-related

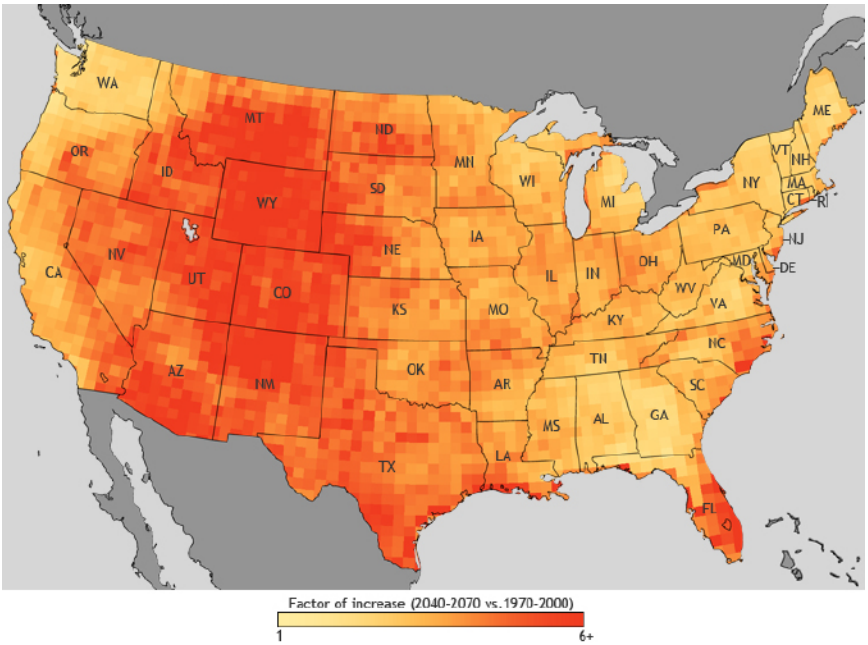

FIGURE 3.1.2 Increase in summer heat wave days over time. Reproduced from NOAA.

illness and death. One study using heat wave data from Chicago, Detroit, Minneapolis, and Pittsburgh found that African Americans had a 5.3% higher risk of heat-related mortality than Caucasians and that 64% of this disparity was potentially attributable to disparities in air conditioning.

Heat reduces work productivity, especially in active outdoor jobs. The 2018 *Lancet* Countdown estimated that 153 billion hours of work were lost in 2017 because of excessive heat, an increase of 62 billion hours lost relative to 2000. Lack of acclimatization to heat is an important risk factor. Workers in hot environments are most likely to develop heat-related illness during their first 2 weeks on the job. Research has shown that people living in normally cooler areas tend to be more susceptible to health effects from heat waves. As one example, during the 2006 California heat wave, the greatest increase in emergency department visits occurred in the normally cooler coastal cities. This phenomenon is probably both because fewer buildings are air-conditioned in these areas, and because people there are less physiologically acclimated to heat.

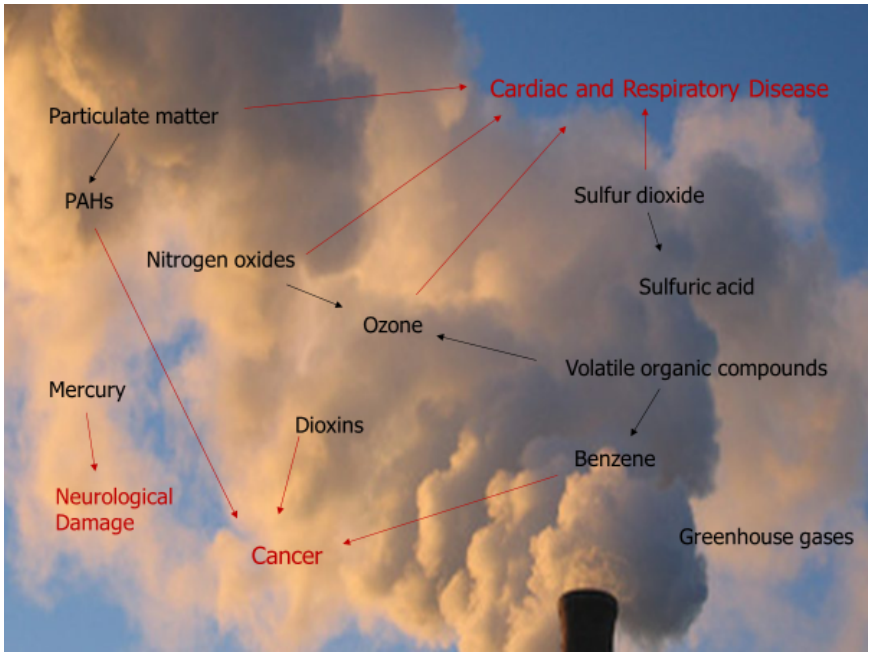

FIGURE 3.1.3 Complex mix of air pollution from a power plant. Slide by Gina Solomon.

Health effects of air pollution

Heat increases the atmospheric conversion of air pollution from gasoline and diesel exhaust into ozone smog. Thus the health threat on hot days stems both from heat itself and from ground-level ozone pollution that can cause respiratory and cardiac damage. Ozone is created from other pollutants such as volatile organic compounds (VOCs) and nitrogen oxides that are emitted from industrial sources, power plants, cars, and trucks (Figure 3.1.3). These chemicals are transformed by sunlight in a chemical reaction that breaks down oxygen in the air and results in ozone formation. Heat dramatically speeds up this chemical reaction. As the ambient temperature rises, ground-level ozone levels also rise. Ozone in the upper atmosphere is beneficial because it protects us from the damaging ultraviolet rays of the sun. But ground-level ozone is extremely toxic to our lungs. Ozone in the lower atmosphere is also known as smog because it creates a gray-brown haze that looks like a combination of smoke and fog.

The health effects of inhaled ozone include cough, difficulty

breathing, chest pain, decreased lung function, and asthmatic symptoms. These symptoms send people to the emergency department with acute illness. Over time, ozone can also cause significant long-term damage to airways, affecting the white blood cells that protect our lungs.

Warmer weather conditions with higher concentrations of carbon dioxide (CO_2) in the air also foster the growth of allergenic weeds such as ragweed. Studies in greenhouses with carefully controlled atmospheric composition have shown that air slightly enriched in CO_2, at concentrations we expect to see due to climate change within the next few decades, causes ragweed to grow more lushly; worse, the plants produce about three times more pollen. That extra airborne pollen will seriously worsen the suffering of individuals with pollen allergies. These findings suggest an increase in health challenges associated with nuisance symptoms such as hay fever, as well as more serious conditions such as asthma.

In addition to ozone pollution and allergens, particulate matter is also a threat to health. Particulate matter is discussed in more detail below, since it is produced in massive quantities from wildfire smoke and also from the combustion of petroleum and coal—the same sources that produce most of the carbon dioxide in the atmosphere.

Health effects of wildfires

A warming climate places enormous stress on many species of trees as weather conditions become too warm and either too wet or too dry for the climate to which the trees are adapted. Stressed trees are much more susceptible to fungal infestations, and bark beetles have been decimating the conifer forests of the western United States. Dead trees create conditions that are ideal for massive wildfires. In December 2017, the US Forest Service estimated that there were 129 million dead trees in California, mostly due to drought and bark beetle infestation. Drought conditions in numerous countries around the world are similarly fueling fires in places ranging from Australia and Indonesia to Canada. Rainy conditions that may follow a drought come too late to save the trees, but rain results in fast growth (and subsequent dieback) of grasses and shrubs that provide kindling to start massive wildfires. Wildfires are a natural part of forest cycles, but the fires that occur with

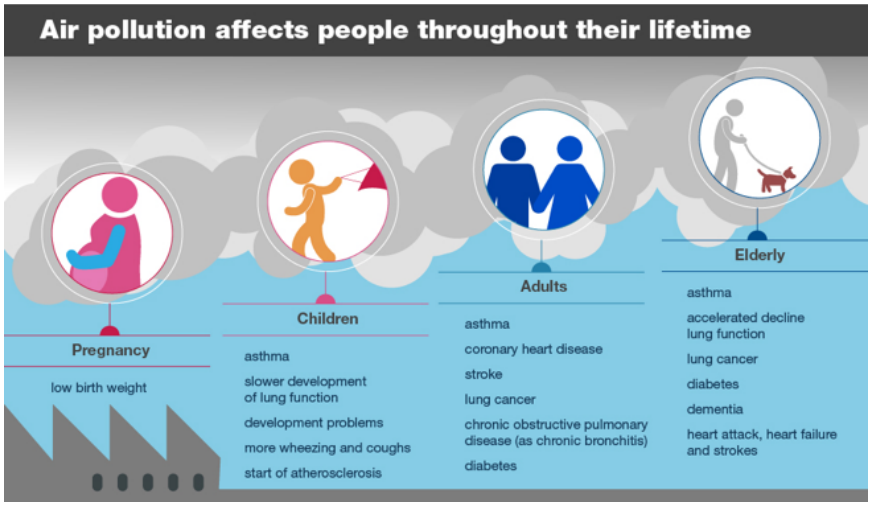

FIGURE 3.1.4 Health effects of air pollution. Reproduced from Public Health England.

climate change are intense firestorms that cover vast areas, burn so hot that they destroy everything in their path, and damage ecosystems while they threaten humans. In rural areas, fast-moving wildfires can burn down homes and destroy communities. In recent fires, deaths have occurred among both emergency responders and local residents when they were unable to escape from the path of the fire or their escape route was cut off.

The health effects of wildfire smoke are similar to the health effects of other particulate matter (PM) in the air (Figure 3.1.4). The small particles (known as $PM_{2.5}$ because they are less than 2.5 micrometers in diameter) are less visible but more dangerous. These particles cause lung inflammation that results in impaired function, cough, phlegm, bronchitis, worsened asthma, heart attacks, heart failure, and premature death. These effects especially occur in people with underlying health conditions, such as heart disease, lung disease, and asthma. Even healthy people can be sickened when wildfire smoke is severe, leading to decreased exercise tolerance, cough, sore throat, and eye irritation. Smoke from large fires can cover areas of hundreds of square miles and can affect entire cities or even entire states for periods of time that can range from days to months.

Health effects of flooding

Although it is difficult to pin any single weather event on climate change, climate models show that extreme weather fluctuations increase as the Earth warms. For example, rain is more likely to fall in large amounts when it does occur, leading to increased risk of flooding. Sea level rise will result in inundation of low-lying coastal areas, especially during high tides and storm surges. Hurricanes are projected to become more powerful as a result of warming waters in the Atlantic and the Gulf of Mexico. The combination of major storms and sea level rise will predictably result in both coastal and river flooding, both in the US and worldwide.

When Hurricane Florence flooded the Carolinas in 2018, not only did people lose their lives, but there were enormous health implications, both immediately and in the longer term. Hurricane Florence was considered a "1,000-year storm," but such storm events will no longer be rare in the future, as what is now considered an unusual or extreme storm will become a relatively frequent occurrence.

Fifteen percent of all deaths related to natural disasters are due to floods. People who are disabled or elderly are often less able to evacuate before a major storm. In some floods, nursing homes and hospitals are inundated, leaving elderly and sick people in miserable conditions, without adequate care. In the flooding after Hurricanes Katrina, Sandy, and Maria, emergency generators at medical facilities failed, and oxygen supplies, respirators, heart monitors, and all other advanced medical systems stopped functioning, as did air conditioners and lighting. Conditions in these facilities were horrific, and many people suffered and died in the days and weeks following these storms.

Flood waters are often contaminated with sewage and chemicals, resulting in gastrointestinal illnesses and skin diseases after contact. After people's homes are flooded and the waters recede, it looks like the contents of the home have been picked up and swirled around in a huge blender. The walls grow a thick carpet of black and brown mold over mud and scum (Figure 3.1.5). Testing in flooded homes reveals high airborne levels of mold and endotoxin, which are extremely dangerous to people's health. Endotoxin is produced by certain kinds of gram-negative bacteria that thrive in damp conditions; it can cause respiratory distress, low blood pressure, and shock. Mold can cause allergic reactions,

FIGURE 3.1.5 Flooded homes after Hurricane Katrina, New Orleans, 2005. Photographs by Gina Solomon.

asthma, and other health problems. For these reasons, returning home to sift through personal belongings can be dangerous and requires respirators, protective coveralls, and gloves.

Floods also cause massive destruction of residential and commercial structures, making neighborhoods completely uninhabitable. There can also be damage to oil and gas pipelines, water mains, roads, sewage treatment plants, and other infrastructure that creates contamination across the entire landscape. Industrial facilities, hazardous waste sites, and petroleum storage tanks may rupture in the flood and spread toxic contamination into the mud and soil, both outdoors and inside the flooded homes. Testing in New Orleans after the 2005 flood from Hurricanes Katrina and Rita revealed toxic petroleum chemicals, heavy metals such as lead and arsenic, and pesticides in the sediment that was left behind from the flooding. All of these issues need to be addressed in the

cleanup, and they pose hazards to returning residents and to cleanup workers.

Floods cause massive population displacement and homelessness. Some people can evacuate the area and stay elsewhere with family or friends, at least for a while. Others have no place to go and must be housed in temporary shelters, sometimes for months. The large numbers of displaced people need food, water, and health care. Evacuees with underlying chronic diseases frequently experience exacerbations of their illness, often from lack of essential medications. For example, diabetics who don't have their insulin, people with seizure disorders, and people with severe psychiatric illnesses are all at high risk of serious and sometimes life-threatening exacerbations. Family and community structures and daily routines are completely disrupted, leading to depression, anxiety, post-traumatic stress disorder, and confusion for many people, especially the elderly. Rates of suicide almost always spike after hurricanes and floods.

Infectious diseases

Flooding causes obvious immediate risks of injury and death but also can impair drinking water quality by increasing runoff of contaminants into surface water sources. Runoff of soil and sediment into rivers and streams can lead to growth of parasites in the water, especially *Cryptosporidium* and *Giardia*. Both of these parasites can cause severe diarrhea and especially severe illness in people with immunosuppression. The combination of extreme rainfall and a malfunction at a drinking water treatment facility is the most likely set of factors that can lead to a major outbreak of one of these parasitic diseases.

Increased heat from climate change is another factor that substantially increases the risk of infectious disease spread. The combination of warmer conditions and altered rainfall patterns can lead to ponding of warm, stagnant water—conditions ideal for the life cycle of numerous pests, including the mosquitoes that carry diseases ranging from malaria and yellow fever to dengue fever and chikungunya.

As one example, the *Aedes albopictus* mosquito—known as the Asian tiger mosquito—came into Southern California in a shipment of imported ornamental "lucky money trees" (*Pachira aquatica*) from Asia in the early

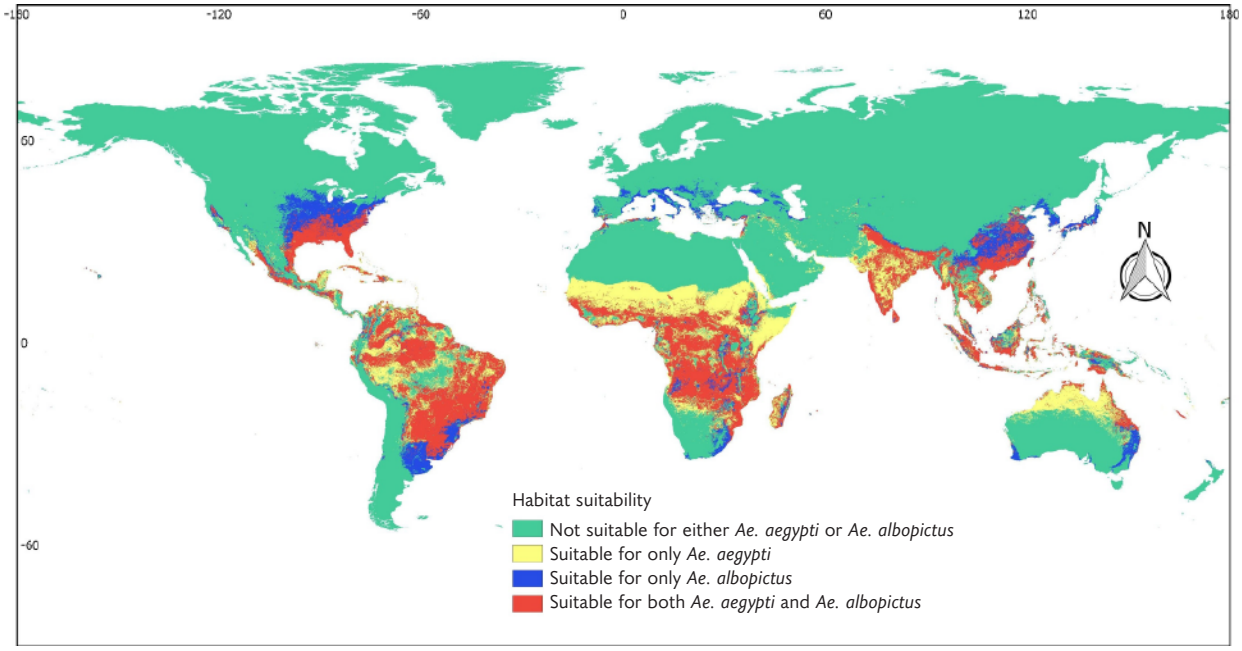

FIGURE 3.1.6 Habitat suitability for disease-carrying mosquitoes in the United States. Reproduced from Centers for Disease Control and Prevention.

2000s. It entered Texas at about the same time in shipments of used tires. *Aedes albopictus* and a similar mosquito known as *Aedes aegypti* are both relatively new to the United States but have been spreading northward rapidly (Figure 3.1.6). In the past, these species would not have survived the winters in temperate climates, but their range has been steadily extending northward as a result of the warming climate. In the tropics, the range of these pests is extending to higher elevations in mountainous areas, exposing new populations to threat. For example, the highlands of sub-Saharan Africa had a 27.6% rise in the potential for transmission of malaria from 1950 to 2017 due to warming. The *Aedes* mosquitoes are hard to avoid, because they prefer to prey on humans, they bite during the day, and they breed in little pools of water, such as in plant pots, abandoned tires, kiddie pools, bird baths, and other items that lie around collecting water in many people's yards.

Aedes mosquitoes are capable of transmitting a variety of diseases that weren't previously thought to occur in the United States and that are not carried by local mosquitos, including dengue fever, chikungunya,

and zika virus. Zika caused a well-publicized epidemic in South America and raised public fears because it can cause microcephaly—a devastating birth defect—in infants when women are exposed during pregnancy. Zika was also detected in southern Florida in 2016 and has become endemic to the area since that time.

Dengue is nicknamed breakbone fever because people who have it feel like their bones are breaking. The illness is characterized by severe headaches, generalized aches and pains, high fevers, and total loss of appetite with nausea and vomiting. The symptoms of chikungunya are similar, with high fever and body aches; this disease entered Italy in 2007 and recurred in 2017 after a decade's hiatus.

Lyme disease and other fevers that include rash and arthritis are spread by ticks. The populations of ticks that carry these diseases are moving northward into Canada. Agricultural pests and invasive plant and animal species are also moving around the globe as a consequence of air travel and trade. When invasive species arrive in an area, they can outcompete local plants, animals, or insects and may thrive in the warmer conditions brought by a changing climate. One reason that agricultural pests and invasive species are important is that they can be enormously destructive to native species and to local food crops; the other reason they are important is that they can result in major increases in pesticide use to fight them. Many pesticides are associated with serious human health risks, ranging from neurological toxicity, to reproductive effects, to cancer.

Food-borne diseases are also a concern with climate change. Many people are familiar with *Salmonella* and *E. coli* food poisoning outbreaks. Warming conditions are ideal for bacterial species, since bacteria proliferate far more rapidly as temperatures increase. Several species of *Vibrio* cause severe skin diseases after water contact, and severe gastrointestinal illness from consumption of contaminated shellfish. *Vibrio* shellfish poisoning has now moved into the cool waters off Alaska during summer seasons.

Harmful algal blooms and health

Harmful algal blooms (HABs)—sometimes called red tides—are another health threat associated with climate change. The combination of

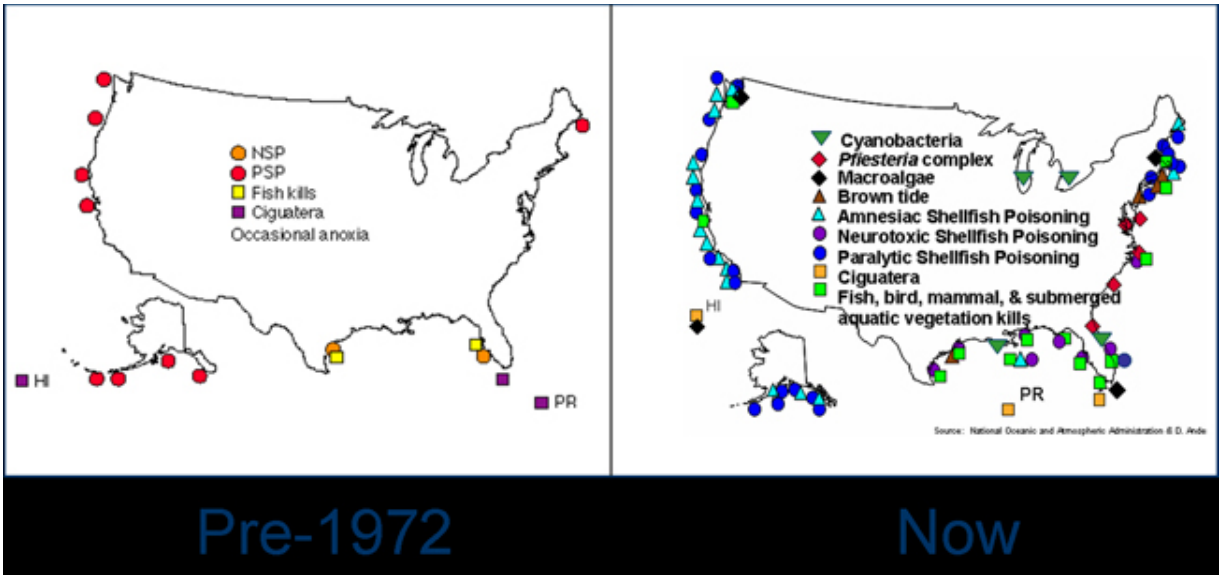

FIGURE 3.1.7 Increase in reported harmful algal bloom events over time.
Reproduced from NOAA.

nitrogen- and phosphorus-rich water and heat creates conditions ideal for the explosion of small marine organisms and algae. The nutrients are often contributed by fertilizer runoff in rain events, resulting in pollution of lakes and coastal waters. Explosions of algal growth are toxic to fishes and amphibians because the oxygen levels in the water drop to dangerously low levels. HABs are doubly dangerous because they produce toxins that can directly poison creatures that are in contact with the water. In many cases, HABs are quite visible, creating greenish, blue, or red material on the surface of the water. In some cases, the problem is less visible, thereby failing to alert people to the danger.

HABs often result in major die-offs of aquatic species, including fishes, birds, and marine mammals. Dogs and livestock that drink from, or swim in, contaminated water are also at high risk of death. People can be affected in some cases from skin contact with the contaminated water, or inhalation of ocean spray. In most cases, however, people are poisoned from contaminated seafood. The symptoms of HAB poisoning vary depending on the organism. Brevetoxins, most commonly associated with "red tides" off the Florida coast, are respiratory toxins when inhaled, leading to asthmatic symptoms even in those who do not

have asthma. Cyanobacteria, known as blue-green algae, are found in freshwater as well as in salt water. They produce toxins such as microcystin that affect the liver and gastrointestinal tract, causing vomiting, diarrhea, and sometimes fatal liver failure. Some of these toxins are also potential carcinogens. Other categories of HAB toxins affect the nervous system. Most of these toxins affect humans through consumption of contaminated shellfish. For this reason, the names of the diseases include "paralytic shellfish poisoning," "neurotoxic shellfish poisoning," and "amnestic shellfish poisoning."

Amnestic shellfish poisoning is caused by domoic acid, which is produced by a microscopic diatom in the genus *Pseudo-nitzchia*. This organism grows explosively in salt water when there is nutrient pollution from runoff and when the ocean gets warm, but it does not cause a visible bloom like a red tide. Shellfish, including clams, mussels, oysters, and crabs, consume the organism and do not die. Instead, they sequester large quantities of the toxin in their bodies, poisoning anything that eats them.

Domoic acid is neurotoxic, causing seizures and death in marine mammals and birds. The first sign of an offshore bloom is marine mammals washing up on the beaches: sea otters, sea lions, seals, whales. The toxin also affects humans. Symptoms start quickly, within 24 hours after ingesting contaminated shellfish. Initially it seems like any other food-borne illness, with nausea, vomiting, diarrhea, and abdominal pain. Then the neurological symptoms begin, including headache, dizziness, weakness, seizures, and changes in mental status. And ultimately, for those people who do recover, some develop anterograde memory loss, which means that from the time of the illness onward, they are not able to retain memories. These people classically can't remember what they had for breakfast that morning, even though they have clear memories of their lives prior to the poisoning event. The treatment is supportive care. There is no antidote.

The first reported outbreak of amnestic shellfish poisoning was in 1987 in Prince Edward Island, Canada. Three people died in that outbreak, and over 100 people suffered permanent neurological effects. Since that time, the US, Canada, the European Union, and numerous other countries have put in place programs to monitor seafood and

attempt to ensure that scientists detect domoic acid and other HABs before people become ill. The California Dungeness crab fishery was shut down for the entire 2015 season because of domoic acid contamination, resulting in enormous economic losses but also saving many lives and preventing severe debilitating illness.

Health and social inequality

Climate change has a disproportionate impact on vulnerable and socially marginalized populations. Globally, those countries most threatened by the risks of global warming are generally the ones that have the fewest resources to respond and protect themselves; these are also the same countries that are least responsible for climate pollution. According to the World Health Organization (WHO), diarrhea, malaria, malnutrition, and heat stress are the top causes of death worldwide associated with climate change. WHO estimates that the direct health costs of climate change will be approximately $2.4 billion per year within the next few decades.

Within wealthy countries such as the United States, poor communities are at greatest risk of harm. Researchers have developed the term *the climate gap* to describe the disproportionate affect of climate change on people of color and the poor. Risk to any community or individual is a function of hazard multiplied by vulnerability. Hazard in this context could include any climate stressor such as living in an urban heat island or in a floodplain. Vulnerability describes the ability to anticipate, cope with, resist, and recover from a stressor, such as a heat wave or flood. Both hazards and vulnerabilities are often greater in poor communities of color, resulting in greater overall risks of harm.

Climate change also exacerbates social inequality by increasing costs for basic necessities such as food and water. Insurance rates in flood and fire zones also rise, resulting in a higher proportion of uninsured or underinsured individuals in poor communities. Despite the burdens on the poor and on communities of color, however, studies have shown that such communities are more inclined to support strong government action to reduce greenhouse gas emissions.

The State of California has taken an innovative approach to addressing climate change and social inequality. Over a billion dollars of

funding from the state auctions of carbon credits has been allocated to disadvantaged communities for projects to improve rail and other public transit, transit-oriented development, affordable housing, bike lanes and sidewalks, agricultural land preservation, rebate programs for zero-emission vehicles, weatherization programs for low-income communities, urban forestry, and fire risk reduction. In addition to reducing greenhouse gases, these investments bring jobs into disadvantaged communities, create local conditions that promote health, and help redress environmental injustices. This program has the potential to serve as a model for a way to use a market-based greenhouse gas cap-and-trade program to generate funds that serve to also address principles of health and climate justice.

Direct health threats from fossil fuels

Fossil fuels, including coal, oil, and natural gas, continue to be the main sources of energy in our global economy. These energy sources fuel power plants, providing us with electricity; they fuel our automobiles and trucks; and they fuel our industrial sector, producing plastics, chemicals, cement, and consumer products. Fossil fuels also are used in agriculture to make fertilizer, pesticides, and all the equipment used to grow, harvest, and process food.

Fossil fuels have direct health effects at every stage of their production and use. Coal mining, oil drilling, and hydraulic fracturing ("fracking") for oil and gas cause emissions of toxic chemicals to air and water, as well as occasional dramatic disasters, ranging from worker fatalities in mine collapses, explosions, or fires, to massive spills such as the 2010 Deepwater Horizon BP oil spill in the Gulf of Mexico. Transport of these fuels is beset with pipeline leaks, rail disasters including explosions, and spills from ocean tankers. Processing of fossil fuels at refineries affects local communities on a daily basis with air pollution that includes known human carcinogens such as benzene and formaldehyde, asthma-causing chemicals like nitrogen oxides, and reproductive toxicants. Worse still, the highly flammable mixtures under high pressures and temperatures at refineries can result in explosions and fires, sometimes killing workers or sending hundreds or even thousands of local residents to emergency departments.

Combustion of fossil fuels results in release of carbon dioxide, the

greenhouse gas that has the longest atmospheric life and is the greatest contributor to climate change. Other air pollutants released when fossil fuels are burned include particulate matter, benzene, other volatile organic compounds that can be transformed into ozone, and heavy metals such as mercury. Harmful chemicals such as sulfur oxides and nitrogen oxides are also released.

Particulate matter is a special concern; black carbon particles small enough to be inhaled deep into our lungs are released from power plants, refineries, many industrial facilities, diesel engines, diesel generators, and many other sources. Particulate matter has serious effects on our hearts and lungs—it increases death rates by increasing arrhythmias (abnormal heartbeats), causing abnormal clotting in blood vessels, worsening bronchitis, triggering asthma attacks, and causing strokes and heart attacks. In 2015, particulate matter from fossil fuel combustion was responsible for 2.9 million premature deaths, with coal burning being responsible for more than 16% of these deaths. Black carbon particles from coal or diesel exhaust contain high concentrations of cancer-causing chemicals known as polycyclic aromatic hydrocarbons (PAHs), which over time can lead to lung cancer and other cancers.

Poor people of color are more greatly affected by the fossil fuel industry, from the points of production near refineries, to the points of emission near power plants, major roadways, ports, rail yards, and airports. An analysis of the demographic patterns of exposure to particulate matter and nitrogen oxides from power plants and petroleum refineries found that minorities are more likely than non-Hispanic whites to live near these facilities, even when the analysis controlled for household income.

Assessing local risk from climate change

As we live our daily lives, it's easy to ignore the dangers around us. Many people think that the scenes they see on television or in the newspapers couldn't happen to their own community. It is hard to imagine how our own communities would look after a devastating fire, storm, or flood. In fact, most communities are at risk from climate change in the coming years and decades. The way to protect ourselves is to open our eyes to the hazards and vulnerabilities in our communities and to

prepare, so if disaster does occur, we can protect both ourselves and others around us.

The steps to assessing local risk include first identifying the hazards. For example, low-lying areas may be at risk of flooding, especially if they are in the potential path of coastal storm surge or river flooding. However, the widespread flooding in September of 2018 after Hurricane Florence in North and South Carolina included low-lying areas simply inundated by heavy rainfall. Areas along the urban-wildland interface may face a high risk of catastrophic fire. Highly urbanized neighborhoods without much tree cover may be at particular risk from extreme heat events, especially if many people lack air conditioning or in the event of a power failure. Coastal and lake areas face the potential for HAB events, and warmer, wetter zones have higher risk of mosquito-borne disease outbreaks. Identifying local hazards from climate change can help create plans to either reduce those hazards or to prepare for a potential event.

Local vulnerabilities can also be assessed at any scale, from a single family to an entire state. For example, identifying the presence and locations of elderly or disabled people who may need extra assistance in the event of an evacuation, or who may be more vulnerable to heat, can help ensure that those people receive the assistance they need. Schools, day care centers, hospitals, nursing homes, and other facilities that can be difficult to evacuate are also critical to locate. Such facilities should have extensive plans for preparing and responding to disasters.

In climate catastrophes, relatively few people will die in the immediate event. The main brunt of the illnesses and deaths occurs in the aftermath, when the effectiveness of the response and recovery is critical to determining the outcome for many people. For example, if people with underlying illnesses or acute injuries are able to access timely medical care, they may avoid serious outcomes. Mental health services, relocation services, housing, food, safe drinking water, and social support are all essential components for recovery.

Ultimately we will need to make very difficult decisions as a society. For example, rebuilding homes and communities after flooding may be seen as an increasingly unwise investment of resources. Adequately protecting against sea level rise or flooding is a very expensive effort, and it can realistically be done only in limited areas. Strategies to reduce the

risk of wildfire are also evolving, as people realize that fire suppression is ultimately bound to fail, and as massive tree die-offs occur from drought and pest infestations. Yet optimal forest management is controversial and complex.

Reducing climate vulnerability

The interconnections between climate change, health, and justice suggest the importance of incorporating co-benefits into climate mitigation policy to ensure that solutions leverage improvements in community health while advancing climate justice. Linking social equity, health, and sustainability goals in environmental policy can mobilize key constituencies to address climate change.

The State of California has made significant efforts to integrate equity into policies and programs to address climate change, in order to ensure that disadvantaged populations receive an appropriate distribution of benefits as well as protection from additional harms. Disadvantaged communities in California have been identified and prioritized for funding, using the California Communities Environmental Health Screening Tool (CalEnviroScreen). CalEnviroScreen was developed through a public process that included extensive community input. It enables the identification of communities in California that are burdened by multiple sources of pollution and face a combination of factors, including contact with pollutants, adverse environmental conditions in their community, biological vulnerability due to underlying disease burden or age distribution, and social vulnerability due to poverty and other community characteristics. The concept of using cumulative impacts in communities to prioritize areas for funding allows some principles of climate justice to be integrated into climate mitigation decisions.

Other approaches to reducing greenhouse gases (GHGs) while adapting to a changing climate and protecting public health include the following:

- Promote alternative modes of transit, including walking, biking, and public transit. These strategies reduce GHGs while directly enhancing health by reducing motor vehicle pollution and increasing physical activity.
- Make communities greener by planting trees and developing green/

cool roof projects, parks, and buffer zones in flood-prone areas. These strategies reduce air pollution and noise, directly improve mental and physical health, and reduce the urban heat island effect.

- Construct green, efficient buildings that reduce GHGs while also improving indoor air quality, thereby directly benefiting the health of occupants. Such buildings may also be more resilient to heat while using less energy for cooling.
- Reduce fossil fuel use, and gain a series of direct benefits to public health in communities affected by air pollution. Reduced fossil fuel combustion will reduce toxic chemical emissions and particulate matter pollution. It will also reduce the emissions of ozone precursor chemicals, thus reducing smog despite a warming climate.
- Reduce consumption of meat and high-fat dairy products to substantially reduce emissions of methane, which is sometimes referred to as a super pollutant because of its potency as a GHG. Reduced meat and dairy fat consumption would also reduce risks of cardiovascular disease and cancer, both of which are associated with diet.

There are numerous actions we can all take in the near term to reduce our climate footprint while also benefiting our health and the health of our communities. At the same time, we must evaluate the risks in our local areas and develop strategies to reduce those risks or increase our resilience so that we will escape the worst effects of climate change and protect our families, our neighbors, our environment, and people around the globe.

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CHAPTER 4

Overview of the Ten Solutions for Bending the Curve

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Learning Objectives

1. **Summarize the basic concepts and the urgency of climate mitigation.**
   You will learn why immediate action to mitigate emissions of climate pollutants is needed if we are to avoid severe impacts on human and natural systems. Central to these mitigation efforts is a transition away from CO_2-emitting fossil fuels as well as drastic reductions of short-lived climate pollutants (SLCPs). You will also learn why actions on these pollutants must be scaled up rapidly over the next few years to avoid dangerous levels of warming.

2. **Describe the multidimensional scope of climate change mitigation.**
   You will see that a wide range of societal sectors will feel the impacts of climate change. Moreover, solutions to climate change require expertise from a range of fields and must be addressed through interdisciplinary collaborations including both experts and ordinary citizens. It's also important to keep in mind that some of the most severe impacts will be felt by future generations and by the global poor, whose emissions are very low. Thus, both intergenerational and intragenerational equity must be considered in the development and evaluation of climate solutions.

3. **Explain why we need to organize mitigation under six clusters and ten solutions.**
   Because climate change solutions cover so many sectors and require knowledge from so many fields, we need a framework to help us organize and evaluate solutions. In 2015, an interdisciplinary group of experts came together to develop broad strategies to mitigate emissions and the impacts of climate change. They distilled these strategies into a list of ten solutions, grouped into six clusters. This structure of ten solutions in six clusters provides the core organizing principle for this book.

4. **Provide examples of mitigation actions already underway.**
   Finally, you will get a first look at how cities, states, businesses, universities, and other institutions have already begun to serve as "living

laboratories," implementing and testing climate solutions and forming networks to coordinate their efforts and share lessons learned.

Overview

In Chapter 1, we looked at the science of climate change. We saw the strong scientific consensus that human emissions of climate pollutants are causing warming of our planet on a scale not experienced in over 10,000 years. Continuing on a "business as usual" pathway could lead to dangerous and even catastrophic changes in the Earth's climate, with severe adverse impacts on human and natural systems. We have at most a few decades to change this trajectory and bend the curve of warming. In this chapter, we will take an initial look at strategies to mitigate future climate change.

The challenges presented by climate change cannot be solved by technological innovations alone. Dealing with this problem will require changes in our attitudes toward each other and toward nature, as well as changes in our behavior. We will need a broad-based effort, with active involvement by individuals from a wide range of fields, including researchers, academics, engineers, community leaders, and ordinary citizens.

This book is organized around a set of ten solutions designed to bend the curve—to reverse the trend of increasing human greenhouse gas emissions and keep the planet below dangerous levels of warming. Until 2015 it was generally assumed that warming above 2°C would represent the threshold for danger. More recently, we have come to understand that the dangerous warming level is lower: 1.5°C. Warming limits, such as the 1.5°C goal, should be viewed as broad planning tools and not confused with a well-defined geophysical threshold for the onset of dangerous changes. As you learned in Chapter 1, dangerous impacts of climate changes have already begun at local levels in the form of intensified droughts, wildfires, hurricanes, and floods, among other extreme weather-related disasters. Such impacts are already being felt by several tens of millions; when the warming reaches 1.5°C to 2°C, 1 billion to 2 billion people could be affected adversely—at which stage,

global warming may have to be renamed global *heating*, and climate change renamed climate *disruption*.

The ten solutions to climate change are organized under six solutions clusters. This set of six clusters and ten solutions was developed by a multidisciplinary group of over 50 experts from across the University of California system who came together in the summer of 2015 to discuss a comprehensive approach to combating global warming and climate change. Their findings and recommendations are included in the report *Bending the Curve: 10 Scalable Solutions for Carbon Neutrality and Climate Stability*.

Although the time to act is short, the good news is that we are not starting from zero. International agreements, including the Montreal Protocol on Substances that Deplete the Ozone Layer (Montreal Protocol), signed in 1987, and especially the Paris Agreement, signed in 2015, have laid the groundwork on which we can build future actions. The Montreal Protocol's original focus was on banning emission of chlorofluorocarbons (CFCs) that damage the ozone layer. While damage to the ozone layer is a separate problem from climate change, those same CFCs have powerful climate-warming effects; per ton of emissions, the warming effects of CFCs are about 10,000 times stronger than the effect of carbon dioxide. If they had not been banned, current global warming would have been even greater. Moreover, the Montreal Protocol itself has been expanded to include climate change. The 2016 Kigali Amendment to the Montreal Protocol calls for the phaseout of hydrofluorocarbons (HFCs), which do not damage the ozone layer but have very significant warming effects (Box 1.3.1 in Chapter 1). The Montreal Protocol and the Kigali Amendment are discussed in more detail in Chapter 15.

The Paris Agreement represents a historic advance because it is the first international agreement on climate change to include commitments (albeit voluntary) from all nations on the planet. This agreement has its drawbacks; as we will see in Chapter 10, current national commitments under the Paris Agreement are not sufficient to keep warming below 2°C, and many issues remain regarding monitoring and reporting of reductions in emissions. However, as the first truly global agreement on climate change that commits countries to specific mitigation actions, the Paris Agreement provides a foundation for future progress.

Beyond these international agreements, significant efforts to mitigate emissions and combat climate change have already begun at a wide range of institutions, cities, states, and regions, which can act as living laboratories to test societal, governance, economic, and technical solutions. Lessons learned from these models can help guide the implementation of mitigation efforts at national and global scales.

4.1 Setting the Stage for Mitigation

In this section, we will look at two key questions:

1. Why should we mitigate climate change?
2. How much time do we have to begin mitigation efforts?

Why should we mitigate climate change?

The scientific findings presented in Chapter 1 make a compelling case for mitigation of climate pollutants. Unmitigated warming along a business-as-usual pathway presents serious and possibly existential threats to human society and natural ecosystems. Human societies have already experienced significant impacts from the 1°C of warming that has occurred since the Industrial Revolution, including increases in extreme weather events such as heat waves, droughts, and flooding; a 40% loss of summer sea ice in the Arctic; and major episodes of coral reef bleaching. Future warming could cause major population displacements due to sea level rise and extreme weather, as well as massive disruption and extinction of natural species. These impacts could become catastrophic and pose existential threats if warming were to exceed 4°C. The long lifetime of carbon dioxide in the atmosphere means that the effects would linger for centuries to millennia, affecting our children, grandchildren, and generations still unborn.

The impacts of climate change will be felt in almost every aspect of human society and social systems and in natural ecosystems as well. Sea level rise, floods, and forest fires will threaten residential and commercial buildings, as well as the insurance companies that could face rising liability costs as damage to insured properties increases. Employment in the energy sector will be affected by major shifts as the industry transitions from fossil fuels to renewables and other low-carbon energy sources. Agriculture will be heavily affected by shifts in growing zones; in particular, millions of agricultural workers in the subtropics could

be displaced by drought and heat waves. Even recreation will be affected. For example, increasing snowmelt is already beginning to affect the ski industry, migration of species can affect recreational fishing, and increasing temperatures and more frequent heat waves will affect your opportunities and ability to enjoy outdoor sports.

As you will read in the coming chapters, mitigation of climate change will require a shift away from fossil fuels (coal, oil, and natural gas) as our primary energy source. Fossil fuels currently supply about 80% of the energy used worldwide, and they are by far the largest source of carbon dioxide emissions.

There are many co-benefits to moving away from fossil fuels. Beyond their warming effects, emissions associated with the use of fossil fuels are also a major health hazard. Aside from the future warming avoided, significant health co-benefits will result from phasing out fossil fuels. Fossil fuel combustion generates black carbon, which can cause heart disease and lung cancer, and ozone, which aggravates respiratory conditions and inhibits growth of agricultural crops. Air pollution (outdoors and indoors) is estimated to cause 7 million premature deaths each year, with about half of those deaths attributed to pollutants associated with fossil fuel burning. Full implementation of the short-lived climate pollutant (SLCP) mitigation measures discussed in this chapter and in Chapter 15 could save 2.4 million lives that would have been lost to outdoor pollution and 3 million lives otherwise lost to indoor pollution each year, and it could save up to 140 million tons of staple crops (maize, rice, soybean, and wheat) that would have been destroyed by ozone exposure.

A shift from fossil fuels to low-carbon energy sources would have other co-benefits as well. While there would be job losses in traditional fossil fuel industries, there would also be significant new employment opportunities in sectors such as renewables and energy storage. In light of the rapid advances in energy storage technology and dramatic decreases in the price of wind and solar energy over the past decade, renewables have the potential to provide abundant, affordable energy for all people and dramatically improve the lives of the 3 billion global poor.

How much time do we have to begin mitigation?

The short answer is: not much. Humanity has reached a crossroads; the consequences of our actions over the next decade or so will affect our descendants and the planet for centuries and millennia to come. Given the scope and scale of transformations that will be required, it's clear that we must begin mitigation efforts now and bring them up to full speed by the middle of this century. We can see this more clearly by focusing on two approximate time periods: between now and 2030, and between 2030 and 2050.

Since the beginning of the Industrial Revolution, humans have emitted approximately *2 trillion* metric tons (actually 2.2 trillion tons as of 2017) of CO_2 into the Earth's atmosphere. About 44% of these 2 trillion tons still remain in the atmosphere (the rest has been taken up by the oceans, land plants, and soil organisms). By 2030, under a business-as-usual scenario we will have added another 1 trillion tons, bringing cumulative emissions to 3 trillion tons, and by 2050 they will reach 4 trillion tons. In short, unchecked emissions would lead to a warming of 1.5°C by 2030 and more than 2°C by 2050.

In Table 4.1.1 we show the actual or projected warming that would be realized in a given year, as well as a quantity called "committed warming," a term that has different meanings depending on the context. Here, we define the term *committed warming* as follows: it is the warming that will ultimately happen even if CO_2 concentrations stay at current levels. The warming continues to increase even after the concentrations have stopped increasing because Earth takes roughly a decade or two to adjust to increased CO_2 in the atmosphere. Currently, the Earth's surface temperature is constantly playing catch-up as we continue to increase concentrations of CO_2 and other super pollutant greenhouse gases.

Figure 4.1.1 shows possible future temperature trajectories. The purple line represents measured global temperatures from 1950 to about 2010, and the labeled lines represent future temperature projections under different scenarios. The business-as-usual scenario is represented by the gray line that borders the colored zones. The other labeled lines represent mitigation pathways that we'll discuss later in this chapter and in Chapter 15 (a stylized version of this curve can be seen on the title page of the book).

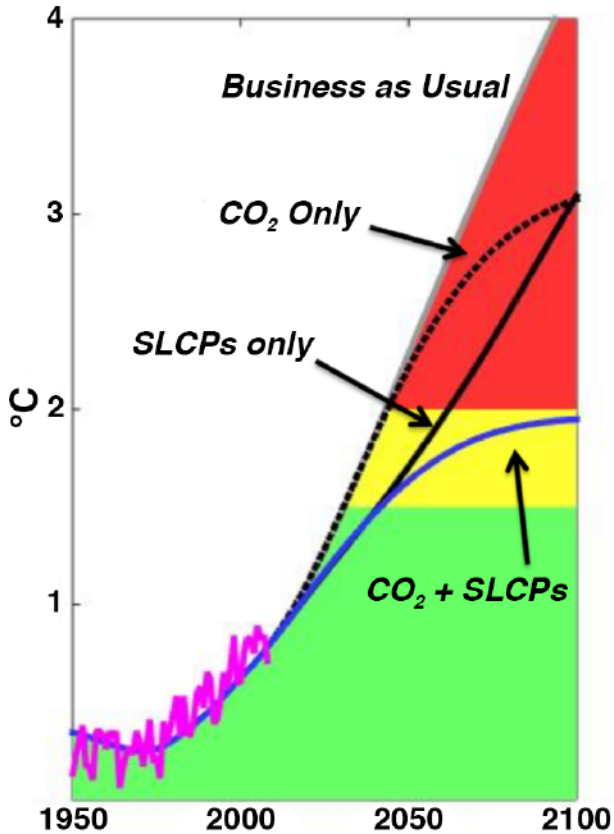


FIGURE 4.1.1 **Projections of future warming, showing business-as-usual and pathways for CO_2 mitigation only, SLCP mitigation only, and mitigation of both CO_2 and SLCPs. The purple line represents the historical temperature record.** From Ramanathan et al. 2017.

If unmitigated emissions continue, we will emit another trillion tons between 2030 and 2050, making the total emissions 4 trillion tons. At that point we will be committed to 3°C warming, well into the "danger zone" of severe impacts on climate, not all of which can be foreseen at the present. In that case, we would actually reach 3°C warming around 2070.

If we do not mitigate emissions during this century, the temperature of the Earth will increase by at least 4°C by 2100. More specifically, climate models show a 1 in 2 chance (50% probability) that temperatures by 2100 will be at least 4°C warmer than the preindustrial era, with a 1 in 20 chance (5% probability) that warming will be 6°C or greater. As we saw in Section 1.4, warming exceeding 4°C could represent an existential threat to human society and natural systems. Although the risk of this level of warming is "only" 1 in 20 based on current projections, most

TABLE 4.1.1 Emissions, actual or projected warming, and committed warming under a business-as-usual scenario

Year	*Cumulative CO_2*	*Actual or Projected Warming*	*Committed Warming*
2017	2.2 trillion tons	1°C	1.5°C
2030	3 trillion tons	1.5°C	2°C
2050	4 trillion tons	2.2°C	3°C

The committed warming is the equilibrium warming estimated by assuming atmospheric concentrations are held fixed at the indicated year. The warming estimates include the effects of SLCPs and cooling aerosols. Figures are approximate.

people would find this an unacceptable level of risk for a possibility with such serious consequences. As pointed out in Chapter 1, few people would choose to board a plane if there was a 1 in 20 chance that it would crash.

4.2 The Six Clusters

Although the time to act is limited, you and the million other climate champions still have a range of solutions you can employ to avoid dangerous warming of the planet. So, how do you go about bending the warming curve?

Major emission sources will need to be addressed in all sectors, including electricity generation, residential and commercial buildings, transportation, and industrial processes. Solutions will require collaborative efforts on unprecedented scales, not only by scientists and engineers, but also by civic, business, and religious leaders, as well as community members. Given the wide range of impacts, emitting sectors, and areas of expertise required, you need some sort of organizing principle to sort through potential solutions, rank them, and identify the groups or institutions best qualified to carry them out. The approach outlined in *Bending the Curve*'s executive summary and used in this book is to lay out ten broad solutions, organized into six major solutions clusters.

Development of the six clusters

The 50 interdisciplinary University of California experts who came together in the summer of 2015 quickly concluded that a comprehensive approach requires solutions from a wide range of sectors and areas of expertise. They developed a set of ten broad solutions but found there was no single category that would cover them all. In the end, they grouped the ten solutions into six solutions clusters. The ten solutions represent ten actions that, taken together, can bend the curve and avoid dangerous warming of the planet. The six clusters represent the sectors and areas of expertise that will be needed to implement these solutions.

The six solutions clusters, listed in rough order of importance, are

1. Science Pathways Solutions
2. Societal Transformation Solutions
3. Governance Solutions
4. Market- and Regulation-Based Solutions
5. Technology-Based Solutions
6. Natural and Managed Ecosystem Solutions

This ranking does *not* mean that any of these clusters are optional; all will be needed in order to avoid dangerous warming. However, clusters ranked higher on the list are generally considered more *fundamental*; solutions clusters that appear lower on the list tend to be in some way dependent on the higher clusters. For example, science pathways solutions are placed first because without a scientific understanding of the causes of warming and the most effective emissions pathways for bending the warming curve, we would be unable to take meaningful actions.

In particular, *Bending the Curve* was the first report to rank societal transformation solutions so highly, listing it as the second solutions cluster. There were several motivations for this high ranking. Without broad-based societal understanding of the risks and potential impacts of climate change, there will not be sufficient public support to implement governance, economic, and technological solutions. Social movements can energize individuals by bringing them together to act for broader interests. Moreover, some of the individuals and groups most vulnerable to climate change typically have little voice in global governance and economic mechanisms. Social movements and collective action can help ensure their concerns are heard and addressed. Finally, many of the solutions we will examine are dependent on the collective impact of individual actions and choices. Realizing these solutions will require a transformation of our societal attitudes toward each other and toward nature.

Intragenerational and intergenerational equity

There is one more important issue that we need to consider before we look at our ten solutions. Fundamental to the development and evaluation of climate solutions is consideration of *equity*: whether the distribution of benefits and harm caused by our actions is fundamentally fair.

Note that *equity* is not the same as *equality*: for example, distributing an equal amount of food to everyone in a group might not be seen as equitable if some have overflowing refrigerators while others are starving. Discussions of equity are ultimately based in ethics and personal values, and different observers might reach different conclusions as to whether a particular situation is equitable or not. However, most people seem to believe that it is fundamentally unfair for those who did not share in the benefits of an activity to be burdened with its costs or other negative impacts.

In the context of climate change, there are two important aspects of equity to consider: **intergenerational equity** and **intragenerational equity**.

Intergenerational equity refers to equity between different generations, for example, between us and our grandchildren or their descendants. It essentially considers equity between groups of people who are separated in *time*. The impacts of our current emissions will not be felt only in this century. A large fraction of the carbon dioxide we emit now by burning fossil fuels will remain in the atmosphere for hundreds and even thousands of years, meaning that unborn generations will have to deal with its impacts even though current generations received the benefits of the energy produced. If warming pushes the Earth's climate past one or more tipping points, it could well become impossible to return our planet to the temperatures of the relatively stable Holocene climate in which human civilizations developed and flourished (Section 1.1).

Intragenerational equity refers to equity between individuals who are alive now but separated by location (for example, living in different countries) or social factors (for example, belonging to different economic classes). Among those alive on Earth today, there are billions who have largely been left behind by the technological advances of the past few centuries. We can divide the roughly 7.5 billion people living on Earth into three broad groups:

- The top 1 billion are the most economically well off. Their consumption of fossil fuels contributes roughly 50% of global CO_2 pollution.
- The bottom 3 billion have very limited access to fossil fuels and the energy they produce. This group contributes only 5% of global CO_2 pollution. We refer to these as the "bottom" 3 billion, not in any

FIGURE 4.2.1 Rich and poor communities living side by side in Mumbai, India. Photograph reproduced with permission from Johnny Miller.

pejorative sense, but because they represent the least affluent of the Earth's population and are at the bottom of the economic and energy pyramids. On a per-person basis, they emit about one-thirtieth as much as individuals in the top 1 billion, but they are often the most vulnerable to the impacts of climate change.

- The middle 3.5 billion are neither the poorest nor the richest; their situation is intermediate between the top 1 billion and the bottom 3 billion. Their per-person emissions are about ten times higher than the bottom 3 billion, but only about one-third of the top 1 billion.

Consider where you, your family, or your household might be classified among these groups. It will be helpful to keep this rough division in mind when evaluating the equitability of climate solutions and determining responsibilities for their implementation.

As Pope Francis noted in his 2015 encyclical, *Laudato Si'*, "[w]e are faced with not two separate crises, one environmental and the other social, but rather with one complex crisis which is both social and environmental. Strategies for a solution demand an integrated approach to combating poverty, restoring dignity to the excluded, and at the same time protecting nature."

4.3 The Ten Solutions

In this section, we'll introduce the ten solutions, show how they fit into the six solutions clusters, and describe each of them briefly. The following chapters will provide in-depth exploration of each of these solutions.

These ten solutions represent an integrated approach to climate change across a wide range of expertise and sectors. These solutions are described as scalable solutions because they can first be implemented in local or regional living laboratories. Lessons learned can then be scaled up to national and global levels.

Figure 4.3.1 gives a visual overview of the six clusters, ten solutions, and three levers (discussed under Solution #1 below). Table 4.3.1 defines the ten solutions and their relationship to the six solutions clusters.

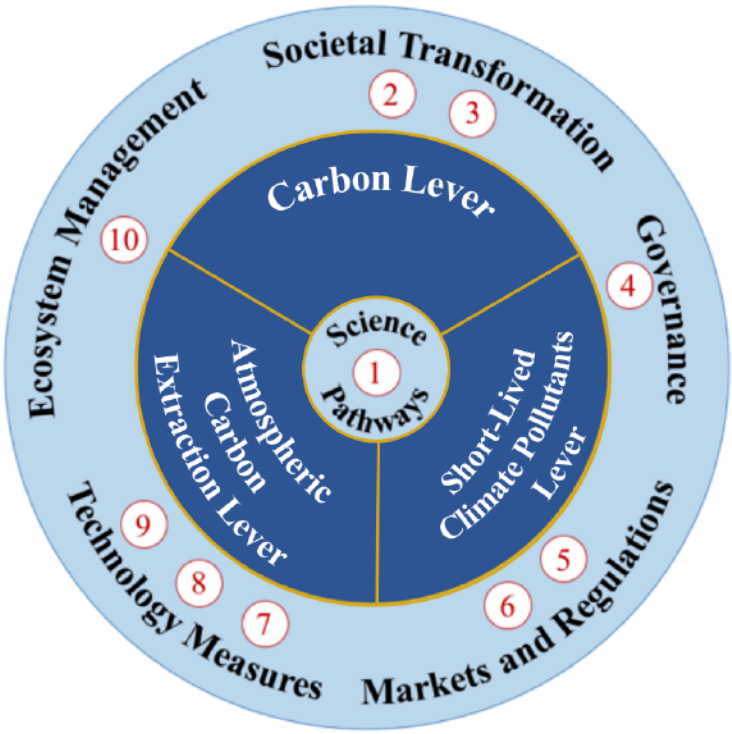


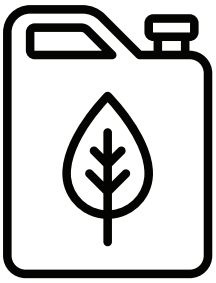
FIGURE 4.3.1 The six clusters, three levers, and ten solutions. From Ramanathan et al. 2017.

TABLE 4.3.1 The ten solutions

Solutions
I. Science Pathways
1 Bend the warming curve immediately by reducing short-lived climate pollutants (SLCPs) and sustainably by replacing current fossil-fueled energy systems with carbon-neutral technologies and by extracting carbon dioxide from the air and sequestering it or repurposing it for commercial uses.
II. Societal Transformation
2 Foster a global culture of climate action through coordinated public communication and education at local to global scales.
3 Deepen the global culture of climate collaboration.
III. Governance
4 Scale up subnational models of governance and collaboration around the world to embolden and energize national and international action.
IV. Markets and Regulations
5 Adopt market-based instruments to create efficient incentives for businesses and individuals to reduce CO_2 emissions.
6 Narrowly target direct regulatory measures—such as rebates and efficiency and renewable energy portfolio standards—at high-emissions sectors not covered by market-based policies.
V. Technology Measures
7 Promote immediate widespread use of mature technologies, such as photovoltaics, wind turbines, battery and hydrogen fuel cell electric light-duty vehicles, and more efficient end-use devices, especially in lighting, air conditioning, appliances, and industrial processes.
8 Aggressively support and promote innovations to accelerate the complete electrification of energy and transportation systems and improve building efficiency.
9 Immediately make maximum use of available technologies combined with regulations to reduce methane emissions by 50% and black carbon emissions by 90%.
VI. Ecosystem Management
10 Regenerate damaged natural ecosystems and restore soil organic carbon to improve natural sinks for carbon (through afforestation, reducing deforestation, and restoration of soil organic carbon). Implement food waste reduction programs and energy recovery systems to maximize utilization of food produced and to recover energy from food that is not consumed.

I. The science pathways cluster

This cluster describes emission pathways that were derived from climate science with the primary goal of keeping the warming below perceived dangerous levels. Until about 2015, the threshold for dangerous warming was generally perceived to be 2°C. However, recent data on the impacts of the 1°C warming that has already taken place (from preindustrial times to 2015)—for example, on extreme weather and on the melting of the Greenland and West Antarctic ice sheets—have led climate scientists and policymakers to conclude that the threshold for dangerous warming should be redefined to 1.5°C. It should be noted, however, that data from past climates suggest that even a warming of 1.5°C, if it is allowed to persist for more than a century, could lead to 6 to 9 meters of sea level rise (Chapter 1 for a discussion of the Eemian interglacial period 130,000 years ago).



SOLUTION #1: Bend the warming curve immediately by reducing short-lived climate pollutants (SLCPs) and sustainably by replacing current fossil-fueled energy systems with carbon-neutral technologies and by extracting carbon dioxide from the air and sequestering it or repurposing it for commercial uses. Achieve the SLCP reduction targets prescribed in Solution #9 by 2030 to cut projected warming by approximately 50% before 2050. To limit long-term global warming to 1.5°C, achieve carbon neutrality by 2050 and in addition extract as much as 500 billion to 1 trillion tons of carbon dioxide from the air by 2100. Solutions #7 to #9 cover technological solutions, and Solution #10 describes ecosystem solutions to accomplish these targets.

Frequently used terms with respect to CO_2 emission sources are defined here:

- **Low-carbon** refers to energy sources that emit substantially less CO_2 per unit of energy than conventional fossil fuels. Solar, wind, hydroelectric, and nuclear power fall under this category because

fossil fuels are used in the production and transportation of the products used in solar cells, wind turbines, and nuclear plants.

- **Zero emissions** refers to energy sources or systems that truly have zero associated emissions of CO_2 and other greenhouse gases. This is an ideal that is not realized by any current energy sources, including solar, wind, hydroelectric, and nuclear, but could be approached as associated emissions from manufacturing or transportation systems approach zero.
- **Renewables** are energy sources that are replenished naturally. Solar, wind, hydroelectric, and geothermal fall under this category.
- **Carbon-neutral** refers to energy sources or systems that absorb as much CO_2 as they emit. An energy source that is derived from fossil fuels can still be carbon-neutral as a whole if the carbon released is captured and stored indefinitely.

As discussed in Section 4.1, climate studies and computer model projections make it clear that the only solutions pathway that sustainably keeps warming below 2°C is one that combines mitigation of both SLCP and CO_2 emissions. We will refer to these different mechanisms to reduce warming as levers to bend the warming curve. The *Bending the Curve* report, published in 2015, emphasized mainly the carbon and the SLCP levers because its goal was to keep warming below 2°C. Since the threshold for dangerous warming has been decreased to 1.5°C, we need to pull on a third lever, which we refer to as the atmospheric carbon extraction (ACE) lever. Numerous studies since 2015 have shown that we may have to extract as much 500 billion to 1 trillion tons of CO_2 by 2100 to keep the warming below 1.5°C. We have modified the two-lever strategy of the *Bending the Curve* report to a three-lever strategy as discussed below and shown in Figure 4.3.1 and Table 4.3.1:

The *SLCP lever*: take immediate action to cut emissions of short-lived climate pollutants.

Because SLCPs—methane, black carbon, and hydrofluorocarbons (HFCs)—have comparatively short lifetimes in the atmosphere, their mitigation provides a rapid reduction in temperatures relative to the business-as-usual path, helping to buy us time for

carbon dioxide mitigation. In particular, we must reduce methane emissions by 50%, reduce black carbon emissions by 90%, and phase out HFCs completely by 2030. Solution #9 specifies the measures needed to achieve these goals.

The *carbon lever*: drastically reduce emissions of carbon dioxide to near-zero levels well before the end of this century. This lever, as well as the person pulling on it, is intentionally made larger than the SLCP lever in recognition of the immense challenges of making the planet carbon-neutral. Specifically, we will need to cut CO_2 emissions approximately 40% by 2030 and 80% by 2050, with emissions dropping to as close to zero as possible after that. Solutions #7 and #8 describe the technologies needed to achieve these reductions in emissions.

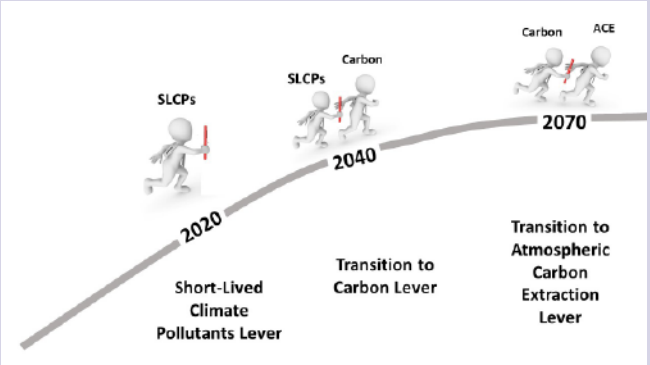
The "CO_2 + SLCPs" pathway in Figure 4.1.1 represents the combined effects of the carbon and SLCP levers. The SLCP lever should reduce projected warming of the planet by approximately 50% by 2050, compared with business-as-usual projections.

The *atmospheric carbon extraction (ACE) lever*: remove carbon dioxide from the atmosphere, with removal efforts ramping up significantly over the course of this century. Because carbon dioxide can remain in the atmosphere for centuries or millennia, keeping warming below dangerous levels for the long run requires this third lever. To give an idea of the enormous magnitude of this effort, it should be noted that to keep warming below 1.5°C throughout this century, as much as 1 trillion tons of CO_2 have to be extracted between 2030 and 2100 (corresponding to a rate of roughly 15 billion tons per year), in addition to pulling on the SLCP and carbon levers. Accordingly, the ACE lever is shown with the person having to bend backward along with the backward bending of the lever.

A range of technologies can be used to remove carbon dioxide from the atmosphere, including reforestation and agricultural practices that restore degraded soils and enhance the ability of soil to store carbon. Solution #10 focuses on these measures. In addition, CO_2 can be

Box 4.3.1 Your Goal: Winning the Relay Race

All of this sounds super complicated, so let us offer a metaphor: the three levers can be thought of as three runners in a relay team. Solving the challenge of climate change is like running a relay race, and time is against you. The SLCP runner is the starter who sprints forward quickly to gain some time for your team. The baton represents warming of 1.5°C or less. Assuming SLCP mitigation starts by 2020 and is completed by 2040, the SLCP starter can take the baton (1.5°C or less) to the decade of 2040 to 2050. Around this time, the SLCP runner hands the baton over to the carbon runner. Provided your team achieves carbon neutrality (zero CO_2 emissions) by 2050, the carbon runner can take the baton until 2070 at least, with warming still hovering around 1.5°C. By then, despite the efforts of the first two runners to bend the warming curve, the cumulative emissions of CO_2 (since 1850) will be working hard to bend the curve upward. This is when the baton is passed over to the finishing runner in your team, the ACE runner, who takes it to 2100 and beyond, still keeping the warming under 1.5°C.



It's important not to confuse the timeline of when each runner begins to bend the curve downward with the time when that runner needs to get into action. For the carbon runner to take the baton around 2040, carbon mitigation efforts must begin immediately (by 2020 at the latest) and achieve carbon neutrality by 2050. The ACE runner has to be ready for action beginning around 2030. Why? We may have to take out as much as 1 trillion tons of CO_2 before 2100. This amount is so large that it cannot be done in a few decades. We have to start taking out about 15 billion tons of CO_2 by 2040 and continue at this rate until the end of the century.

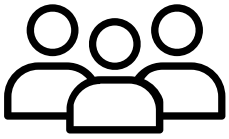
Figure adapted from images in shutterstock.com.

extracted from the air by a variety of chemical and biological processes. These measures are still under experimentation and are not yet scalable to the hundreds of billions of tons of CO_2 removal that will be required. Atmospheric carbon extraction technologies are discussed in more detail in Chapter 18.

Box 4.3.1 provides perspective on the three levers through the metaphor of a relay race.

II. The societal transformation cluster

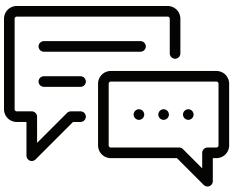
Science can define the necessary pathways to avoid dangerous warming, but the pathways will not be realized if there is not broad understanding of the problem at all levels of society and a willingness to take the measures required. The solutions in this cluster focus on communication, education, and collaboration strategies to develop a culture of consensus and support for climate action.



SOLUTION #2: Foster a global culture of climate action through coordinated public communication and education at local to global scales. Combine technology and policy solutions with innovative approaches to changing social attitudes and behavior.

Increasing societal awareness of the impacts of climate change and the benefits of climate mitigation is critical to solving the climate problem. Building support for the actions necessary to combat global warming will require societal changes in attitudes toward our fellow human beings and toward nature. Solution #2 focuses on communication and education needed to foster these societal transformations. Efforts will include communications targeted toward key stakeholders, including decisionmakers and investors in low-carbon development, but also broad educational efforts at all levels, from kindergarten through college. While it's important to make the severity and urgency of the climate problem clear, communications should focus on practical, achievable *solutions*. The goal of climate communication is to motivate action, not to create a sense that the challenge is too overwhelming to tackle. This book and its companion course are examples of the type of educational outreach recommended as part of this solution.

Communication and educational initiatives should also consider the different needs, responsibilities, and abilities to access information of the world's top 1 billion, middle 3.5 billion, and bottom 3 billion.



SOLUTION #3: Deepen the global culture of climate collaboration. Design venues where stakeholders, community, and religious leaders converge around concrete problems with researchers and scholars from all academic disciplines, with the overall goal of initiating collaborative actions to mitigate climate disruption.

For a global culture of support to really take root, we will need to engage in dialogue at all levels: international, national, city, and neighborhood. This dialogue will involve a wide range of stakeholders—decisionmakers; community members; researchers and academics; and business, community, and religious leaders—in collaborative action, developing solutions to specific, concrete problems. An understanding of the local-scale impacts of climate change and development of localized mitigation interventions can help motivate participation by a wide spectrum of citizens.

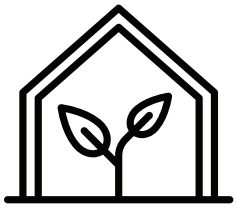
Note the specific inclusion of religious leaders in the solution statement. Religion is often overlooked as part of the solution to climate change, but religious leaders and religious communities can play a vital role. Both religions and climate scientists want to protect nature (or *creation*). Religious spaces can be natural venues to discuss the ethical issues raised by climate change. In addition, in the United States, where climate change has become extremely politicized, religious spaces offer scientists and climate solution seekers like you a nonpolitical forum to discuss the problem and its solutions. Climate change is also an issue where science, policy, and religion converge. While scientists and policymakers talk in terms of intergenerational equity and the protection of nature, major religious traditions often frame these same concepts in terms of a duty to care for our fellow human beings and for creation. An excellent example of the broader framing of climate change impacts in human terms is Pope Francis's climate change encyclical, *Laudato Si': On Care for Our Common Home*, published in 2015. Because of the broad and deep penetration of religious faith across the world, religious settings

can also facilitate dialogue between members of the top 1 billion and the bottom 3 billion on our planet.

Solutions #2 and #3 will be discussed in Chapters 5, 6, 7, and 8.

III. The governance cluster

In addition to a broad societal consensus for climate action, implementation of the recommended pathways will require support and coordination at all levels of government, from local neighborhoods to international coalitions.



SOLUTION #4: Scale up subnational models of governance and collaboration around the world to embolden and energize national and international action. Use the California examples to help other state- and city-level jurisdictions become living laboratories for renewable technologies and for regulatory as well as market-based solutions, and build cross-sector collaborations among urban stakeholders because creating sustainable cities is a key to global change.

With the 2015 Paris Agreement as a framework for international action on climate, this solution focuses on governance models from cities, states, and regions that can be scaled up to national and global levels. Cities cover less than 2% of the Earth's surface but produce more than 60% of global CO_2 emissions. States, cities, and other subnational jurisdictions have the ability to develop innovative solutions that are responsive to local needs, implement them on a relatively short time scale, and make adjustments as needed. The C40 initiative (https://www.c40.org) and the Under2 Coalition initiated by the governor of California are exceptional examples of subnational activities that can leverage international agreements at a local scale, as we'll see in Section 4.4. In short, they can act as innovative, nimble living laboratories to test, refine, and promote governance and other solutions, which can then be adapted and expanded to strengthen and enhance national and global efforts. Actions under way in California provide particularly relevant examples of subnational models; we'll take an initial look at some of these in Section 4.4.

Solution #4 will be discussed further in Chapters 9 and 10.

IV. The markets and regulations cluster

To make mitigation a reality, policymakers need to send clear signals to companies and individuals. Appropriate economic and regulatory measures can encourage investment in existing low-emission technologies and innovation for the future. The next two solutions explore market-based instruments and direct regulation.

SOLUTION #5: Adopt market-based instruments to create efficient incentives for businesses and individuals to reduce CO_2 emissions. These can include cap and trade or carbon pricing and should employ mechanisms to contain costs. Adopt the high-quality emissions inventories, monitoring, and enforcement mechanisms necessary to make these approaches work. In settings where these institutions do not credibly exist, alternative approaches such as direct regulation may be the better approach—although often at higher costs than market-based systems.

Both economic theory and real-world experience indicate that the most economically efficient, lowest-cost way to achieve emissions reduction is through market-based incentives. Market-based mechanisms add a cost to emissions that reflect the long-term environmental damages they cause. Two major categories of market instruments are a direct carbon price, such as a carbon tax or fee on emissions, and a system of cap and trade under which total emissions from large sources are capped and allocated through a system of tradable permits. Cap-and-trade systems for carbon dioxide emissions have been implemented in a variety of markets, including California, the northeastern US, and the European Union. In 2017, China initiated a national cap-and-trade market that began with its power sector and will gradually be expanded to other sectors of the economy.

While carbon prices and cap and trade could reduce emissions, current fossil fuel subsidies support production and consumption and incentivize CO_2 emissions. Fossil fuel subsidies include tax advantages, low-interest loan guarantees, and access to public natural resources at

below-market rates. As estimated by the International Monetary Fund (IMF), global fossil fuel subsidies are as much as US$540 billion annually.

According to the IMF, when fossil fuel impacts on mortality due to air pollution (about 3.5 million premature deaths a year) are included, the total subsidy increases to as much as US$5 trillion annually. In comparison, the International Energy Agency estimates that the cost of changing the entire infrastructure of the world to zero-carbon emissions over a 30-year period would only be about US$1 trillion dollars annually, about one-fifth of the subsidy cost.

A recent study estimated that the net effect of continued tax preferences and other subsidies in the US alone would be to increase domestic oil production by 17 billion barrels (equivalent to 6 billion tons of CO_2 emissions) through 2050, relative to a scenario with no subsidies. Removing these subsidies, as well as providing subsidies for low-emission sources as appropriate, would create strong economic incentives to transition to low-carbon sources of energy.

One criticism of market-based initiatives is that added costs (for example, increases in fuel and energy costs) can be passed on to consumers, with a potentially disproportionate impact on the least affluent. These negative impacts can be reduced if some portion of the revenues from cap-and-trade or carbon pricing mechanisms are used to reduce impacts on disadvantaged communities and others who are adversely affected by higher prices.

SOLUTION #6: Narrowly target direct regulatory measures—such as rebates and efficiency and renewable energy portfolio standards—at high-emissions sectors not covered by market-based policies. Create powerful incentives that continually reward improvements to bring down emissions while building political coalitions in favor of climate policy. Terminate subsidies that encourage emission-intensive activities. Expand subsidies that encourage innovation in low-emission technologies.

Regulatory measures are given lower priority than market-based incentives on our solutions list because they are generally less

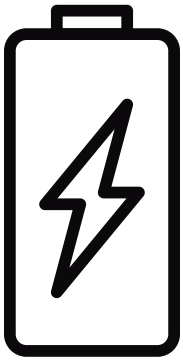
cost-effective. However, direct regulations provide an alternative instrument for emissions reduction, particularly where economic measures may not be technically or politically feasible. Where regulations are necessary, they should be targeted toward high-emission sectors to maximize their impact and designed to contain the costs of compliance.

Solutions #5 and #6 will be covered detail in Chapters 11 and 12.

V. The technology measures cluster

We have set the stage with broad public support for climate solutions along with governance, market, and regulatory instruments for their implementation; this cluster provides the technological means to make those reductions happen. Both wider use of existing technologies and future innovations will be required. The three solutions in this cluster focus on both carbon dioxide and short-lived climate pollutants. These represent the first two levers discussed above: the carbon lever and the SLCP lever. Solutions #7 and #8 represent two stages of pulling the carbon lever. Solution #7 pulls the carbon lever nearly halfway by 2030, and Solution #8 pulls it the rest of the way by 2050. Solution #9 represents pulling the SLCP lever by 2030.

To keep warming below dangerous levels, both of these levers will be required. Fully implemented, the CO_2 reductions in Solutions #7 and #8 could reduce global warming by as much as 1.5°C by 2100, relative to a business-as-usual scenario. In combination with the SLCP reductions envisaged in Solution #9, this solutions cluster gives us a good chance of keeping warming below 2°C during this century and beyond.



SOLUTION #7: Promote immediate widespread use of mature technologies, such as photovoltaics, wind turbines, battery and hydrogen fuel cell electric light-duty vehicles, and more efficient end-use devices, especially in lighting, air conditioning, appliances, and industrial processes. These technologies will have even greater impact if they are the target of market-based or direct regulatory solutions such as those described in Solutions #5 and #6 and have the potential to achieve a 30% to 40% reduction in fossil fuel CO_2 emissions by 2030.

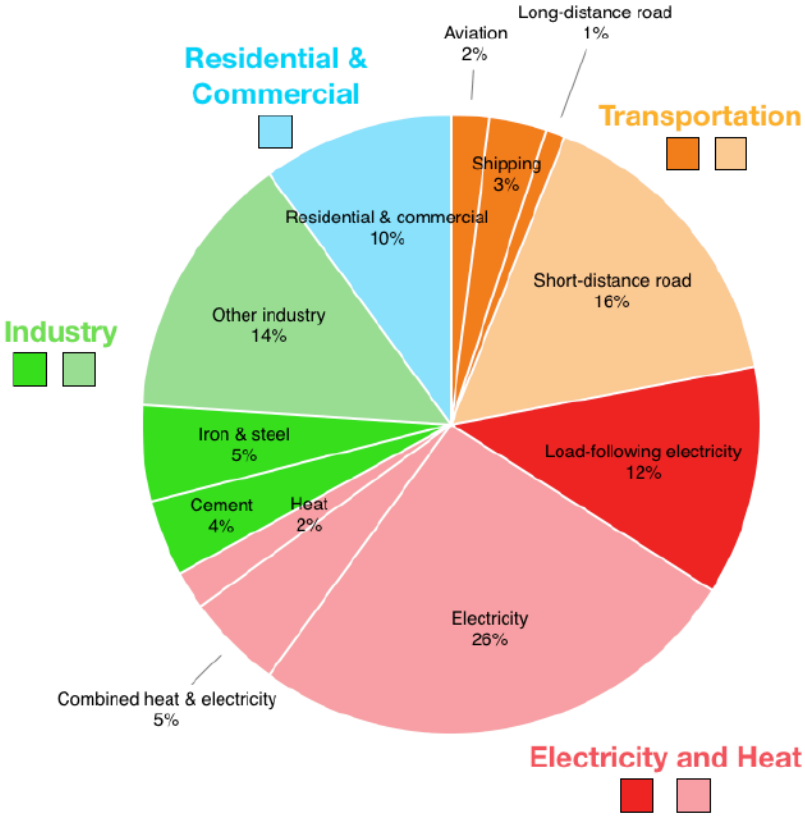


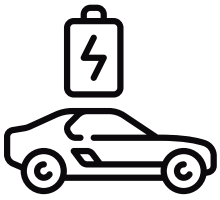
FIGURE 4.3.2 Global CO_2 emissions from fossil fuels and industry, 2014. The darker colors indicate the emissions that are most difficult to eliminate; they account for just over a quarter of the global total. Data from Davis et al. 2018.

Figure 4.3.2 shows the major global sources of fossil fuel and industrial carbon dioxide emissions, grouped by sectors. Many of these emissions can be reduced through expansion of currently available technologies, such as electricity generation by solar photovoltaics and wind turbines. Significant technical advances and decreasing costs have led to a rapid increase in the deployment of renewable electricity over the past decade, mostly from photovoltaic solar panels and wind turbines. However, reducing emissions from some sectors will be more challenging and will require innovative new technologies. These difficult-to-eliminate emissions, which account for just over a quarter of the global total, are indicated by darker colors in Figure 4.3.2 and described under Solution #8.

Nuclear power has the advantage of generating on-demand electricity

with no direct carbon dioxide emissions, but it is controversial because of the possibility of nuclear accidents and concerns with storage of radioactive waste. Some countries, such as China, are expanding their nuclear power capacity, while others, like Germany, are phasing it out. In the US, there are currently (as of late 2018) only two new nuclear reactors under construction. The high cost of building new nuclear plants means that at present they are generally not economically competitive with alternatives such as solar or wind. However, new designs such as small modular reactors may provide for lower-cost nuclear power in the future, with less nuclear waste and a far lower risk of catastrophic accidents.

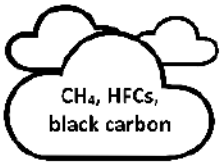
In the transportation sector, cars and light-duty trucks with electric motors powered by lithium ion batteries or hydrogen fuel cells could drastically reduce emissions if low-carbon sources were used for battery charging and hydrogen production. Emissions from homes and commercial buildings could be reduced by use of energy-efficient heating and cooling systems, lighting, and appliances. It's estimated that full implementation of strategies involving existing technologies has the potential to achieve a 30%–40% reduction in fossil fuel emissions by 2030. We can think of this as pulling the carbon lever about a third of the way toward carbon neutrality. A combination of market and regulatory incentives, as discussed in Solutions #5 and #6, could help accelerate this technological transition.



SOLUTION #8: Aggressively support and promote innovations to accelerate the complete electrification of energy and transportation systems and improve building efficiency. Support development of lower-cost energy storage for applications in transportation, resilient large-scale and distributed micro-scale grids, and residential uses. Support research and development of a portfolio of new energy storage technologies, including batteries, supercapacitors, compressed air, hydrogen, and thermal storage, as well as advances in heat pumps, efficient lighting, fuel cells, smart buildings, and systems integration. These innovative technologies are essential for meeting the target of 80% reduction in CO_2 emissions by 2050 and transitioning to zero emissions soon after.

Moving away from fossil fuels will require electrification of nearly all end uses, including transportation and heating systems, with the electricity generated almost exclusively by carbon-neutral energy sources. Because wind and solar energy production are inherently variable, increasing penetration of renewables depends on affordable systems to store energy during periods of excess power production and to feed it back into the grid when production falls; energy storage is a crucial area of innovation needed for the transition to low-carbon energy, as discussed in Box 4.3.2.

Power generation systems will also become more widely distributed, ranging in scale from large-scale utility power plants to rooftop solar for individual buildings. This will require the development of "smart" electrical systems that can manage power from sources with variable production and a variety of scales. Microgrids that can function independently of the main power grid when necessary would further increase the ability of the grid to handle variable electric generation and power outages. These ideas will be further discussed in Chapters 13 and 14.



SOLUTION #9: Immediately make maximum use of available technologies combined with regulations to reduce methane emissions by 50% and black carbon emissions by 90%. Phase out hydrofluorocarbons by 2030 by amending the Montreal Protocol. In addition to the climate and health benefits described under Solution #1, this solution will provide access to clean cooking for the poorest 3 billion people who spend hours each day collecting solid biomass fuels and burning them indoors for cooking.

As discussed in Chapter 1, black carbon, methane, ozone, and hydrofluorocarbons (HFCs) are referred to as short-lived climate pollutants (SLCPs) because their lifetimes in the atmosphere—from a few weeks to a few decades—are relatively short compared with that of CO_2. They are also **super pollutants** with warming effects tens to thousands of times stronger than CO_2. This combination of short lifetimes and powerful warming ability means that targeting SLCPs for reduction can have a significant and comparatively rapid impact on global temperatures, as we saw in Section 4.1. Solution #9 represents pulling the SLCP lever all the way.

Box 4.3.2 Examples of Difficult-to-Eliminate Sectors of Carbon Emissions and Required Innovations

Providing reliable electricity

As more sectors are electrified and as a greater portion of electricity is produced by intermittent renewable energy sources, there will be an increasing need to provide reliable, load-following electric systems that can be ramped up quickly to accommodate any mismatch between energy supply and demand. A key technological approach is improved energy storage. One alternative is to use excess electric power to produce hydrogen, which can then be converted back to electricity by using fuel cells. Hydrogen fuel cell technology is already in use to power vehicles, but the bulk of the hydrogen is produced from natural gas. CO_2 emissions from hydrogen generation can be eliminated if hydrogen is produced by electrolysis (the splitting of water into hydrogen and oxygen) using renewable energy sources.

Aviation, shipping, and long-distance road transportation

Advances in battery technology and hydrogen fuel cells have made short-range battery electric and fuel cell vehicles commercial realities. However, eliminating emissions from long-distance transportation will require new technologies. Improved hydrogen fuel cells may prove suitable for long-distance road transport, but aviation and shipping will require power sources with greater energy density (energy content per unit weight). Biofuels are promising candidates since they are carbon-neutral, but they are energy intensive to produce and can take up agriculturally valuable land.

Cement and steel

Cement and steel production are the two highest-emission industrial processes, generating 4% and 5% of global CO_2 emissions, respectively from the burning of fossil fuels to provide the high temperatures required for production and from materials used in production (such as limestone for cement and coke for steel). Reducing CO_2 emissions from cement and steel production will require the development of new chemical and industrial processes. In the case of cement production, it may also be possible to capture and store CO_2 directly from the kiln's exhaust gases.

Another advantage of SLCP mitigation is that SLCP emissions can generally be reduced more quickly and easily than CO_2, and reductions in SLCP emissions translate into a more immediate impact on the climate than do reductions in CO_2 (Chapter 1). Fossil fuels have been used intensively since the Industrial Revolution and are deeply embedded in a wide range of human activities. As discussed in Solutions #7 and #8, phasing out CO_2 emissions will require several decades and new technological innovations. SLCPs, on the other hand, are generated by fewer sectors of society and can be addressed with existing technologies. Also, SLCP mitigation is often more easily accepted because many of the co-benefits (to health and agriculture sectors) accrue locally.

The two largest sources of black carbon (up to 95% of the total) are diesel vehicles and domestic cooking and heating, with 3 billion people still relying on eighteenth-century technologies that burn firewood, dung, and coal. Black carbon emissions from diesel vehicles can be reduced by about 98% through adding diesel particulate filters. Replacing inefficient solid-fuel-burning stoves in India, China, sub-Saharan Africa, and many countries in South America with less-polluting models can reduce as much as 80% of their black carbon emissions. Such measures not only reduce the warming effect of black carbon soot, but also provide significant health benefits by reducing particulates that can cause respiratory illnesses. Worldwide, roughly 3 million people die prematurely each year because of indoor smoke from cooking, heating, and lighting with solid fuels.

Another major SLCP, methane, can be addressed through a variety of means, including capture and burning of methane emitted by coal mines, oil wells, gas production and distribution facilities, and landfills. Methane emissions from animal manure and wastewater systems can be controlled through anaerobic digesters. Mitigation of methane would avoid 0.5°C warming by 2050.

Ozone in the troposphere (the lowest layer of the Earth's atmosphere) is another important short-lived climate pollutant. It is not directly referenced in Solution #9, but decomposition of methane is an important source of ozone. Measures to mitigate methane would result in reduced tropospheric ozone as well. Like black carbon, ozone has

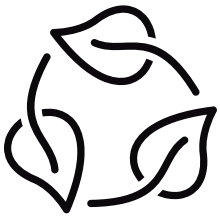
negative health impacts and can cause respiratory illnesses; moreover, it is a major source of agricultural crop losses.

HFCs are primarily used as refrigerants in air-conditioning systems, refrigerators, and auto cooling systems. Substitutes with far lower warming potential are already available. Left unchecked, HFC emissions alone would warm the planet by 0.1°C by 2050 and 0.5°C to 1.0°C by 2100.

Solution #9 will be covered in more detail in Chapter 15.

VI. The ecosystem management cluster

The previous five clusters focus on mitigating our emissions of climate-damaging pollutants. However, most projections indicate that for long-term temperature stability we will also need to remove CO_2 from the atmosphere. This cluster focuses on reducing emissions from managed ecosystems, particularly agricultural lands and rangelands, and managing ecosystems to enhance their ability to absorb CO_2 from the atmosphere. This represents a portion of the third and last of our three levers, the atmospheric carbon extraction (ACE) lever. It should be noted, Solution #10 by itself cannot meet more than a third of the carbon extraction requirements of 500 billion to 1 trillion tons of CO_2 extraction by 2100. We will most likely have to resort to direct capture of carbon dioxide from the air, using some of it for commercial and residential needs and sequestering the remaining carbon. However, thus far only pilot projects exist for direct capture, and there are yet no clear pathways to scale these up to the level of carbon capture required. These technologies are discussed in Chapter 18.



SOLUTION #10: Regenerate damaged natural ecosystems and restore soil organic carbon to improve natural sinks for carbon (through afforestation, reducing deforestation, and restoration of soil organic carbon). Implement food waste reduction programs and energy recovery systems to maximize utilization of food produced and recover energy from food that is not consumed. Global deployment of these measures has the potential to reduce as much as 25% of the current annual emissions of about 40 billion tons of CO_2. In addition, Solution

#10 will help meet the recently approved sustainable development goals of the United Nations by creating wealth for the poorest 3 billion.

After fossil fuels, the second largest anthropogenic source of CO_2 is deforestation. Burning or clearing trees for agriculture and croplands is estimated to release about 2 billion tons of CO_2 into the atmosphere annually. Reducing deforestation would reduce these emissions; reforestation (restoration of forest cover in deforested areas) and afforestation (the planting of trees in areas that did not previously have forest cover) would actually *remove* CO_2 from the atmosphere. Creating payment mechanisms for the environmental services provided by forest ecosystems can be an effective mechanism to promote reduced deforestation, while providing an income source for forest-dependent communities around the world.

Restoration of degraded ecosystems, including wetlands and mangrove swamps, and soil management and restoration can provide another mechanism for CO_2 reduction. Soils contain significant quantities of organic carbon in the form of plant matter, microbes, and other organisms. Intensive agriculture tends to disturb the soil, promoting CO_2 release. Encouraging alternative agricultural and grazing practices, including reducing tillage of agricultural fields and promoting greater biodiversity, can promote CO_2 absorption and storage in the form of organic carbon.

One caveat: the capacity of forests and agricultural soils to store carbon is not unlimited. For example, a 2018 study by the US National Academies of Sciences, Engineering and Medicine estimated that the capacity of agricultural soils to store carbon gradually drops to zero over two to four decades as the soils approach carbon saturation.

Reducing food waste is another key element of Solution #10 and one of the most significant actions we can take in addressing climate change. Globally, about one-third of food production is wasted; in the US, this figure rises to 40%. When food is wasted, the energy and associated emissions that went into its production, transportation, and storage are wasted as well. Further, food waste in landfills is a major source of methane emission.

It's estimated that combined, these measures for reduced deforestation, afforestation, reforestation, soil carbon restoration, ecosystem restoration, and reduced food waste could reduce greenhouse emissions by about the equivalent of 10 billion tons of CO_2 annually, about 25% of our current CO_2 emissions. This solution will be explored further in Chapter 16.

4.4 Living Laboratories

As discussed in Solution #4, cities, states, and regions can serve as living laboratories to test climate solutions and apply the lessons learned to scale solutions up to national and international levels. This living laboratory approach applies not only to governance solutions, but also to the entire range of climate solutions we have discussed.

Mitigation efforts are already underway in a range of local and regional jurisdictions worldwide and at a range of major corporations and universities. As described below, dozens of major cities worldwide have adopted climate action plans (CAPs), setting targets for mitigation and describing specific actions they will take to achieve those targets. Many of these CAPs include emissions reduction targets of 10%–30% by 2030 and 80%–90% by 2050, consistent with the targets described in Solutions #1, #7, and #8.

Cities are well positioned to engage in climate action, as they are typically more responsive to the needs and demands of their citizens, and their smaller scale enables them to act relatively quickly, compared with national governments. Several major cities, including Stockholm, Oslo, Melbourne, and Seattle, have pledged to become completely carbon-neutral by 2050. Successful climate solutions can be scaled globally as cities share their solutions and best practices through networks such as C40 and the Under2 Coalition, as discussed below.

State and regional initiatives can provide a bridge between city-scale actions and national policies. In addition to cities, the Under2 Coalition includes both state and regional jurisdictions. Another example of state-led initiatives is the US Climate Alliance of state governors, established in 2017 in response to the US federal government's announcement of its intention to withdraw from the Paris Agreement. Member states have committed to greenhouse gas reductions consistent with the original US commitment to cut emissions 26%–28% below 2005 levels by 2025.

While the group is still in the early stages of development, its membership has grown to include 17 governors from both major political parties, representing roughly one-third of the US population and 40% of its economy.

Similarly, major corporations typically have greater autonomy to act on climate change than most national governments. Several major corporations have already achieved carbon neutrality or plan to reach carbon neutrality in the near future. Many of the companies that have become carbon-neutral or are close to achieving carbon neutrality are in the technology sector, such as Google, Microsoft, and Adobe; or in the financial sector, such as Goldman Sachs and Swiss Re. However, manufacturers such as Volvo and Siemens have also committed to carbon neutrality by 2040. These plans have impacts beyond the companies themselves; for example, local communities hoping to attract large companies such as Google may be motivated to invest in renewable energy to meet their corporate requirements.

In the following sections we'll look at a few examples of groups and initiatives that are aimed at testing solutions in local or regional living laboratories and at sharing their results at national and international levels.

C40

The C40 Cities Climate Leadership Group (C40) is an international organization of cities committed to taking action on climate change. The group originated when Ken Livingstone, then mayor of London, called together representatives from 18 different cities to design an agreement to mitigate climate pollution. In 2006, the group merged with the Clinton Climate Initiative, increasing the network to 40 cities. As of 2017, the C40 network included 96 of the world's largest cities (Figure 4.4.1), representing over 700 million citizens and 25% of the global gross domestic product.

To participate, a city must (1) set a target for reducing emissions, (2) develop a climate plan with concrete initiatives to meet its target, and (3) actively share best practices with other cities in the C40 network. A new condition was added in 2017: by the end of 2020, every member city must have a comprehensive, measurable climate action

FIGURE 4.4.1 Map of C40 member cities. Reproduced with permission from C40.

plan designed to provide low-carbon development that is consistent with the goal of limiting global warming to no more than 1.5°C above preindustrial levels, as recommended in the 2015 Paris Agreement. C40 indicates that cities have the potential to carry out more than 40% of the emissions reductions required to achieve this target.

Through C40, city officials are linked to a range of collaborative networks that share knowledge on best practices and data metrics that advance climate actions and inspire their city peers. Thirty percent of all climate actions in C40 cities are being delivered thanks to city-to-city collaboration. The networks cover topics of high priority to C40 cities and are categorized under five initiative areas: adaptation implementation; air quality; energy and buildings; food, waste, and water; and transportation and urban planning. C40 also provides financing for technical assistance to help cities in Africa, Asia, and Latin America develop climate action plans.

Under2 Coalition

Like C40, the Under2 Coalition is a prime example of efforts to scale up local and regional solutions to the national and international levels. Initiated by California and the German state of Baden-Württemberg in

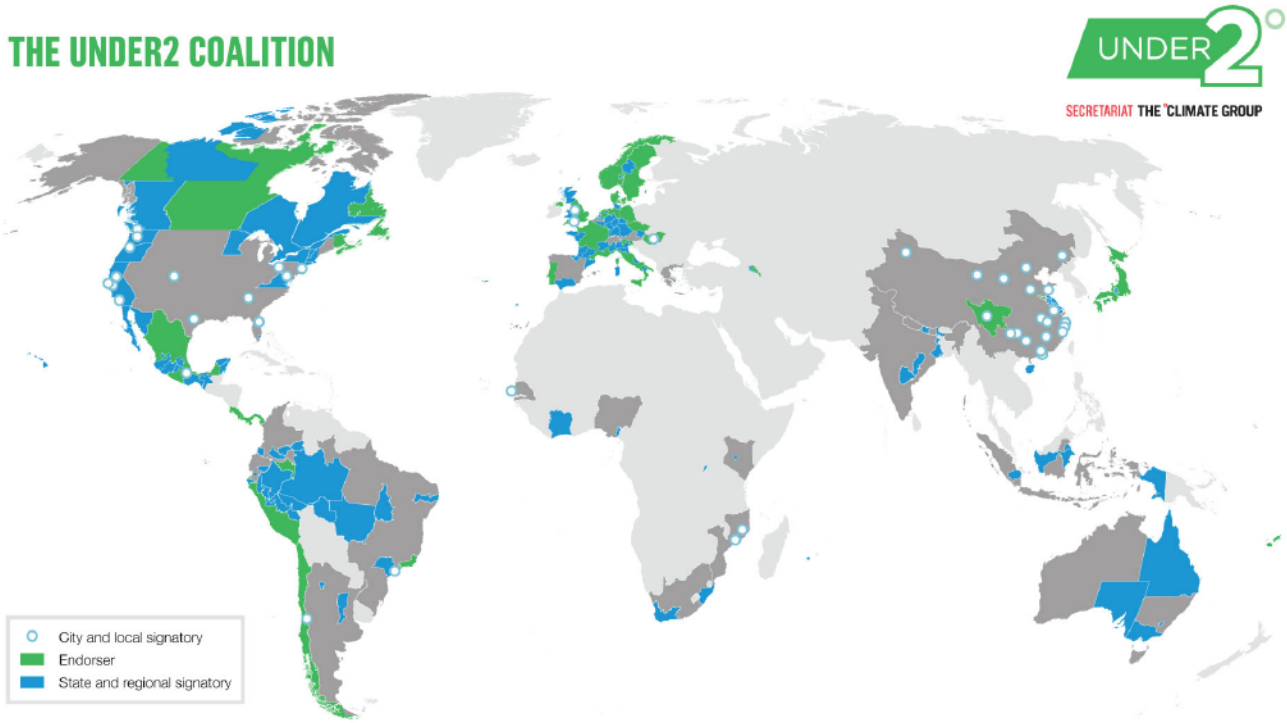


FIGURE 4.4.2 Map of Under2 Coalition members as of late 2017. Reproduced with permission from Under2 Coalition.

late 2015, the coalition grew to 205 members in 43 countries by late 2017, representing more than 1.3 billion people and 40% of the world's economy (Figure 4.4.2). Members have committed to plan for emissions reductions of 80% below 1990 levels by 2050 and have agreed to work in partnership to learn from each other's experiences. The coalition has set a goal of including the most significant subnational governments from all parts of the world by 2020, with every member government actively participating in the coalition's work.

California as a living laboratory

The state of California is well positioned to act as a living laboratory for climate solutions. California is a large and diverse state, with a population of nearly 40 million and the fifth-largest economy in the world. The state encompasses major urban centers but also large areas dominated by agriculture and forestry, providing the ability to test a wide range of climate solutions.

Moreover, California is regarded as a global leader in addressing climate change. The centerpiece of California's climate policies is Assembly Bill 32, the Global Warming Solutions Act, enacted in 2006 and extended through subsequent legislation.

FIGURE 4.4.3 **California's climate strategy.** Reproduced with permission from the California Air Resources Board.

The policies employed by California to meet its climate goals span most of the six clusters and ten solutions introduced in the previous sections, including increased building energy efficiency, renewable power generation, increased vehicle fuel efficiency, and low-emission vehicles (Figure 4.4.3). California has adopted the three-lever approach recommended in Solution #1, targeting emissions of both CO_2 and super-polluting SLCPs and promoting carbon sequestration in soils. California has also established a market-based cap-and-trade emissions permit system (discussed in Chapter 9).

As seen in Table 4.4.1, California has defined emissions targets for three time periods. The first target, established by executive order in 2005, is a return to 1990 emissions levels by 2020, with 33% of electric power generated from renewables. California is well on the way to meeting its 2020 goals. Analysis shows that the state achieved its emissions target in 2016, 4 years early, and generated 32% of its electricity from renewables in 2017.

The state also established a goal of cutting emissions to 80% below

TABLE 4.4.1 California climate targets

	Targets	
Year	*Greenhouse Emissions*	*Electricity from Renewables*
2020	Return to 1990 levels	33%
2030	40% below 1990 levels	50%
2050	80% below 1990 levels	100% (by 2045)

1990 levels. In 2015, new legislation set an intermediate target to cut emissions to 40% below 1990 levels by 2030 and to generate 50% of electricity from renewables. In 2018, California added a new goal, passing legislation that requires 100% of its electricity to be generated by renewables by 2045. These targets are ambitious but highlight California's strong and ongoing commitment to leadership in climate mitigation.

Fears that California's ambitious emissions targets might inhibit economic growth have so far proved to be unfounded. Between 2000 and 2014, California cut its emissions by 5%–10% while its gross domestic product (GDP) grew by over 25%. This example clearly shows that we can decouple economic growth from CO_2 emissions.

University of California Carbon Neutrality Initiative

Universities typically have access to a wealth of policy and technical expertise and are well positioned to act as living laboratories. One particularly noteworthy example is the University of California (UC) Carbon Neutrality Initiative. Under this initiative, announced in 2013 by UC president Janet Napolitano, the ten UC campuses have pledged to become carbon-neutral by 2025, with net zero greenhouse emissions from their buildings and vehicle fleets. Many UC campuses are pursing innovative climate solutions. For example, UC Irvine has adopted a Campus as a Living Laboratory for Sustainability model and is pursuing a range of mitigation options, including energy-efficient buildings, wide-scale adoption of solar power, buses powered by hydrogen fuel cells, and the development of its own microgrid. In addition, UC San Diego has created its own microgrid, which supplies more than 90% of campus power needs.

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PART TWO

Ten Solutions

CHAPTER 5

Your Leadership

Social Movements and Social Solutions to Climate Change

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Learning Objectives

1. Understand climate change as a multidimensional problem of power. We will learn how social solutions, social movements, and social transformation can help us confront climate change.
2. Examine the role that collective action plays in social transformation. We will reflect on the theories of change that we bring to problems of power and on why problems of power require social solutions.
3. Understand the role leadership plays in social movements. *Leadership* is one of those words that people use all the time, but it is often unclear what it means. We will define leadership in the context of social transformation and climate solutions.
4. Reflect on your own ability to call other people to action. In other words, no matter where you come from, what can you do in your own life and your own communities to engage other people in this project of creating climate solutions?

Overview

This chapter was originally transcribed from a lecture that Hahrie Han gave as part of the University of California's Bending the Curve course. In this chapter, we will explore the role that social movements can play in tackling climate change. Why social movements? This book examines a wide variety of climate solutions—scientific solutions, technological solutions, and economic solutions. Where do social movements and social solutions fit in?

This chapter argues that climate change is not only a scientific, technical, and economic problem, but also very much a problem of power. And problems of power require social solutions. This chapter shows how and why climate change is a problem of power and how social movements—along with scientific, technological, and economic solutions—can help confront it. We will examine examples drawn from a wide range of social movements, past and present, to understand how

we can apply what we know about successful social movements to the problem of climate change.

We will also focus on the role you, as students, can play as climate champions. Some of you are computer science majors; some of you are biology majors; some of you are English majors. You come to this course (or perhaps subject) from a wide variety of different disciplines, backgrounds, and places. But social movements bring people in no matter where they start. As we will see, that is one of the key features of social movements. What can you do in your community, no matter what your background and interests are?

In the first section of this chapter, we will focus on why climate change is a problem of power and how to understand it as such. Why do we need collective action to address climate change? How can bringing people together in social movements help create climate solutions?

If we want to bring people together, then we have to understand how to do that. So in Section 5.2, we will examine what a social movement is. How do social movements bring people together? How do they aggregate individual people's actions in a way that creates social change?

In Section 5.3, we will turn to the role that leaders play in social movements. What is leadership? How do leaders create social movements and make them effective?

The last two sections focus on the nuts and bolts of leadership. In the fourth section, we will examine the role that leaders play in building up the power that social movements need to make the change that they seek.

Finally, in Section 5.5, we will investigate how leaders of social movements take the resources that they've built and use them for social transformation.

5.1 Theories of Change, Problems of Power, and Collective Action

Why do we need collective action, anyway? Why don't we let the scientists, policymakers, and business leaders solve the problem of climate change for us? There's an important reason that we need collective action: it has to do with what some scholars call a **theory of change**. Our theories of change shape how we think we can create the change we need; as a result, they inform the actions we take.

Let's start with a story that has nothing to do with politics or social movements, to explain what theories of change are. Imagine that you are taking a class and the professor changes the date of the exam at the last minute. You thought the exam was going to be 2 weeks away, and all of a sudden the professor tells you it is going to be next Thursday. Dismayed by the sudden change, maybe you and several of your classmates stand outside talking about the dilemma after class. You are all upset, but what can you do? People will have different ideas. "Let's send the professor an email asking to stick with the original date." "Oh no," someone might say. "It's much better to talk about this in person. Let's go to office hours." "But wait," someone else might say. "If the professor thinks it's only four of us who are upset, nothing will change. Should we send a note to the whole class to see how many other people agree with us?" "Nah," the fourth person might say. "The professor was clear. Nothing we do can make a difference." And so on. Each of these students has a theory of change in mind. The first student's theory of change is, If I send an email, then the professor will respond. The second student's theory of change is, If I only email, then the professor will not respond, but if I show up in person, then the professor cannot ignore me. The third student believes, If we show that we have a lot of support, then the professor will listen and things will change. The fourth student thinks, If we take action, then we will have no impact. Each of these students would take a different action based on a personal theory of change.

Of course, theories of change are not just for students trying to influence their professors. Whenever we try to solve problems, we are relying on some kind of theory of change. Whenever we create a solution, it's based on a theory about how our actions will change a particular situation or address a particular problem—regardless of whether we pause to consciously reflect on that theory. Because climate change is a complex, multifaceted problem—some scholars call it a "wicked" problem—it is especially important to pause and examine the theories of change that underlie the solutions we're pursuing.

What theories of change do we bring to the problem of climate change? For example, if we consider technological innovation a solution to climate change, then our theory of change treats it as a technical problem that we lack the expertise to solve at present. Our theory of change suggests that if we can only develop the right skills or technology, we'll solve the problem.

Many problems have been solved through technology. For example, when polio was a rampant disease and a major societal problem, the solution was developing a new technology—a vaccine—that could eradicate polio. Sometimes the trick is developing a new technology that solves one problem without creating others. An example of this is the so-called hole in the ozone layer, a much-discussed environmental problem in the 1980s and 1990s. The "hole" was caused by chlorofluorocarbons (CFCs) and other chemicals used in refrigeration and air conditioning that thin or deplete the ozone layer that protects humans and other forms of life from harmful radiation. When scientists identified the problem, national and international leaders came together to solve it, signing the Montreal Protocol, an international agreement that phased out CFCs and similar chemicals, in 1987 (Chapters 10 and 15).

The Montreal Protocol is a strikingly successful example of turning scientific knowledge into effective global environmental policy, but it required a replacement for CFCs. The companies that dominated the refrigeration and air-conditioning industries insisted that hydrofluorocarbons (HFCs) were the only feasible option. But HFCs, while safe for the ozone layer, are potent greenhouse gases and have made the climate change problem worse—they solved one problem at the expense of another. In response to this situation, German scientists and Greenpeace

joined together to develop and promote new coolant technology using ozone-safe hydrocarbons, which have much less impact on climate change than HFCs. Their GreenFreeze refrigerators have captured a substantial share of the market around the world, though they have not yet succeeded in North America, where the major companies still sell refrigerators that use HFCs.

Similarly, we've developed a whole host of technologies that respond to the problem of climate change—from wind and solar power to electric vehicles and trains, from increasing the energy efficiency of buildings to reducing fossil fuel emissions from agriculture. In fact, we already have a great deal of the technological innovation that we need. Some scientists, such as Mark Jacobson and Mark Delucchi, have estimated that the developed world has the technology to be feasibly carbon neutral by 2050. The developing world can leapfrog many fossil fuel technologies by skipping over them and adopting renewable energy technologies directly.

But even though we *have* the technology, we are still not solving the problem of climate change. That suggests a flaw in our theory of change. Though climate change does require us to make deliberate choices about the technologies we use, maybe it is more than a technical problem that can be solved entirely through technological innovation.

Let's explore some other theories of change. Often, people think climate change is an information problem—that is, people do not have the information they need to reduce their greenhouse gas emissions. In that case, our theory of change says that if only people had the right information, they would act to solve the problem of climate change.

Accurate information has, in fact, helped people solve a host of problems. One example has to do with the effort to reduce SIDS, or sudden infant death syndrome, in the mid-twentieth century. In the past, pediatricians used to tell parents to put their babies to sleep on their stomachs, because they thought that reduced spit up and helped the babies (and their parents!) sleep better. They discovered, though, that for very young babies, sleeping on their stomachs could contribute to SIDS because young babies did not have the neck control or muscles to be able to move their heads if their mouths and noses got buried in blankets or the mattress. They realized that if babies slept on their

backs, they were much less likely to suffocate and, therefore, much more likely to survive. Pediatricians began a campaign—Back to Sleep—to tell parents to put their babies to sleep on their backs, reversing their previous recommendations. Once they sent this information out to the public, parents made different choices and began to put their babies to sleep on their backs. The data show that spreading this information significantly reduced rates of SIDS. In other words, SIDS is an example of a problem where people acted differently once they were given the information they needed.

Unfortunately, however, scholars have found that there is a gap between opinion and action when it comes to climate change. Even though more and more people understand that climate change is a problem and think that we should do something about it, there's a big gap between those who believe that climate change is a problem and those who actually take action.

Misinformation exacerbates that gap. For example, because of misinformation about climate science, the public thinks that only about 55% of climate scientists agree that global warming is occurring, when in fact it's 97% or more of climate scientists. Almost all climate scientists agree that the climate is changing because of greenhouse gas emissions caused by human activities. But because of misinformation, 59% of Americans say that they're still unsure about whether climate change is happening and whether humans are causing it, as Anthony Leiserowitz and colleagues at the Yale Program on Climate Change Communication have found.

If there's so much misinformation out there, shouldn't we correct that by giving people more of the accurate information? In fact, research on misinformation in politics has shown that confronting people who believe misinformation with more information is not always productive. When people believe that climate change is not real and you try to disprove their ideas with information and evidence, it usually does not persuade them. Instead, it often entrenches them in their original beliefs and makes it harder to change people's minds. Sometimes, just trying to win the argument with the best data is not the best strategy.

Though there are some problems that we can solve simply by informing people, climate change does not seem to be one of those.

People do not always perceive the information we give them in the way that we expect. And even those who know that climate change is a problem don't always take action on it.

What about market solutions? Isn't climate change really a problem for businesses to solve? What if we could convince all the corporations to reduce their greenhouse gas emissions sharply? The theory of change underlying market solutions is that if we could only give people who run companies the right set of incentives to behave the way that we want them to behave, then we could solve the problem.

Indeed, many capable people have developed incentives for individuals, families, and businesses to take action on climate change. But even though incentive programs have been set up, they are not scaling up enough to address the problem effectively. For example, carbon pricing is an important solution that is often discussed, but as of 2015, the World Bank reported that only 12% of global greenhouse gases are subject to carbon pricing (Chapter 12).

When we put all of these theories of change together—science, technology, communications, markets—we have to confront a difficult question. Climate science, technological innovation, communicating accurate information, and economic incentives are all essential to tackling climate change, but they're not solving the problem on their own. In particular, they are not yet transforming key behaviors by corporations, governments, and societies at the scale required to mitigate or slow climate change. So what else do we need?

That's where **collective action** comes in. Collective action, of which social movements are one form, involves people coming together to transform society and is most useful when we're trying to solve problems of power. More information, a better piece of technology, a catchier message, or more streamlined incentives won't solve a problem of power on their own. We can define a **problem of power** as one where the people who are most directly affected don't have the authority or ability to make the necessary change.

Ordinary people are being affected by climate change now. Those of us who are affected by climate change urgently need to protect the world that we and our children, grandchildren, and great-grandchildren will live in—but we don't have the authority or the power to make the

changes we need on our own. It is true that individuals can reduce their carbon footprints through everyday choices, such as eating less meat, using less energy to heat or cool their homes, and biking, walking, or taking public transportation instead of driving. But individual action is not even close to enough: action on a much larger scale than anything you or I alone can do is required to solve the problem of climate change. Instead, those who have the power to change the structural drivers of our dependence on fossil fuels must act. Our national governments and international bodies must make decisions that set the world on a different course.

If people don't have the power to make the change that they need, then how do they acquire that power? First, they have to consider what their resources are. A famous organizer named Saul Alinsky once said that when you're trying to make political change, there are two sources of power: organized money and organized people. And if you're not on the side of organized money, what you need is organized people.

Because climate change is a problem of power, we need to adjust our theory of change. Technological innovation, climate science, accurate information, and market mechanisms are essential but will not be enough on their own. Our theory of change also has to include some way of moving power. In other words, we have to get those in power to adopt all the climate change solutions that have already been developed—all the solutions outlined in this book—on a scale large enough to make a difference. Acquiring that power is what collective action and social movements do.

To address multidimensional societal problems like climate change that are in some part problems of power, where the people who need change the most don't have the power to make it, bringing people together is necessary. Social movements are a way to do that. Social movements are a type of collective action in which the people who want change the most also work with others to acquire the resources they need to make the change that they want. The rest of this chapter will examine how leaders and ordinary people in social movements acquire the resources and power to make the change that they want.

5.2 Defining Social Movements

What are social movements? As you might imagine, many social scientists have studied this. One scholar, Edwin Amenta, defines a **social movement** in a simple, clear way: "a set of actors and organizations that are seeking to alter power deficits and to effect social transformation through the state by mobilizing regular citizens for sustained political action."

As the last section showed, when it comes to problems of power, people who want change the most cannot make the change that they want, given the situation as it currently stands. That's a lack of power. Sometimes people think *power* is a scary word. But here it only refers to this question about whether ordinary people who want change have the ability to make the change that they want.

Social movements are efforts to solve problems of power. To do that, social movements have to face two challenges. First, how do you get ordinary people involved in sustained political action? Second, how do you translate that political action into the kind of influence or power necessary to make the change that you want to see?

Social movements address these challenges by fundamentally transforming people and their resources. Sometimes people think social movements just bring people together to do something. But there are many examples of bringing people together to do something that we wouldn't call social movements. For instance, companies try to convince you and many other people to buy ketchup. And many people do buy ketchup of one brand or another, but we don't call that a social movement, because buying ketchup is not a fundamentally transformative act.

In the 1830s, a French diplomat and historian named Alexis de Tocqueville toured the United States. He was trying to understand how American democracy worked. At the time, democracy was a new experiment around the world. No one thought that it would really work. But

over in North America, people were trying it out, and de Tocqueville investigated their democracy and observed it from all angles.

One of the strange things that de Tocqueville noticed was that Americans, weirdly, get together to do everything. They get together to drink beer. They get together to garden. They get together to talk about politics. At first, he just dismissed it as a funny little cultural habit that Americans had. But over time, he realized that this habit of coming together was fundamental to the way democracy worked. As he wrote famously in his book *Democracy in America*, the process of joining with others is fundamentally transformative.

How is it transformative? De Tocqueville argues that joining with others is fundamentally transformative in three ways. First, when people come together, inequality of resources becomes equality of voice. Even though people start with different kinds of resources, they all have an equal voice in the process if they join with others to make change.

Second, he realized, when people join with others, their individual self-interest is transformed into collective interest. In other words, when I first join a group, I might only be thinking about my own desires. For example, I might want to build a garden so that I can have more tomatoes to eat. But then I realize that the garden is not just about my tomatoes. It's about feeding my entire community. In this way, an individual's self-interest is transformed and she comes to understand and care about the broader collective interest.

Third, de Tocqueville argues, the process of joining together is transformative because it teaches people how to work with others. We all know that working together is not easy; it requires particular skills, capacities, and even motivations. As students, you have undoubtedly done group projects that made you tear your hair out because it's so hard to work with others. De Tocqueville points out that the process of learning to work with others transforms people because it forces them to learn how to navigate their differences, speak up for what they believe in, and understand the power of working together.

How does this relate to social movements? Social movements make the political change they want by transforming the individuals who are part of them. And then social movements take those transformed individuals and translate their resources into political voice.

From talking with people about this process of transformation, we know that they're often skeptical. The first question they ask is, Can social movements really transform people that way? A sociologist named Ziad Munson did a fascinating study of the "pro-life" movement against abortion in the United States. He was trying to understand how the people who are most active in the movement first got involved. Munson did long, 3-to-4-hour interviews with people on the very front lines of the pro-life movement—people who organize pro-life groups in their communities. They not only attend the rallies and the marches, but also spend a lot of time trying to get other people involved. Munson asked them, among other things, what they were doing before they became activists in the pro-life movement.

One of Munson's most interesting findings undercuts a key assumption about social movements. Usually we assume that people join a movement because they believe strongly in the issue or cause it is centered on. According to that assumption, people would join the pro-life movement because they believe strongly that abortion is wrong. And people would join environmental movements because they are environmentalists—they already believe that it is important to address climate change, conserve resources, protect biodiversity, and preserve wild lands.

However, Munson found that almost half of the people he interviewed were either pro-choice or indifferent to issues of abortion when they first joined. That's a surprising finding, because we presume that social movements draw in people who already support the cause for which they advocate. But in fact, Munson found that half the people on the front lines of the pro-life movement didn't get involved because they believed in it. They got involved for a variety of other reasons. Maybe a working woman became a stay-at-home mom and was looking for something to do outside the house. Maybe someone had just moved to a new community and was trying to meet people. Maybe someone had just joined a new church and wanted to get involved in church activities. Or maybe a friend invited me to come to a meeting and I just felt bad saying no.

In other words, people came into the movement for a wide variety of reasons—often social and biographical reasons having to do with an

FIGURE 5.2.1 This view of the crowd at the March on Washington for Jobs and Freedom on August 28, 1963, where Dr. Martin Luther King Jr. gave his famous "I Have a Dream" speech, embodies our usual assumptions about what social movements look like. Photograph by US Information Agency, Press and Publications Service. Reproduced from Wikimedia Commons.

individual's particular situation. But then, once they came to that first meeting, something happened that made them want to keep coming back. That's the process of **social transformation**. Social movements begin to change people's minds—not only in terms of what they believe, but also in terms of what they think they have to do because of what they believe. It wasn't just that those who joined went from being pro-choice or indifferent to abortion to being anti-abortion. It was more that they also thought, "Wow, now that I understand these issues, I've got to act on them. I've got to organize a group in my community. I have to attend these rallies. I have to attend these marches."

That is how social movements work. They start by transforming the individual, and by transforming the individual, they begin to transform society.

Social movements are not all about marches and protests. Some of you might be thinking, "I'm not really an activist. I'm just a science major. And I'm not sure if I'm the kind of person who can stand up in front of a group of people and attend rallies." It is easy to assume that social movements are nothing more than the large protests and rallies that we see covered in the media—that only a March on Washington with hundreds of thousands of people counts (Figure 5.2.1). But those of us who study social movements understand them as complex ecosystems. They are constellations of what some scholars would call arenas and players.

Social movements operate in many different arenas. That is, they happen in a variety of places and through a variety of forums—organizations, companies, government bodies, neighborhood associations, schools and universities, and so on. In those arenas, there are a variety of people who all play their own roles. The players might be movement insiders, like the activists whom Munson interviewed in his study, but they can also include the heads of corporations, directors of nonprofit foundations, professors, union leaders, intellectuals, teachers, and journalists.

Teach-ins are an example of the role that teachers and students can play in social movements. Organizers of the first Earth Day, including Wisconsin Senator Gaylord Nelson, wanted to plan one day of action—April 22, 1970—to raise awareness about environmental issues. Earth Day has expanded in subsequent years to include marches, tree plantings, and community cleanups, but in those early years, "environmental teach-ins" all over the United States were a big part of it (Figure 5.2.2).

Nowadays, the work of building the environmental movement happens all over, in places that we may not even think about as political. It happens in people's living rooms as they discuss ways to take action with their neighbors. It happens in churches where religious leaders teach people the importance of being stewards. It happens in educational settings where children learn about the impact of human activity on the natural world. All of these people have a role to play.

In the next three sections of this chapter, we will turn to leadership. All of you climate champions have a role to play as leaders.

THE GAYLORD NELSON NEWSLETTER

Washington, D.C.

November 1969

Environmental Teach-In Planned

National Effort Set For Spring

The development of comprehensive plans to kick off a national teach-in on the Crisis of the Environment to take place this spring on college campuses across the country will be announced this month by Sen. Gaylord Nelson.

The Wisconsin senator said he has been traveling around the country talking about his teach-in idea and seeking support for the proposal.

By the end of the month, Nelson expects to have a national headquarters on the teach-in set up in Washington with a staff that will be contacting students all across the country.

The teach-in plans call for a day, probably in April, when normal campus activities will be set aside for the university and the local community to get together and discuss the mutually shared environmental problems.

Apostle Islands Legislation

The Nelson bill to establish Apostle Islands as a part of the national park system passed the Senate in June, and the Senator is hopeful the House will authorize the necessary money to make the proposal a reality by the end of next year.

Discussions, Rallies

On that day, special programs designed and planned by the students will take the form of symposiums, convocations, panel discussions or outdoor rallies where the crisis of the environment will be discussed.

Nelson said the topics of discussion will vary with the university and the section of the country in which it is located. For example, students at the University of California might want to discuss oil spills in the ocean, while students at the University of Wisconsin might want to talk about the pollution crisis in the Great Lakes. At Columbia University the subject might be air pollution of American cities.

"The initial reaction to the teach-in idea has been impressive and beyond what I had hoped," Nelson said. "My office has been receiving mail from students and people from all parts of the nation wanting to know how to become involved and how to plan a teach-in."

The Washington office will be filtering the mail and offering whatever support the various colleges are requesting.

Student Commitment

Nelson said he decided on a teach-in for college students because the present national commitment toward environmental problems indicates it may be too late to convince the established leadership of the seriousness of the crisis.

"This generation of youth is vitally concerned about the environment, because it will inherit the disaster of years of wanton, indifferent waste and destruction of the natural resources of the country," Nelson argued. "If something isn't done soon, there may be nothing left for their children."

The senator believes that the same concern the youth of the nation took in changing the country's attitude on the war in Vietnam and on civil rights can be shown for the problems of the environment.

"What is heartening," Nelson continued, "is that modern youth is not satisfied with coming out the loser in man's drive for progress and profit. Because of the indifference of their elders, the young people of today face an ugly world of the near future with dangerously and deadly polluted air and water, sprawling, crowded development, festering mounds of debris, and an insufficient amount of open space to get away from it all."

Quality Of Life

He said he is hopeful that the climax of the teach-in will be a demand for a quality of life in the final third of the 20th Century "that gives the same priority and money to the crisis facing the environment as has been given to national defense."

Nelson added that "it will take the same kind of commitment that put men on the moon and built one of the most massive defense machines ever seen on earth to solve the environmental crisis."

Environmental Guinea Pigs

"WE DON'T REALLY KNOW WHAT THE LONG-TERM EFFECTS OF VARIOUS TYPES OF ENVIRONMENTAL DETERIORATION WILL BE, AND THE KIDS ARE THE GUINEA PIGS."

Barry Commoner
Biologist
Chairman, St. Louis Committee for Environmental Information

FIGURE 5.2.2 The first Earth Day, in 1970, was a nationwide "teach-in" that involved much more than marches, as this November 1969 issue of Senator Gaylord Nelson's newsletter shows. Reproduced with permission from the Wisconsin Historical Society and the Nelson Institute for Environmental Studies, University of Wisconsin.

5.3 The Role of Leadership

Leadership is one of those words that people like to use all the time. In this section, we will examine what leadership is in the context of the kind of social movement that we need to address climate change.

Social movement leadership is a particular kind of leadership. Marshall Ganz, a longtime organizer who is now a scholar, argues that **leadership** is "enabling others to achieve purpose in the face of uncertainty." There are three parts of his definition that are important to notice.

First, you need leadership when you face uncertainty. We don't need leadership to do many ordinary things in our everyday lives, like getting up each morning, having breakfast, getting the kids to school, and going to work. At work, you might have an annual budget review, or a weekly meeting on Fridays. You don't need leadership for those, either; you need managers. Someone has to manage the process of the annual budget review. But when you face a situation that is uncertain—like when you're trying to make some kind of social change—that's when you need leadership.

Second, leadership is not about doing something yourself. It's about enabling others. Leaders are not people who do all the work themselves. Instead, they make it possible for others to do the work that they need to do.

And third, leadership helps others achieve their purpose. Leaders do not necessarily designate the end point or set the destination that the movement tries to reach. Rather, leadership is about figuring out how to enable others to achieve the purpose that they want and to navigate the uncertainty that they face.

Let's make that broad but vague definition of leadership more concrete. In the last section, we said that leaders of social movements confront two main challenges: how to get people involved in sustained

political activism and how to translate that activism into the political influence or power that can make change.

So, first, as a leader, how do you get people involved in sustained activism? Think of all the people out there that a social movement might want to engage, and then picture them as a tree with some low-hanging fruit and some high-hanging fruit. The low-hanging fruit are the people who, for whatever reason, have some kind of latent motivation to get involved. Maybe their parents are environmentalists, and they're already on board with the idea that we need to create climate solutions. Or maybe someone took a class about bending the curve and decided to become a climate activist. These kinds of people know they want to do something, but they need an opportunity to get involved. They're the low-hanging fruit because they're the easiest to engage.

Other people, up near the top of the tree, are much harder to engage, sometimes for reasons unrelated to the movement itself. For example, at the very top of the tree, we might imagine that there are people who, even if they were motivated, don't have the capacity to get involved. They might not have much free time because they have to work multiple jobs to make ends meet. Or maybe they have never even heard of climate change. Or maybe they have heard about it, but they don't feel like they can act on it, because that would go against the social norms of their community.

About halfway up the tree, you might find some people who are motivated to get involved but don't really know how. Maybe they don't feel comfortable talking about their political views in front of other people. Maybe they don't feel comfortable talking about science in front of other people. They need to develop some particular capacities and skills.

Leadership means figuring out how to engage both the low-hanging fruit and the high-hanging fruit. The most successful social movements in history not only grabbed that low-hanging fruit and pulled in people who were already motivated, but also figured out how to draw in the people who weren't motivated at first.

How do the leaders of social movements do that? Social movement leaders push people up a ladder of engagement. In any kind of movement or organization, there are different tiers of involvement. At

the very bottom of the ladder, there are people who say, "Hey, I think climate change is a problem, and I'm going to sign up for an email list so you can send me information about climate issues." At the next tier of involvement are the people who say, "I'm not just going to sign up for your email list, I'm also going to give you 2 hours a week of my time to act on it. If you send me alerts, then I'll call my legislators. If you send me petitions, I'll sign the petitions. If you want, maybe I'll even come into your office and I'll stuff envelopes for 2 hours a week." People at this level of involvement are willing to do certain kinds of tasks, but they don't want to take any responsibility for outcomes.

As we continue up the ladder, we find people who not only are willing to give some time or be responsible for particular tasks, but also want to take responsibility for outcomes. Taking responsibility for an outcome might involve someone saying, "Hey, I'm not just going to come to your meeting on Friday; I'm going to be responsible for getting 20 other people to come to that meeting too. And if it takes me 5 minutes to send an email and get those 20 people, that's great. But if it takes me 10 hours of knocking on doors, I'll do the 10 hours." Their commitment no longer depends on how much time something takes; instead, they are committed to achieving a particular outcome.

Social movements need people at all levels of that ladder of engagement. They need a lot of people at the bottom, but they also need people at the top. Scholars have found that social movement leaders push people up that ladder of engagement by cultivating what we call their agency. What is agency? Martin Luther King Jr. famously defined **agency** as a person's own power, or their ability to achieve purpose. If I have the capacity to achieve the purpose that I want to achieve, then I have agency.

Often, we assume that agency is just a belief. But social psychologists have found that agency is not just about whether people *believe* they can achieve their purpose—and that it's not just about competence either. It's also about whether someone has the autonomy or the space to act. Agency requires both competence and autonomy.

Social movement leaders not only help activists cultivate that sense of competence, that sense that they can do what they're trying to do,

but also give them the autonomy and space to act on their goals. What does that look like?

This is a question that Hahrie Han, an author of this chapter, set out to study in her research lab. She asked: Why are some organizations and movements better than others at getting people involved, and keeping them involved, in ways that cultivate their sense of their own agency and push them up that ladder of engagement? After a multi-year, multimethod comparative study, Han's lab found that the strongest movements understood that it is not just about getting people involved, but it is *how* you get them involved that matters. Not every form of participation is the same.

In fact, many movements make the distinction between **mobilizing** and **organizing**. Mobilizing involves trying to get as many people involved as possible by making it as easy as possible for them to take action. While that can build numbers, it often does not build agency. Organizing, on the other hand, is about constantly designing ways for people to take action that push them up that ladder of engagement by cultivating their sense of agency.

The difference between mobilizing and organizing is not simply semantic. In fact, Han's research lab has found that organizers and mobilizers have different theories about how to do the work. On the one hand, mobilizers reach out to as many people as possible and ask them to take a simple, quick action, so that they can convince more and more people to do more and more things. On the other hand, organizers have a theory of building power that involves developing leaders who will, in turn, motivate others.

Han's lab found that mobilizers only convinced the low-hanging fruit, the people who were already motivated, to do something quick and easy. We call this **transactional mobilizing** because the actions taken, such as sending an online petition or signing up for an email list, are a simple exchange of resources like a transaction—like going into a store and buying something. You give your money to the store and walk out with your ketchup and there are no strings attached.

Organizers, in contrast, asked people to do things that were not quick or easy but that would put them into relationships with other people. For example, instead of asking people to write letters to the editor

by filling out a template online and pushing a button to send it, organizers asked people to join with others in their community, compose a letter together, and then send it off to the local newspaper. According to the organizers' theory, by working with others, people develop both the motivation and the capacities that de Tocqueville identified many years ago as fundamental to making democracy work—and that are fundamental to making social movements work as well.

Mobilizers and organizers differ not only in the kinds of things that they ask people to do, but also in how they structure their organizations. Mobilizers tend to concentrate all the responsibility in the hands of just a few people, whereas organizers distribute that responsibility across a broad group of people. We found that by distributing that responsibility, organizers were more likely to create social movements that transformed people. Through this **transformational organizing**, social movement leaders are able to engage people in the sustained political activism that leads to the kind of change that they are seeking.

The challenge, of course, is that asking people to take small, transactional steps is a lot easier than asking people to transform themselves, take responsibility for outcomes, and become leaders. Leaders turn transaction into transformation and make it possible to build social movements and create change.

5.4 What Can I Do? Building Power

In this section and the next one, we will turn to a set of leadership practices that you can use to build power and engage people around you in the kinds of social movement that we need to address climate change. Most of the leadership practices discussed here were developed by Marshall Ganz, who was a longtime organizer with the civil rights and migrant farm workers' movements and now teaches at Harvard. Ganz has developed a set of leadership practices that takes the mystery out of how social movements are able to engage people in sustained activism.

Leadership practices separate organizations that don't work from organizations that do work.

You can surely think of organizations that you've been a part of that have worked and organizations that you've been a part of that haven't worked. Just take a minute to reflect on the differences between those kinds of organizations. We have all been part of teams, groups, organizations, and clubs that don't really seem to work—and they have some characteristics in common. Organizations that don't work tend to be divided. People don't agree. They tend to be passive and reactive. Instead of thinking ahead about what they want to do, they just wait until things happen to them and then they react.

In contrast, organizations that work tend to be full of people who are motivated and committed to the cause. Their members are unified, all working together, and that makes it possible for them to be purposeful and proactive. Individuals within the organization can work on the agenda that they are all trying to achieve without waiting for other people to delegate tasks to them and define their work.

Social movement organizations try to engage people in sustained activism in order to build the power they need to make the change they want, through creating organizations that work. According to Marshall Ganz, there are three important leadership practices that help to build

power: creating shared purpose, building relational commitment, and developing a clear structure.

First, how do you create shared purpose? In social movements, it is essential to make sure that everyone is engaged with the same agenda and has a sense of shared purpose. Often, we tend to try to persuade people with scientific or policy details. We try to explain exactly how a carbon tax will work, or we tell people what we know about human-caused climate change. That is important because it speaks to our heads and helps us develop a strategy for how to take action.

But we've learned from decades of research in neuroscience, psychology, and other fields that human action is not only about the how, but also about the why. The why is about the heart—the values that move us to take action. And we communicate our values not through arguments, details, or abstract statements, but through stories.

Someone could stand up and say, "I believe in equality" or "I believe in freedom," and that wouldn't really mean much to you on its own. It wouldn't move you to take action. But if someone stood up and told you a story about a particular injustice that they witnessed and explained how they took action to counter it, then you might have some insight into their commitment to equality. You might have a more concrete sense of why equality is important, and that concrete sense could motivate you to take action as well. Through stories, we're able to communicate what we value.

Sometimes the concept of stories can seem abstract. But, as Marshall Ganz teaches, for decades, film makers in Hollywood have known that there is a formula for telling stories, and it's not that complicated. What you need is a character who faces a challenge that puts her in a place of uncertainty. Then, she has to make a choice, and that choice has an outcome. By telling a story with that clear formula—character, challenge, choice, outcome—we can communicate what we believe in through the choices we make. We can tell stories about ourselves, our organizations, and our movements. That's how we use stories to help create shared purpose.

The second leadership practice is building relational commitment—that is, building people's commitment to their relationships with others in the movement. Organizers often say that it is important to have

one-to-one meetings. That's where a casual social relationship, a personal relationship, or a new relationship turns into a public relationship.

Relationships become a source of power when two people exchange their interests and resources and make a commitment to acting together. People who come into a new setting or a new relationship bring their own set of interests. They might want to start a new club around climate solutions or talk to their local elected officials about climate issues. And people bring their own sets of resources as well. Maybe one person has taken the Bending the Curve online course and now understands climate science, while another is really good at social media. Maybe someone else is a visual artist and a wonderful designer. These are all resources that people bring to the table.

In a one-to-one meeting, people build relational commitment by exchanging their interests and their resources with each other. In doing so, they create a new set of shared interests and shared resources, and those become a source of power for the movement.

From decades of research in social movement studies by scholars such as Meredith Rolfe and Betsy Sinclair, we have learned that when the going gets tough, people don't stay committed because of their commitment to the issue. They stay committed because of their commitment to each other. When it's Thursday night and I have an exam the next day and I'm not sure if I want to go to that meeting, I don't go to that meeting because I'm so committed to the issue. Usually I go to that meeting because I don't want to let my friend down. In other words, it is important to build relational commitment because that is the glue that holds social movements together.

The third leadership practice is developing clear structures. Let's say an organization has people who are committed and who share a purpose and a narrative. Then how should that organization structure its work so that the whole is greater than the sum of its parts?

We can imagine three different leadership structures. The first one is a dependent leadership structure where you have one leader who's in the middle and all the work has to pass through that one leader (Figure 5.4.1). The leader organizes everything. Those of you who have been part of organizations like that know what goes wrong. The person in the middle gets overwhelmed, stressed out, and burned out, and the

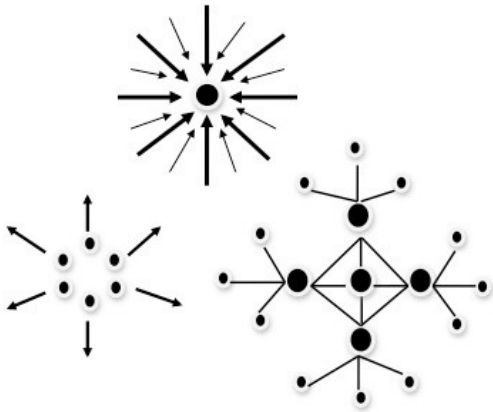

FIGURE 5.4.1 Dependent (top), independent (left), and interdependent (right) leadership structures. Images from Hahrie Han based on Ganz 2014.

organization is only as strong as that person. If that person gets sick or doesn't have enough capacity, the organization can't do any work. And the people on the outside feel unmotivated because they don't have any real say in how things work.

Another structure is the opposite of that: an independent leadership structure. Some organizations don't want to have a situation where there's only one leader, so they decide to make everyone a leader. The problem then becomes that, even though everyone is motivated, they are going in 24 different directions. It's difficult to build a movement that makes sustained change if everyone is working on 15 different things.

Social movements usually work best with an **interdependent leadership structure** where everyone is working on the same vision and in the same direction, but the work is chunked out into pieces so that it can be distributed. Though each person is working with others for a shared purpose, each person is also responsible for a specific piece of that work. Because the meaningful work is distributed, individuals have autonomy and agency; they themselves are transformed by working with others toward the common goal of transforming society.

5.5 What Can I Do? Developing Creative Strategies and Taking Effective Action

In this final section, we turn from leadership practices that you can use to build your power to a second set of leadership practices that you can use to deploy your power. These leadership practices continue to draw on Marshall Ganz's work. We will focus on two different practices he identifies: developing a creative strategy, and taking measurable, effective action.

Imagine that you're a social movement leader and you have used the leadership practices we discussed in the previous section to create shared purpose, build commitment, and develop a structure through which you organize all the activists whom you have engaged. The next question is, How do you turn that sustained activism into power? You do that through strategy and action.

Developing strategy

Let's start with developing a creative strategy. **Strategy** is fundamentally the process of turning what you have into what you want—in other words, turning your resources into your goals. One thing scholars have learned from research on social change and political change is that simply having more of something—whether it's money or people—doesn't necessarily result in achieving a particular purpose. It doesn't mean that you're going to win.

Sometimes people say, Of course the fossil fuel companies win because they have more money. But researchers found that, when we look at different kinds of political or social change efforts, the side that has more money only wins 50% to 53% of the time. It's little better than flipping a coin. Simply having more money doesn't mean that you're going to achieve your goals. Instead, the extent to which a movement or organization develops creative strategies that help them achieve their purpose separates those who reach their goals from those who do not.

How do social movements develop strategy? Scholars have found

that one of the key ways in which social movements develop creative strategy is to reflect on their outcomes on multiple levels at key points in the trajectory of their work. Most movements organize their work into a campaign with a variety of peaks. A movement might be building toward a peak, like a rally or a march, or maybe a media event or a meeting with an elected official. Activists do a great deal of work leading up to that peak. Then the work will slow down a bit afterward, and it will go back up before the next peak.

At each peak, social movements measure their outcomes at several levels. Leaders ask the obvious questions about immediate outcomes: did we bring out the number of people we wanted to the march? Did we convince the elected official to support our proposals? But leaders also reflect on three other outcomes. They ask themselves: First, did we make the change in the world that we want to see? Second, did we make that change in a way that built greater capacity for the movement? And third, did we develop individual leaders in the process?

The analogy of a company clarifies why those last two questions matter. At the end of the year, a company sends its investors an annual report. Their annual report says not only what their profits were for the past year, but also what their assets are going forward. For a company like Boeing, their assets might include their engineering crew, their patents, the quality of their airplane designs, and so forth.

What are a social movement's assets going forward? They include the movement's leadership capacity and organizational capacity. So after any campaign peak, social movements develop strategy by thinking about how to make the change in the world in a way that also builds the individual and organizational skills, capacity, and motivation that they need.

Taking measurable, effective action

The second leadership practice Marshall Ganz identified to help you to deploy your power is taking measurable, effective action. Sometimes organizations become caught in a snare of preparation. It's easy to spend all of your time developing strategies and plans and making sure that your plans are perfect—but never actually putting them into practice.

Scholars have found, perhaps unsurprisingly, that movements that

win are really good at taking action. They do so at the individual and local level, at the community level, and even at state, regional, and global levels. To address an issue like climate change, we cannot focus only on the local community. Movements also need to take action at national and international levels.

Social movements link together all the work at those different levels, and a story about a woman named Frances Willard shows how. In the United States in the early twentieth century, Willard started the temperance movement—the movement against alcohol that eventually led to Prohibition. But she started out as an advocate against domestic violence. When Willard realized that alcohol was causing a great deal of domestic violence, she decided her goal was to pass a constitutional amendment banning alcohol.

In the United States, passing a constitutional amendment is quite difficult. That amendment has to be passed by a supermajority in both houses of Congress, and then three-quarters of the states have to agree to it as well. But that was Frances Willard's goal, and she went about it by starting a social movement. She traveled all over the US by train, trying to identify people who wanted to join the movement. If someone wanted to join, the first thing she asked that person to do was take a pledge to swear off alcohol. She started with the individual's own behavior.

Then, after a new member of the movement swore off alcohol, Willard asked the person to join with others in the local community to shut down a bar. She did this not because she thought that whether Joe's Bar was open in Anytown, USA, mattered much for the movement, but because she wanted people to have the experience of working with others. She wanted them to realize what they could do when they came together with others to achieve a particular purpose, so that they would be committed to that process of collective action.

Finally, after they tried to shut down that bar—it didn't matter if they had succeeded in doing so or not—she would invite them into the movement. By inviting a set of people into the movement who had developed those capacities of working with others, and who had been personally transformed in that way, Frances Willard was eventually able to get a constitutional amendment banning alcohol passed.

FIGURE 5.5.1 Finding our "Joe's Bar"—the experience that teaches us to work with others—can be difficult, but people around the world are coming together to call for climate action, as these fossil fuel divestment activists did at the University of California in 2013. Photograph by Jamie Oliveira. Reproduced from Flickr.

We tell that story not to advocate for banning alcohol, but simply to make the point that whenever we take measurable, effective action, we need to think about how we can link individual action to community action to national or international action. A major question and challenge that we confront when we consider social movements to address climate change is: What is our Joe's Bar? Where can we join with others to realize the power that we can have together—not study it by reading a book or taking a class, but instead believe it in our gut so that conviction carries us forward into the work that we have to do? (Figure 5.5.1.)

By actually engaging in all of these leadership practices—creating shared purpose, building relational commitment, creating interdependent structures, developing creative strategy, and taking measurable, effective action—we come to realize that, whether we're addressing climate change or any other kind of issue, the work begins with us, because we are the change that we need.

5.6 Summary

We have taken a journey together over the course of this chapter, so let us pause here to summarize what we have learned. We started by recognizing that climate change is not a problem that can be solved by any one fix. Solutions that involve technological innovation, economic incentives, communications, and information are all important in addressing it. But climate change is also a problem of power, so our efforts to confront it also have to include collective action and social movements. Sections 5.1 and 5.2 defined problems of power as those in which the people who need change the most don't have the authority or ability to make that change.

Social movements and collective action help us address those power imbalances. Sections 5.2 and 5.3 discussed examples of social movements and examined the role that leadership plays in enabling such movements to make change. We focused on how social movements transform individuals and then society. Social movements address power imbalances by engaging people in political action that is fundamentally transformative—through transformational organizing, which differs from transactional mobilizing. In particular, Section 5.3 focused on the role that social movement leaders play in engaging people in ways that build their capacity for sustained activism.

Finally, in Sections 5.4 and 5.5, we ended by looking at a particular set of leadership practices that enable transformation. Leadership practices that are focused on building power include developing relational commitment, creating shared purpose, and building interdependent structures. Social movement leaders then take all the power that they've built and deploy it to create political influence by developing creative strategy and taking measurable, effective action.

We hope that this chapter has shown how you, as climate champions, can embrace opportunities to join with others to build social movements that can enable and demand action on climate change.

Remember that social movements are much more than marches, and seek out your Joe's Bar—the local place that can serve as a focus for your actions on this global problem.

Sources for the Figures

Figure 5.2.1: March on Washington, August 28, 1963. Photograph by US Information Agency, Press and Publications Service. (Public domain.) Reproduced from https://commons.wikimedia.org/wiki/File:View_of_Crowd_at_1963_March_on_Washington.jpg.

Figure 5.2.2: November 1969 issue of Senator Gaylord Nelson's newsletter. Reproduced with permission from the Wisconsin Historical Society and the Nelson Institute for Environmental Studies, University of Wisconsin. http://www.nelsonearthday.net/earth-day/proposal.php.

Figure 5.4.1: Dependent, independent, and interdependent leadership structures. Image by Hahrie Han based on Ganz, M. 2014. Organizing notes. Materials for the course Organizing: People, Power, Change at the John F. Kennedy School of Government, Harvard University.

Figure 5.5.1: Fossil Free Cal attends the UC Regents meeting at UCSF, March 14, 2013. Photograph by Jamie Oliveira. Reproduced from https://www.flickr.com/photos/350org/8559011268/in/album-72157632993369915/. CC BY-NC-SA 2.0.

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CHAPTER 6

Social Transformation

Changing Attitudes, Norms, and Behaviors

FONNA FORMAN

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Learning Objectives

1. Understand why integral solutions, including social and behavioral change, are necessary for tackling climate change.
2. Understand why local solutions are often most effective in producing social change.
3. Examine several exemplary Latin American urban case studies in which social transformation was a key strategy.
4. Prepare to think about what universities and colleges can do to cultivate social transformation in their own communities.

This chapter has four goals. First, it will show why integral solutions—including changing social attitudes, norms, and behaviors—are essential for tackling climate change. Second, you will learn why *localizing* and *personalizing* the impacts of climate change are the most effective strategies for changing social attitudes, norms, and behaviors. Third, you'll be exposed to several exemplary case studies in which social transformation played a key role in efforts to address climate change in Latin American cities. And fourth, you'll be prepared to think about how universities and colleges can cultivate social transformation in their own communities.

Overview

This chapter will explore the importance of transforming social attitudes and behavior, locally and globally, as an essential strategy for tackling climate change.

Clean energy technologies and climate-forward public policy are essential tools for tackling climate change, but they are not enough. The most exciting innovations in green technology will not matter if people are not willing to use them and to integrate these technologies into their lives and livelihoods. Likewise, the best policy proposals, at home and abroad, will only take root and grow if publics are willing to support these policies through political processes. Social attitudes, norms, and behaviors typically determine whether a new technology will succeed in practice, or whether a policy proposal will ever see the light of day.

The chapter will proceed in four sections. Section 6.1 explores

climate change as a complex, integral challenge that requires equally complex, integral solutions. Our emphasis will be on the importance of integrating social transformation into integral solutions thinking and action. Section 6.2 focuses on strategies of social transformation, demonstrating that we are likelier to produce changes in social attitudes and behavior by "going local" and making impacts "personal" in order to motivate public interest and investment in solving the problem of climate change. Section 6.3 explores cities as *living laboratories* for thinking and action based on integral solutions. We will highlight several exemplary case studies in Latin American cities where social transformation played a central role in creating not only more green cities, but more equitable ones as well. Our discussion emphasizes the significance of local action. Section 6.4 introduces a social transformation experiment at UC San Diego, called the UCSD Community Stations. It is a new model of university-community partnership for local social transformation through climate education and participatory climate action that can be replicated at universities and colleges everywhere.

6.1 Integral Solutions: Designing Cultures of Collaboration

> When we speak of the "environment," what we really mean is a relationship existing between nature and the society which lives in it. Nature cannot be regarded as something separate from ourselves or as a mere setting in which we live. We are part of nature, included in it and thus in constant interaction with it. Recognizing the reasons why a given area is polluted requires a study of the workings of society, its economy, its behaviour patterns, and the ways it grasps reality. Given the scale of change, it is no longer possible to find a specific, discrete answer for each part of the problem. It is essential to seek comprehensive solutions which consider the interactions within natural systems themselves and with social systems. We are faced not with two separate crises, one environmental and the other social, but rather with one complex crisis which is both social and environmental. Strategies for a solution demand an integrated approach to combating poverty, restoring dignity to the excluded, and at the same time protecting nature.
>
> His Holiness Pope Francis, *Laudato Si'*, ch.4: 139

Integral ecology

In *Laudato Si'*, Pope Francis's 2015 encyclical on climate change, he described the relationship between humans and the natural world as an "**integral ecology**." With the word *integral*, he means to emphasize that human well-being and environmental well-being are inherently intertwined. We cannot speak of one without necessarily implicating the other. Caring about human health and prosperity entails caring about the environment in which all human life takes place. The concept of integral ecology has been used for decades by environmentalists to describe the inherent interdependence of humans and nature, but it has taken on a particular salience and urgency in our era of rapid global warming.

In *Laudato Si'*, Pope Francis emphasizes two dimensions of this

interdependence between humans and nature. The first relates to the *environmental impacts of human action*. There is no longer any doubt that human activities—especially the energy consumption and production habits of the wealthy minority across our planet—are rapidly accelerating climate change. There is also no doubt that together we must change these behaviors if warming is to be slowed down. The second dimension relates to the *human impacts of climate change*. Climate change is inflaming human suffering across the world, particularly among the world's poorest and most vulnerable populations, exacerbating poverty, dislocation, disease, and mortality. What this means for Pope Francis is that climate change and poverty must be tackled together, as an integral two-headed beast. He wrote: "Strategies for a solution demand an integrated approach to combating poverty, restoring dignity to the excluded, and at the same time protecting nature."

The culpability of our planet's wealthy minority in exacerbating climate change, and in the consequential suffering of the poor and vulnerable majority, raise important issues of climate justice and the imperative for urgent adaptation strategies across the world, which are explored in Chapter 2. Here, we are focused on designing effective strategies to rapidly mitigate climate change, which will alleviate longer-term impacts on us all, rich and poor, born and not yet born.

Tackling a challenge as deep, complex, and urgent as climate change requires new strategies of lateral collaboration across diverse knowledges and capacities. Natural scientists and social sciences need to join forces. Economists, policy experts, and public health researchers must come together with inventors of new technologies and philanthropists who have the capacity to invest in them. But integral thinking requires more than getting experts and elites around a table to share their knowledges and strategies.

Tackling climate change in an integral way also requires vertical collaboration between the politicians and researchers and the grassroots organizations, religious leaders, educators, and cultural producers who are closer to what is happening on the ground. These community leaders are essential partners in designing more effective strategies to transform social attitudes, norms, and behaviors among the young and the old from the bottom up and in cultivating new habits of climate

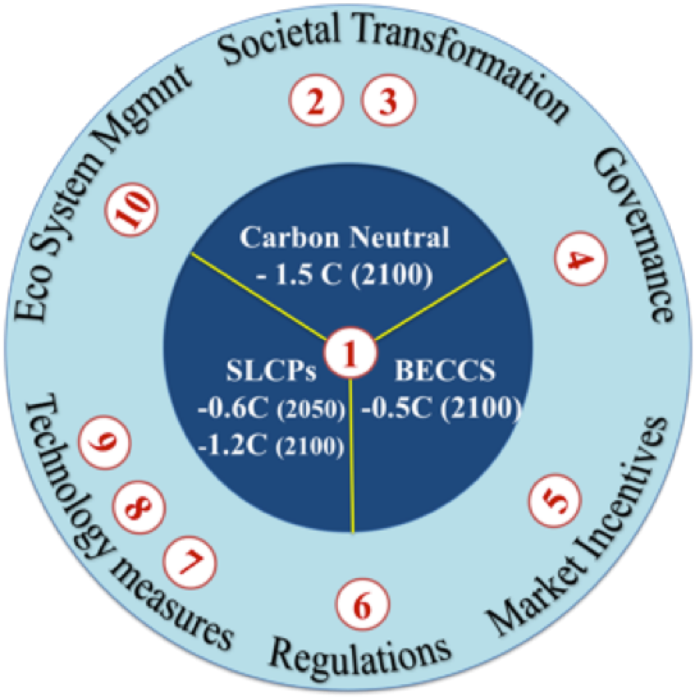

FIGURE 6.1.1 A diagram of the integral climate change solutions proposed in the 2015 *Bending the Curve* report. From Ramanathan et al. 2016.

action among the general public. In other words, the "experts" need to figure out how to mobilize and democratize scientific knowledge to inform public opinion.

The University of California's *Bending the Curve* report of 2015 was a bold experiment in integral thinking that convened diverse knowledges and capacities in both lateral and vertical ways. Under the leadership of UC San Diego climatologist V. Ramanathan, the report drew upon the scientific, technological, economic, social, and policy innovations that have made the state of California a global environmental leader over the past decades. *Bending the Curve* summoned 50 researchers from across the University of California system—from the sciences, social sciences, finance, public health, and the humanities—to identify ten integral and scalable solutions to climate change drawn from the California experience (Figure 6.1.1). *Bending the Curve* marked a powerful moment of unity and vision for the public university. California governor Jerry Brown helped to launch the report, and he carried it with him to COP21—the 2015 United Nations Climate Change Conference in Paris—with the idea that California's successes could be a model for the world.

COP21 was a historic moment for global cooperation on climate

change solutions. The goal of the conference was to create a universal, binding agreement to reduce greenhouse emissions across the planet. On December 12, 2015, the 196 participating countries arrived at a consensus and signed the Paris Agreement, which stipulated that each country agreed to do what was necessary to reduce carbon emissions and keep global warming "well below 2 degrees Celsius." The agreement went into effect on November 4, 2016. Thirteen months later, President Donald Trump withdrew the United States from the Paris Agreement, claiming that it was a "bad deal" for America. But the story is not yet over. We still have time to act together on integral solutions to climate change.

Culture of collaboration

Climate change is too big and too complex a problem for any single sector, discipline, or approach to solve alone. Climate change is not just a technological problem or a scientific problem or a medical problem or a finance problem or a policy problem. Pursuing only one dimension of the problem, or failing to understand how multiple dimensions are connected with each other, will not accelerate climate change solutions. We need to work together across all these disciplinary boundaries.

The 2015 *Bending the Curve* report's third proposed solution focused on designing a new **culture of collaboration** around climate change:

> Deepen the global culture of climate collaboration. Design venues where stakeholders, community and religious leaders converge around concrete problems with researchers and scholars from all academic disciplines, with the overall goal of initiating collaborative actions to mitigate climate disruption.

But recognizing that we should work together across disciplines is one thing; actually learning how to do so is quite another. Working across disciplines is not something people and institutions innately know how to do. Such cooperation needs to be designed and facilitated. Collaboration is a skill—something we must learn how to do. Therefore we must not only cultivate collaborative opportunities, but also develop the skills and habits of collaboration.

Universities tend to be very siloed institutions, which means that the

boundaries we have created between divisions, departments, and majors tend to be thick, with too few opportunities or incentives for movement and cross-disciplinary connection across them. Boundaries are effective tools for organizing complex institutions, but they are largely artificial. They typically don't reflect the way the real world works, or the need to organize integral solutions to our most challenging social problems.

Universities often talk about the value of "interdisciplinarity," and there are certainly opportunities for undergraduates to pursue interdisciplinary minors and take courses team-taught by faculty from different areas of the campus. But these opportunities are rare. They are not the norm on most college and university campuses. If we are serious about fostering cultures of collaboration, we must design new spaces for collaborative research, teaching, and learning around deep social challenges like climate change. No one discipline or way of knowing or doing can solve this problem alone. This means that we need to rethink university culture itself, including the way we conduct our research and our teaching.

University of California's Bending the Curve course provides an excellent model of how universities can create spaces for integral research and education. One of the major benefits of this course is that students come from a great variety of disciplines and together learn how to view the challenges of climate change, and to think about solutions, through multiple lenses. Some students who take this course are required to develop team-based projects on "living laboratories." Through this exercise, they come to recognize the value of distributing tasks to team members who have diverse skills and varying bodies of knowledge. Additionally, these students learn how to communicate their diverse knowledges and skills to classmates in other fields in clear and accessible ways.

Beyond creating new spaces for collaboration across disciplines *within* the university, however, researchers also need to rethink how we engage people *outside* the university, in the so-called real world. Universities too often think of themselves as bearers of knowledge and truth, and of the world as lacking knowledge. Universities, like other institutions of power, often see their relationship to the world in vertical terms, with all knowledge flowing downward. When universities engage other sectors and publics, they too often forget how much knowledge

exists outside of formal educational institutions, and how much university researchers can learn from that knowledge. This becomes particularly true and ethically problematic when universities approach disadvantaged communities as empty receptacles waiting to be filled with "our" knowledge. Academic research is often infused with assumptions that "we" know more, that we are "trained experts," that only we have languages to convey complex ideas—in short, that we enter the world to save it, not to learn from it. However, engagement with worlds of practice reveals that these assumptions are just wrongheaded, that academic researchers do not know everything they think they know, and that they have as much to learn from the world as it does from them—and possibly more.

We need a more horizontal model of collaboration between scientists, designers, and the people who are the intended users of new technologies. There are both pragmatic and ethical reasons for this. Consider the challenges of **technology transfer**. Technology transfer refers to the processes by which innovative designs in science and technology are translated from concept into practice. What might appear to be a good solution to the scientist or designer in the lab may not actually work in practice. We cannot simply design solutions out of whole cloth, drop them down on the world, and expect that they will work. Technology transfer needs the bottom-up participation of intended users, both in the design of new technologies and in the social strategies for adopting and integrating new technologies into existing practices.

Technology transfer has important ethical dimensions as well. From an ethical perspective, people need to be the stewards of their own destiny and to understand and embrace the technologies that will change the way they live, the way they move from place to place, communicate, cook, and so on. This ethical imperative is most profound when engaging the bottom 3 billion—that is, the 3 billion people who are especially vulnerable because of their reliance on natural resources and are already disproportionately harmed by climate change.

Project Surya, led by UC San Diego professor V. Ramanathan, provides a powerful example. This project is committed to tackling both the impact of short-lived climate pollutants on the Earth's atmosphere and their more immediate impact on public health, particularly among

FIGURE 6.1.2 Project Surya: women in a rural Indian village discuss the benefits of adopting a cleaner cookstove. Reproduced with permission from Project Surya.

women and children. Project Surya is an integral intervention—involving scientists, designers, economists, and social scientists—that designs and deploys low-carbon-emission cookstoves in the villages of rural India (Figure 6.1.2).

Project Surya is also an ethical intervention because it engages intended recipients of the stoves as participants in designing, using, and distributing the stoves. It does not drop new technology down upon the poor as if they were passive subjects. Respecting the agency and dignity of these women means listening to their accounts of how new cookstove technology will affect their lives and how it might disrupt their current cooking practices, which are typically deeply rooted in cultural norms and practices. The scientist cannot assume that resistance is a manifestation of ignorance. A woman in rural India might not want to use a clean-burning cookstove because it doesn't work well for her, because it makes her chores more difficult, because her family does not like how the food tastes when she uses it, and so forth.

Ethical technology transfer entails respecting these local responses and integrating them into an iterative design process in which designers take such concerns seriously and continue revising and improving their technologies accordingly. This kind of give-and-take cultivates genuine social receptivity to the new technologies. From the perspective of

climate justice, the participation of vulnerable people in designing climate change solutions is essential.

But there are pragmatic considerations as well. Without social acceptance and buy-in from the bottom up, climate mitigation strategies, like the introduction of clean cookstoves, will be less effective. Climate action in sites of scarcity is best achieved through bottom-up climate education and avenues for participatory climate action that stimulate individual and collective agency, capacity, and hope. If the scientist doesn't take existing cultural practices and constraints into account when designing new technologies and social adoption strategies, levels of adoption may be disappointing. The technology must either accommodate local preferences and practices, or else come with additional incentives that make it attractive to potential users despite any trade-offs.

The conclusion is that researchers, innovators, and climate activists need to be closely attuned to the needs and preferences of intended users for both ethical and pragmatic reasons. Collaborating with intended-user communities is an integral and ethical social strategy for designing more effective and sustainable solutions.

6.2 Social Innovation: Get Personal, Go Local

Social transformation

The 2015 *Bending the Curve* report's second solution focuses on transforming social attitudes, norms, and behaviors around climate change, and cultivating support for the policies, technologies, and actions that are necessary to accelerate a low-carbon global economy:

> Foster a global culture of climate action through coordinated public communication and education at local to global scales. Combine technology and policy solutions with innovative approaches to changing social attitudes and behavior.

In other words, innovations in technology and policy are not enough to change our world. They must be accompanied by *social transformation* at varying scales, from the global to the local, from the very wealthy to the very poor. From the perspective of climate justice, the wealthy global minority must change its energy consumption and production habits as well as invest in sustainable development across the globe. The vulnerable global majority must be welcomed into climate action less as voiceless recipients of charity than as active participants in solutions.

Just as we need innovative clean energy technologies, policies, and financial tools to bend the curve of greenhouse gas emissions downward, we also need innovative and ethical *social technologies* to change attitudes, norms, and behaviors regarding climate change and how to tackle it. Just as our new technologies must draw on the best science and our new policies must be grounded in the best economic and policy research, our social strategies need to be grounded in the best social science research on climate communication and climate education.

Changing hearts and minds is not easy. According to a 2017 Gallup poll, only 42% of Americans believe that climate change will pose a serious threat in their lifetimes. There is much public apathy and a

human tendency to see other social and economic pressures, closer to home, as more urgent. There is also significant public hostility to the idea of climate change and the politicians and scientists who warn us about it. Willful misinformation and distortion in public discourse—often motivated and funded by those invested in the status quo—stoke this hostility. The orchestrated denial of science in recent years has obscured a clear message about the reality of climate change and its projected harms. Additionally, the politicized clustering of contentious social issues has undermined the formation of broader coalitions. Bundling climate change with other policy agendas like abortion, LGBTQ rights, and gun control has forced a wedge between otherwise potentially like-minded publics who could unite to conserve our Earth.

How do we intervene? How do we change attitudes and behaviors around climate change when there are so many conflicting agendas and ideologies, so many counterpressures and disincentives? Research on the most effective strategies of social transformation makes it clear that providing better information alone will not work. Changing attitudes and behaviors is not like pouring knowledge into an empty vessel. Educating people about the facts will not necessarily produce new attitudes and behaviors, since individuals live in social and political contexts in which their beliefs and behaviors are mediated by others. What those around us think and do has a great influence on what we think and do. Through his research, social psychologist Robert Cialdini shows that we must recognize the role that social norms play in motivating our beliefs and actions regarding many policy issues, including climate change.

Moreover, social science research demonstrates that when people understand precisely how climate change will affect their personal well-being, the well-being of their loved ones, and their own cities and neighborhoods, their minds open and their attitudes begin to change. Focus group research demonstrates that when people understand in more particular ways what's at stake *for them*, they become more receptive to climate-friendly public policy. We will explore this focus group research further below, but for the climate communicator, it means that presenting climate change in terms of melting ice caps and polar bears far away will not have the same transformative impact on attitudes as emphasizing the local urgencies for a particular audience.

However, changing *attitudes* is not the same thing as changing *behaviors*. We need to distinguish them. How can people be moved from changing *what they know* to changing *what they do*? Social science has important things to say here. We will see in the same focus group research that attitudes are likelier to inspire new behaviors when concrete opportunities for local climate action are made apparent and available to people. The likelihood of behavioral change increases further when these pathways for action are collective and participatory in nature and pursued in concert with one's friends and neighbors rather than individually.

In this section we will further explore the strategies of "getting personal" and "going local." In our discussion of getting personal, we will consider public health and well-being as a lever for social transformation. In our discussion of going local, we will focus on cities as living laboratories for successful social transformation.

Get personal

Too many people today are insufficiently moved by climate science to support climate change mitigation policies, technologies, and actions. Too many people are also immune to the ethical imperatives of climate justice: that we must mitigate warming for the unborn and for the most vulnerable people on our planet. This book identifies what we might think of as "levers" that can be pulled to bend the curve of global warming. Is it possible to identify a lever to move people who are largely resistant to arguments based in science, ethics, or the public good? How do we rouse people from the status quo and move them to question political agendas and ideologies that deny the reality of climate change? Is it possible to instigate a change in attitudes, norms, and behaviors?

The 2015 *Bending the Curve* report explored the disproportionate public health impacts of climate change. But at that time, we had not yet investigated the value of public health predictions for communicating climate change. Public health *itself* can be a lever to change people's minds and raise awareness about the urgent problems everyone on this planet is facing. Most individuals are typically most interested in what affects them, their families, and their communities. Most of the time, they are not motivated by the interests of others. One important reason

why climate change has not gotten more social traction is because it can seem remote, spatially and temporally, from the everyday interests of most people. People are less likely to make personal sacrifices when climate change is framed as a threat to polar bears or to people on the other side of the planet.

To bring climate change home for people, we must show that its impacts are personal and highly relevant to an individual's understanding of her own interests and well-being. The public health risks of a warming planet—which can cause stroke, cardiovascular disease, and respiratory disease, for example—make it clear that climate change will harm individuals all over the world. This knowledge will give those individuals reason to become personally invested in solutions.

As you know from reading this book, "mitigating climate change" should be synonymous in people's minds with "preserving my health and well-being." But this is not yet the case, and communicating it entails a strategic shift in the language we use to characterize the impacts of climate change. We need to shift from a collective, ethical language about the well-being of the planet and the commons to an individualist language about the well-being of the self—from a language of disproportionate impacts on the distant and the poor to a generalized language of public health risks for all. Even though we know that climate change disproportionately impacts the poor and vulnerable, it will nevertheless affect everyone. It is essential in our public communications to generalize impacts, to expand the circle of potential victimhood, and to stimulate a broader sense of public urgency. Because we are *all* in peril, regardless of our wealth and social position, public health becomes an important social lever for social change.

The early modern idea of **enlightened self-interest** is instructive here. Economist Albert Hirschman characterized this idea as a substitute for ethics. Enlightened self-interest helps explain why individuals using reason sometimes sacrifice immediate pleasures for social or collective ends, even though they are not motivated by social or collective reasons to do so. There is a rational calculation behind such a trade-off: an individual can be motivated to support climate-friendly policy, technologies, and actions through nothing but the prudent exercise of her own self-interest. Prudence in the pursuit of something one loves or

FIGURE 6.2.1 This image is from a protest that occurred in New York City while the COP21 meetings took place in Paris. The message here has been shifted from a conventional ethical mode (protect others, protect the environment) to a prudent mode—one should protect one's own interests, the things that one loves. Photograph by Joe Brusky on Flickr.

wants can restrain present gratification (in this case, unimpeded energy consumption and carbon production) for a greater benefit in the future (health and well-being). Enlightened self-interest serves as a proxy for ethical motivation and demonstrates how individual and collective ends can converge.

Trade-offs are obviously not new to discussion about climate change solutions. The effectiveness of incentives—of using carrots rather than sticks to stimulate climate-friendly choices—is an important public policy lever. One of California's sometimes controversial success stories (cap and trade) highlights the ethical compromises incentives always entail. Along these lines of thinking about carrots, we ought to think strategically about how to communicate the public health risks of climate change.

Faith leaders have sometimes been effective messengers about climate change, depoliticizing the issue through scriptural inspiration,

respect for Mother Earth, and divine compassion for our fellow creatures. Religious communities can help to promote new social norms—an important dimension of sustainable behavioral shifts. Public health may have the capacity to transform attitudes and behaviors at even broader scales by moving people to protect what they love—not Mother Earth primarily, not all humanity primarily, but people's personal well-being and the well-being of their families, friends, and communities (Figure 6.2.1).

To communicate the public health risks associated with climate change, perhaps doctors and health practitioners can be effective messengers. Perhaps they are less susceptible than politicians, journalists, scientists, and intellectuals to being characterized as biased in political rhetoric. They certainly are capable of engaging people where they are—in the intimacy of an examination room—and personalizing the impact of climate change. It may be that the general practitioner, the pediatrician, the obstetrician/gynecologist, the midwife, and the nurse practitioner are among our most important climate communicators and educators right now. This entails, then, that we shift how we train our health professionals today. Medical schools will need to become increasingly more collaborative, interdisciplinary, community engaged, and better insulated from corporate agendas. They need to commit themselves to integrating environmental health, education, and policy agendas more explicitly into their mission.

Go local

"Getting personal" has a lot to do with place. One way to get personal is to help people understand the risks of climate change for their own cities and neighborhoods. The social science research also tells us to "go local": people are more receptive to climate-friendly public policy when they better understand the specific impacts of climate change on their own communities. A study of attitudes and behaviors among residents of low-lying coastal communities in south Florida, commissioned by the Union of Concerned Scientists, found that climate-friendly attitudes are likelier to take root when the impending negative effects of climate change are made concrete and relevant for people, rather than abstract like far-off melting ice caps and polar bears.

FIGURE 6.2.2 Miami Beach residents crossing flooded streets, an accelerating impact of sea level rise in south Florida. Photograph from siralbertus on Flickr.

Proximity matters! Focus group research has found, for example, that when people understand precisely how sea level rise will affect their own city, neighborhood, or block, their *attitudes* change (Figure 6.2.2). They are likelier to become receptive to the idea that global warming is a problem and supportive of local climate-friendly public policy. This is even true for a majority of individuals who describe themselves as politically conservative. This study also found that people are likelier to change their *behaviors* when concrete opportunities for local climate action are made available to them. Knowing the risks without having opportunities to act can produce paralysis.

When people are provided with pathways for action, they are likelier to act and to develop new habits of climate action. The likelihood of behavioral transformation increases when those opportunities for action are collective, participatory actions involving neighbors, friends, fellow congregants, and others in a person's immediate social reference group. This research has been reinforced by the success of neighborhood-based participatory climate action projects across the world, documented by organizations like Climate Action Network International and the Climate

Justice Alliance. These observations are also consistent with network theory in the social sciences, which claims that social behavior is infectious, that people are likelier to engage in a particular behavior when their social reference group (that is, their peers, friends, and neighbors) engages in that behavior. This is true of harmful behaviors like smoking and excessive drinking. But it is also true of positive, pro-social behaviors like seat belt usage, vaccination, and climate action.

6.3 Cities as Living Laboratories

In this section, we further explore the value of "going local" by investigating cities as living laboratories of social transformation. Political theorist Ben Barber founded the Global Parliament of Mayors, which is dedicated to swift, coordinated global action around social challenges that nation-states have often been too slow and clumsy to tackle effectively. He believed this was particularly true with regard to climate change. As Barber put it, "cities are the coolest political institutions on earth."

In the United States, most of the action on reducing emissions and on coping with climate change generally has not taken place at the federal level. States, localities, and corporations have done much more than the national government. This is true across the world as well. There has been deeper commitment to coordinated climate action at the municipal level than at the national level. Agile, environmentally progressive mayors have coordinated integral collaborations and regional coalitions to produce rapid change.

After the release of *Laudato Si'* in spring 2015, Pope Francis called for urgent, coordinated action, and he began by summoning mayors. The mayors who convened at the Vatican in July 2015 urged world leaders to pass a "bold climate agreement that confines global warming to a limit safe for humanity, while protecting the poor and the vulnerable from ongoing climate change that gravely endangers their lives," according to a *New York Times* story about the meeting.

The Pope is from Argentina, of course, and there is perhaps something distinctively Latin American about why the Pope began with mayors. Latin American cities in recent decades have been particularly successful at transforming attitudes and behaviors around climate change and environmental health while producing more equitable outcomes for urban residents. Many Latin American cities have become almost mythical as living laboratories of equitable green urbanization, committed to advancing social justice and climate justice together.

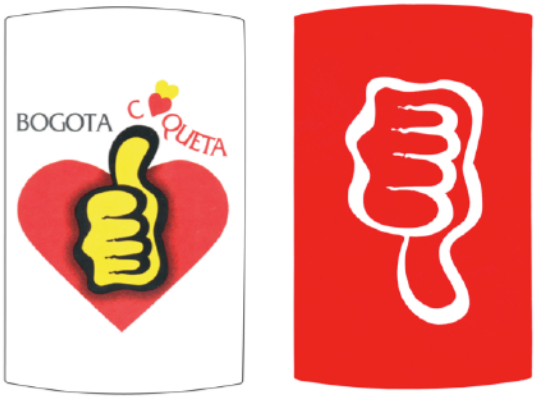

FIGURE 6.3.1 Placards used by Mayor Antanas Mockus in 1995 to stimulate a sense of mutual responsibility among the citizens of Bogotá. He encouraged people to use the thumbs to express approval and disapproval of one another's behaviors. Reproduced from CÍVICO Bogotá.

A good place to begin is Bogotá, Colombia, in the 1990s. Philosopher Antanas Mockus became mayor of Bogotá during its most intense period of violence in the late 1990s and early 2000s. It was a scene of social chaos and urban breakdown, unemployment, poverty, and choking air quality—the worst anywhere on the continent. People referred to Bogotá as the most dangerous city on the planet; it seemed a Hobbesian war of all against all was underway there.

Mockus declared that urban transformation begins not with "law and order" and not with new infrastructure—that would come later—but with civic strategies designed to transform social attitudes, norms, and behavior, to change hearts and minds collectively and individually. He became legendary for the distinctive ways he intervened in the behavioral dysfunction of urban Bogotá, using the arts, culture, and sometimes outrageous performative interventions to dramatically reduce violence and lawlessness, reconnect citizens with their government and with each other, increase tax collection, reduce water consumption, and ultimately improve quality of life for the poor.

One particularly well-known example was the citizenship cards project. Soon after taking office, Mockus distributed small cards across the city, hundreds of thousands of them, each depicting a thumb (Figure 6.3.1). He encouraged people to use the thumb card to express approval and disapproval toward one another as they moved through the city. So when you saw something that violated your sense of urban dignity, you'd show the card thumbs down. At first, people thought this was crazy. But what happened was that people began to look at each

FIGURE 6.3.2 Bogotá's Transmilenio bus rapid transit (BRT) system in the early 2000s became a model for BRTs. Photograph by Felipe Restrepo Acosta on Wikimedia Commons.

other again, and they began to recognize how their actions affect others and how the actions of others affect them. Through this performative gesture, people were deciding together on the kind of city they wanted to inhabit. Social norms began to change; public trust began to emerge.

These cultural changes paved the way for Mayor Enrique Peñalosa's renowned green infrastructural interventions in the succeeding administration. Sometimes called the world's most transit-friendly mayor, Peñalosa launched a multinodal transportation network comprising bus rapid transit, bicycle hubs, ciclovia (bikeways), and dedicated walking paths that stitched sprawling Bogotá together. This project involved massive cross-sector collaboration and helped to revolutionize public transportation in Latin America (Figure 6.3.2). In other words, shifting

social norms came first, and the transit interventions followed. This is an important insight for us today as we think about developing sustainable solutions for cities.

Like Mockus before him, Peñalosa understood that changing social norms was essential to his egalitarian transportation agenda. He famously said, "A developed country is not a place where the poor have cars; it is a place where the rich ride public transportation." Like Mockus, Peñalosa was committed to modeling positive behavior and rode a bicycle wherever he went. He often claimed that a citizen on a $30 bicycle is as important as one in a $30,000 car, bringing social equity together with environmental and climate justice.

Mockus and Peñalosa emerged from a long tradition of participatory urbanization across Latin America, stewarded by climate-forward mayors who were inspired by Brazilian educator and philosopher Paulo Freire and his "critical pedagogy" for reclaiming the humanity of the colonized. These mayors committed to robust agendas of civic participation in order to ignite a sense of collective agency and dignity among the poor and, ultimately, to produce greener and more equitable cities. For example, in the 1980s, Workers' Party mayors in Porto Alegre, Brazil, experimented with participatory budgeting, in which communities got to decide together how to allocate a percentage of the municipal budget for their own neighborhoods. In the same decade, Mayor Jaime Lerner pioneered bus rapid transit and dozens of green interventions across Curitiba, Brazil. In the early 2000s, the "social urbanism" of Mayor Sergio Fajardo of Medellín, Colombia, transformed public spaces and green infrastructure into sites of education and citizenship building—and made Medellín a global model of urban social justice. This tradition still thrives in cities across the continent, from La Paz to Quito to Mexico City, and carries important lessons for equitable green urbanization in cities across the world today.

Researchers at UC San Diego have been inspired by these Latin American models of participatory green urbanization and are working to adapt these lessons to disadvantaged areas in the neighboring cities of San Diego, USA, and Tijuana, Mexico. In the final section of this chapter, we will explore the UCSD Community Stations as a model of integral, university-community partnership for local climate action.

6.4 The UCSD Community Stations

Social science research confirms that individual and collective behavioral change in disadvantaged communities begins with community-based education and that successful educational initiatives localize climate change by linking global challenges to concrete local conditions. In disadvantaged neighborhoods plagued by poverty, violence, failing schools, and failing infrastructure, climate can seem remote from the acute challenges of everyday life. Disadvantaged urban populations are likelier to change consumption and production habits when they understand the linkages between climate and local effects in their neighborhoods and when opportunities for participatory action with local impact are made available to them.

Led by UC San Diego political science professor Fonna Forman (the author of this chapter) and UC San Diego visual arts professor Teddy Cruz, the UC San Diego Community Stations are a network of field stations located in disadvantaged neighborhoods across the San Diego and Tijuana region. In the stations, university researchers and students partner with community-based nonprofits on projects involving environmental literacy and climate action. We have three stations distributed throughout the region (Figure 6.4.1).

The Community Stations are committed to three main climate change agendas: (1) providing community-based climate education for undergraduate and graduate students on our campus, teaching them to become effective climate educators; (2) increasing climate literacy among adults and especially children in the communities we partner with; and (3) stewarding high-impact participatory climate action projects at neighborhood scales. These projects range from small-scale activities like community workshops and demonstrations to designing and financing net zero retrofits of homes, schools, and businesses. Each summer, through the Blum Summer Field Internship, we fund dozens of UCSD students from 15 majors and minors across the campus to work

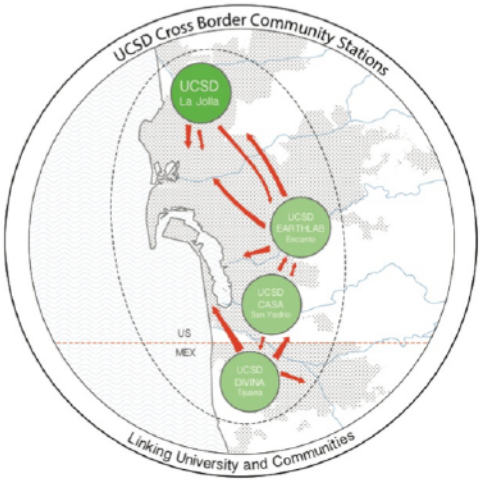

FIGURE 6.4.1 The UCSD Community Stations Network. Reproduced with permission from Teddy Cruz and Fonna Forman.

on integral, team-based research projects on climate change, sustainability, and environmental health in the UCSD Community Stations.*

Take, for example, UC San Diego's EarthLab Community Station, a partnership with the environmental nonprofit Groundwork San Diego, which is located in Encanto, San Diego's most challenged inner-city neighborhood, near Chollas Creek, the city's most polluted waterway. EarthLab is a 4-acre outdoor environmental classroom and climate action park, equipped with community gardens, water-harvesting facilities, a solar house, an energy "nanogrid," and other green infrastructure, all designed by university researchers as learning tools for the six public schools in walking distance of the site. Thousands of low-income youth and their families circulate through EarthLab each year, learning about the impacts of climate change and environmental degradation in their own neighborhoods and participating locally in climate action in concrete ways (Figure 6.4.2).

We're now in the process of designing a master plan for the EarthLab to increase its capacity into the future, focusing on food, energy, and water, the major challenges of environmental justice in underserved communities today. And we've been recognized by the California Energy Commission for our potential to change behaviors and attitudes

*The Blum Summer Field Internship was made possible by University of California Regent Richard C. Blum and the Andrew W. Mellon Foundation.

FIGURE 6.4.2 The UCSD EarthLab Community Station, image tiles. Reproduced with permission from Teddy Cruz and Fonna Forman.

in this community. In 2017, we received an Electric Program Investment Charge (EPIC) grant to design a "near-zero net energy community" for the surrounding neighborhood. EarthLab will serve as a base for the solar power and energy storage infrastructure that will make this possible. This project demonstrates how the university can use its leverage to partner with local nonprofits not only to change attitudes and behaviors, but also to facilitate high-impact climate action projects in underserved neighborhoods.

The UCSD Community Stations also focus on climate change and poverty in the neighborhoods that flank the US-Mexico border separating San Diego and Tijuana. Given UC San Diego's proximity to the international border, we've come to understand this region as a local site for research on the disproportionate impacts of climate change on vulnerable people across the globe. We also believe we have an ethical duty, given our proximity, to figure out how to mobilize our research and capacity to assist these vulnerable communities.

FIGURE 6.4.3 Local youth in the UCSD-Divina Community Station, learning through doing. Reproduced with permission from Teddy Cruz and Fonna Forman.

Our UCSD-Divina Community Station is located in an informal canyon settlement of 85,000 people on the periphery of Tijuana that butts up directly against the wall marking the international border. We work in a neighborhood called Divina Providencia, in close partnership with a nonprofit called Organización de Colonos de la Divina Providencia (Figure 6.4.3). Together, we design and lead environmental literacy programming to help children and their families understand the impact of climate change and environmental degradation on their health and the well-being of their communities (Figures 6.4.4 and 6.4.5). Again, it's not just about filling empty vessels with knowledge. It's about hands-on learning and participatory climate action. When we get people involved at an early age, they come to value the environment and to appreciate its direct impact on their lives and their communities.

We conclude our chapter on social transformation with the UCSD Community Stations because we believe they provide a highly replicable and scalable model of local climate action. Universities everywhere are

FIGURE 6.4.4 Local youth in the UCSD EarthLab Community Station, environmental literacy in situ. Reproduced with permission from Groundwork San Diego, Chollas Creek.

FIGURE 6.4.5 The UCSD Blum Summer Field Internship, Summer 2015, Tijauna, BC, Mexico. Reproduced with permission from Teddy Cruz and Fonna Forman.

positioned to do this kind of collaborative work in their local communities, training our students across disciplines to become the climate educators and communicators of the future and mobilizing university resources for the public good, locally and for the planet.

6.5 Summary

This chapter on transforming social attitudes, norms, and behaviors has asserted four main claims. First, tackling climate change requires integral solutions that combine innovations in technology, finance, and policy with transforming social attitudes and behavior. Second, we're likelier to produce changes in social attitudes and behavior by localizing and personalizing the impacts of climate change and providing concrete opportunities for participatory climate action. Third, many cities have developed compelling models of participatory green urbanization that tackle both climate change and social inequality. We explored several Latin American urban "living laboratories." Finally, universities and communities can be meaningful partners in changing attitudes, norms, and behaviors around climate change. We enjoin you, as climate champions, to think about how organizations you are involved in—whether it's your university or college, city, town, or community group—can do this too.

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CHAPTER 7

Religion, Ethics, and Climate Change

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Learning Objectives

By reading this chapter, you will learn

1. Why it is important to understand climate change as a moral issue.
2. How a variety of religions are addressing climate change as an ethical dilemma.
3. How religious organizations and communities can help develop climate change solutions.
4. How the academic field of religion and ecology brings science, religions, and environmental ethics together to help us understand climate change as a moral issue that requires moral responses.

Overview

Humans are currently immersed in a global environmental crisis that has various manifestations, such as climate change, deterioration of ecosystems, massive loss of species, and pollution of air, water, and soil. The effects of this crisis on human health and planetary well-being are increasingly evident, but the moral response to it has been muted.

Until recently, degrading nature for human use—clear-cutting forests, strip-mining mountains, depleting fisheries—was not considered a critical ethical issue. For many economists, for example, polluting the atmosphere, soil, or waters was simply an external consequence of industrialization and the necessary cost of economic growth. But now our industrializing powers and economic systems are disrupting the carbon cycle and causing the entire planet's climate to change.

Several questions come to mind: Is climate change not a moral challenge? Who will suffer most from the effects of climate change? Do we have an environmental ethics that is broad enough and inclusive enough to respond, especially to the needs of the poor? If nature is not fully valued, how can we develop a robust environmental ethics?

It may be the case that—as with the abolitionist movement in the nineteenth century and the civil rights movement in the twentieth century—we will not respond at the scale and speed required until we see climate disruption as an ethical challenge. The integration of the moral issues

of ecological degradation and climate justice into social consciousness, political legislation, and international negotiations remains to be realized.

Two interrelated questions arise: Where do we begin, and what can we build on? For each part of the world the response will be different, as ethics will be based in different cultural, philosophical, and religious worldviews. For the United States, the task is far from easy, and one of the main messages regarding consumption may be dismissed or ignored. For the hard truth is that our hyperinflated lifestyle—our massive consumption of energy and goods—is having adverse effects on people and the planet, both at home and abroad. With only 4% of the world's population, the United States consumes 25% of the world's resources. Moral awakening, while still elusive, is critical.

It is clear that we in the United States are, and have been for some time, a source of the destruction of the environment, both its intricate ecosystems and its myriad species. Whether intentionally or unintentionally, we are also increasing inequity and injustice for the poor, the vulnerable, and climate refugees who are now suffering from the devastating effects of climate change. This is true in Central America as well as in Africa and the Middle East where refugees are fleeing drought-stricken lands. Even insurance companies, such as Chubb, are recognizing the existential threat of climate change. The US Department of Defense sees it as a national security threat. We are indeed confronting the existential threat of climate change, and what to do still eludes us as the demands of intergenerational justice loom on the horizon.

In Section 7.1, this chapter will indicate the possibilities for and barriers to a new alliance between science and religions to address climate change. In Section 7.2, I will outline the academic field of religion and ecology as well as the moral force of grassroots religious environmentalism. Section 7.3 acknowledges the problems and promise of religions for tackling environmental issues. In Section 7.4, I will outline how religions contribute to a broad moral sensibility for the flourishing of life. Section 7.5 discusses *Journey of the Universe*, a multimedia project, including a book and a film, that aims to develop a comprehensive cosmological story for a vibrant Earth community. Finally, Section 7.6 will highlight key principles, strategies, and tactics for an ethical response to climate change.

7.1 Science and Religion: A New Alliance Needed

While climate action on a significant scale is still lacking, one way forward is to see climate change as an issue that brings science and religion together as never before. We need both scientific knowledge and environmental ethics to confront this massive problem. The challenge is, How can we break through scientific complexity to the moral insight that gives rise to social and political change?

But first there are problems with science and with religion that we need to identify. Clearly a tension between science and religion exists in universities and schools and in churches, synagogues, and mosques across the United States. This is one reason that the moral dimensions of climate change are still invisible, both in academia and in society at large. There are many reasons for this: namely, that religion and ethics are marginalized in secular academia, that schools of theology have not made ecological issues and environmental ethics central to their curricula, and that religion and ecology is still a new field in academia. Yet it is fair to say that this field has significant potential for encouraging a moral environmental force in society. Indeed, grassroots religious environmentalism is growing significantly. The Pope's 2015 encyclical on the environment, *Laudato Si'*, has done much to encourage this by making action on climate change a moral imperative. The Ecumenical Patriarch Bartholomew of the Eastern Orthodox Christian Church has also led the way in highlighting the sacredness of creation and in hosting religion, science, and environment symposia focused on water. He speaks of the degradation of nature as "crimes against creation" and "ecological sin."

Linking spirituality and ecology is not wholly new, of course. Indigenous people's worldviews have been based on this understanding for millennia. Moreover, in the nineteenth century, John Muir fought to preserve the Sierra Nevada in California by representing the wilderness as a temple in his writings. He helped to establish Yosemite and fought to preserve Glen Canyon for its aesthetic and spiritual merit. His feeling

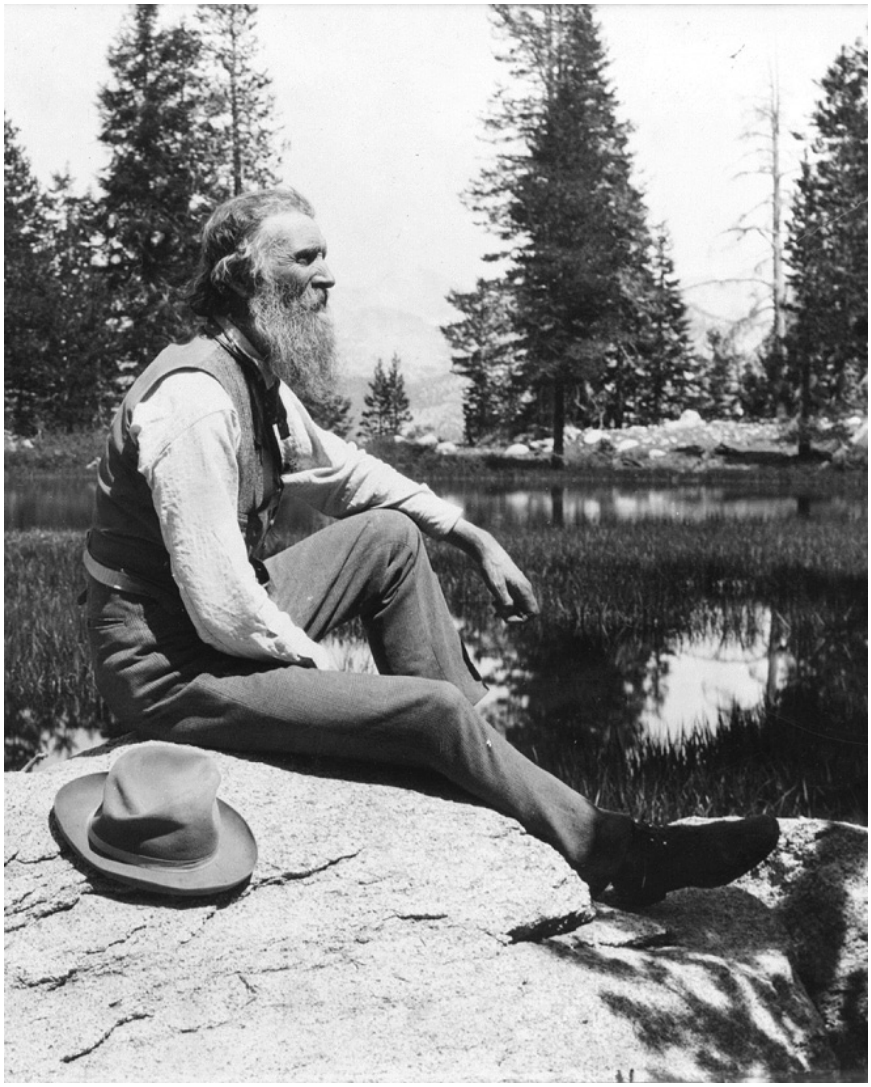

FIGURE 7.1.1 John Muir advocated environmental preservation, in part because he saw nature as sacred. This portrait of him was taken in about 1902. Reproduced from Wikipedia.

for the spiritual dimensions of nature makes him one of the most widely read and admired environmentalists of all time (Figure 7.1.1). This sense of spiritual ecology was an inspiration for him in forming the Sierra Club, which has become the largest environmental group in the United States.

7.2 Religion and Ecology: Academic Field and Moral Force

Our attitudes toward nature have been consciously and unconsciously conditioned by our religious worldviews. Over 50 years ago the UCLA historian Lynn White Jr. observed this when he noted: "What people do about their ecology depends on what they think about themselves in relation to things around them. Human ecology is deeply conditioned by beliefs about our nature and destiny—that is, by religion." White's 1967 article in *Science* marked a watershed in contemporary reflection on how environmental attitudes are shaped by religious worldviews. He critiques Christianity for losing a sense of the sacredness of nature by banishing animism and elevating humans above nonhumans. He cites the Genesis passage (1:26) in which God gives humans dominion over nature and other species. Such dominion, he observes, led to overexploitation of the natural world and to **anthropocentrism**, or human-centered approaches to ethics and daily life. White calls for making St. Francis a patron saint of ecology for his love of nature and his kinship with all species, such as birds and wolves.

Christian theologians pushed back against White's argument and began to develop forms of **eco-theology**, which emphasizes environmental ethics, stewardship, and creation care. Claremont theologian John Cobb helped to lead the way, publishing a book titled *Is It Too Late? A Theology of Ecology* in 1972. Among his many writings is a book with economist Herman Daly, *For the Common Good: Redirecting the Economy Toward Community, the Environment, and a Sustainable Future*. Theologians such as Rosemary Ruether, Sallie McFague, and Catherine Keller took up **ecofeminism**, which links the exploitation of the Earth to the degrading treatment of women. These ecofeminist theologians called for a new understanding of the Earth as sacred, indeed as God's body.

In the last two decades, other religious traditions were drawn into the search for a broader environmental ethics. Indeed, through the work of hundreds of scholars and theologians, a new field of religion

and ecology has emerged within academia. Its rapid growth has been nothing less than remarkable, and its potential to affect change is significant because of the institutional dimensions of the world's religions, which engage 85% of the world's people. This field has undertaken serious reflection on views of nature from the different world religions. For example, John Grim and I organized a 3-year research project of ten conferences at the Harvard Center for the Study of World Religions (1996–1998), resulting in ten edited volumes. The project culminated in two conferences in 1998 in New York at the United Nations and the American Museum of Natural History, attended by over 1,000 people. The Forum on Religion and Ecology was born from these conferences, and we now direct it at Yale University.

The assumption of the Harvard research project was that environmental attitudes and ethics are predominantly shaped by religious and cultural contexts. These are vastly different in China and India than in the West. Indeed, our initial impetus was in large measure to highlight the traditions of China and India, knowing that their rapid development and industrialization would change the face of the planet—as it is already doing. It was also important that we raise up the voices of Indigenous peoples in a conference and a volume. Our conviction was that understanding these varied cultural values and religious ethics will contribute to environmental solutions that include both humans and nature.

That is what the Forum on Religion and Ecology set out to do, beginning with a group of some 800 scholars and environmentalists. We now have a network and email list of some 12,000 people. We have also created a comprehensive website where we have collected the statements of many of the world's religions and annotated the literature published in English on this topic: http://fore.yale.edu. One of our early projects was an issue of the academic journal *Daedalus*, titled "Religion and Ecology: Can the Climate Change?" (2001), which arose out of two conferences at Harvard. Our Forum website highlights various statements on climate change and grassroots projects to address it by the world's religions.

The academic field of religion and ecology makes a number of assumptions, including these:

- Religion and ecology is a newly emerging academic field not more than 20 years old; environmental ethics, on the other hand, coming

out of Western philosophy, is 40 years old. Scholars of religion and theologians have a great deal of work still to do.

- Religious and ethical perspectives have only recently been invited into the arena of "sustainability sciences" and sustainability forums, which are arenas within academia and, beyond that, are trying to respond to climate change and other environmental problems.
- While academia is somewhat comfortable with environmental ethics arising out of Western philosophy, it is perplexed by, or adverse to, the study of religion in universities. This is because it confuses religious studies and history of religions with theology that has been largely carried out within a framework of Christian confessional assumptions, beliefs, and practices.
- Religious studies and the history of religions are not theology. They are the study of the unfolding of various religious traditions, including changes and continuities over time. These studies are more indebted to history and the social sciences (especially the study of culture and anthropology) than theology, which has developed primarily at Christian seminaries. The history of religions identifies ethics within the context of world religions and cultures, not simply within a Western Christian framework. Until recently, Christian ethics has focused primarily on social ethics, not environmental ethics. But important contributions are now being made in this arena.
- As scholars, we do not assume that religions are unproblematic entities. We recognize the havoc they have caused, historically and at present. However, we are suggesting that they are necessary, although not sufficient, partners in seeking environmental solutions. Religions need to be in dialogue with science, policy, and economics. We hope this interdisciplinary dialogue gains further traction through efforts such as this book and course.

7.3 The Promise and Problem of Religions

The problems and promise of religions should be clearly identified (Table 7.3.1). Those in the field of religious studies, in positions of religious leadership, in religious communities, or in divinity schools also need humility to enter the environment and climate field. Important work in these areas has been going on for decades without us.

Religions are indeed late, but their contributions may be indispensable for realizing a sustainable future for the planet. That is our challenge in the years ahead: to contribute to a moral awakening regarding the planetary emergency that faces us. Religions must develop an ethics that not only deals with moral issues among humans, such as homicide or suicide, but also imagines ethical relations with nonhumans and moral responses to biocide or ecocide.

TABLE 7.3.1 A summary of some of the key problems with and promises of religions

	Problems	*Promises*
1.	Rigid, dogmatic	Flexible
	Bound by tradition	Changing over time
	Afraid of modernity	Embracing modernity
2.	Exclusive claims to truth	Broad moral reach
	Looking inward to orthodoxy	Looking outward to practice
3.	Otherworldly concerns	Valuing this world
	Salvation in heaven	Creation-centered spirituality
4.	Hierarchical, patriarchal	Equity, fairness, justice
5.	Present sectarian concerns	Future generational concerns
	Preserving church membership	Supporting the full community of life
6.	Human rights	Rights of nature or creation
7.	Anthropocentric	Anthropocosmic

7.4 Engaging Religions: Toward Economic and Ecological Flourishing

Despite the problems with religion, there is great promise in a partnership between religion and science around climate change. This is vital because we need to encourage a new sense of progress, one that is concerned not just with economic growth, but with the genuine flourishing of the Earth community. The world's religions may offer some ethical norms for enhancing this larger flourishing of life. For example, this is the work of the Interfaith Center on Corporate Responsibility, which urges businesses toward social and environmentally responsible investment and models this in the investment portfolios of religious congregations. To approach investing this way, shareholders have to consider the long term and future generations—that is, broader interests beyond weekly stock market indices and quarterly financial reports.

Such ways of thinking involve enhancing the quality of life, not the quantity of material possessions. In this framework, economic progress should be measured not by a nation's gross national product (GNP), but rather by gross national happiness (GNH) indicators such as those the government of Bhutan has developed. Based on Buddhist principles of right livelihood and well-being, GNH is part of the Bhutanese constitution and is implemented by a GNH Commission (Figure 7.4.1). Religions can assist in such endeavors, as they are well equipped to point toward more lasting values and sources of deeper happiness. They understand the efficacy of long-term thinking and have been attending to this for centuries. Religious communities are active in the fossil fuel divestment movement, and some, such as the United Church of Christ, have led the way. Union Theological Seminary in New York, the Pacific School of Religion in Berkeley, and the Jesuit-based Seattle University have all divested from fossil fuels.

Many religious communities are concerned about the long-term common good and the ecological flourishing of the Earth community—land,

FIGURE 7.4.1 The Paro Taktsang, or Tiger's Nest, a Buddhist monastery built in 1692 on a sheer cliff at an elevation of 10,000 feet, expresses the spiritual values to which Bhutan's gross national happiness (GNH) measures also attest. Photograph by Baron Reznik via Flickr.

FIGURE 7.4.2 Hassan II Mosque, Casablanca, Morocco, is part of the country's effort to green its mosques. Reproduced from Milamber via Flickr.

water, air, soil, and all species, human and more-than-human. They aim to uphold the wonder, beauty, and complexity of nature for present and future generations. This sense of wonder is shared by religion and science and can help reorient our lives by grounding us in gratitude. Life is an extraordinary unfolding process of which we are a small but indispensable part.

Our essential ethical question, then, is What does the ecological flourishing of the Earth community require in the face of climate change? World religions need to develop a moral framework for responding to climate change that allows for common but differentiated responsibilities. The developed world has different responsibilities from the developing world, and yet we must all work together to create the basis for a shared and vibrant future.

I am suggesting that ethical responses to environmental issues such as climate change involve reimagining human-Earth relations on a scale

that is locally differentiated, culturally sensitive, ethically grounded, and globally attuned. An awareness of place-based local concerns is indispensable, as is sensitivity to particular cultures and religions. From this basis an ethics can emerge that is grounded in place and culture, but also globally aware.

Box 7.4.1 Greening Mosques

Morocco has undertaken a project to green its 15,000 mosques, starting with 600 by 2019 (Figure 7.4.2). Through a partnership with Germany's international development agency, GIZ, the Moroccan government aims to make mosques and other buildings more energy efficient and increase their use of renewable energy, particularly solar power. The project's other key goals include raising public awareness about renewable energy, creating new jobs, and training people to fill such jobs.

7.5 *Journey of the Universe*: A Shared Evolutionary Story

Our biggest challenge to realizing this broader perspective in the United States and some other Western-influenced societies is hyper-individualism and an elevation of personal liberties over a sense of the common good. The unanswered question is how to move from a narrow devotion to individual rights toward embracing a larger sense of responsibility for the flourishing of life. We need to articulate and imagine a common well-being that is not hegemonic or totalizing, but inviting, energizing, inclusive, and participatory.

Journey of the Universe has this possibility of bringing humans together

FIGURE 7.5.1 An anthropocosmic worldview puts humans within a broader cosmos, not at its center. Still from the film *Journey of the Universe*.

Box 7.5.1 *Journey of the Universe*

Journey of the Universe narrates the 14-billion-year story of the universe's development, from the great flaring forth at the universe's inception to the emergence of simple molecules and atoms to the evolution of galaxies, stars, solar systems, and planetary life of greater complexity and consciousness. This is a story that inspires wonder as we begin to understand such complexity through science and appreciate such beauty through poetry, art, history, philosophy, and religion.

Journey of the Universe is a cosmology, although not just in the scientific sense of the study of the early universe. Rather, it is a cosmology in the sense of being an integrated story that explains where both humans and other lifeforms have come from. All cultures have had such stories. We now have the capacity to tell a comprehensive story drawing on astronomy and physics to explain the emergence of galaxies and stars, geology and chemistry to understand the formation of Earth, biology and botany to envision life's evolution, and anthropology and the humanities to trace the rise of humans.

Journey draws on all these disciplines to narrate a story of universe, Earth, and human evolution that is widely accessible and allows for a comprehensive sense of mystery and awe to arise. This is in alignment with the call of the environmental ethicist J. Baird Callicott to "reintegrate science and its epistemology into the wider culture by expressing the new nature of Nature as revealed by the sciences, in the grammar of the humanities." Such an approach expands the human perspective beyond an anthropocentric worldview to one that values life's complexity and sees the role of humans as critical to the further flourishing of the Earth community. While humans are gifted with the creativity of symbolic consciousness, we know that different kinds of self-organizing creativity abound in the universe and Earth—the formation of galaxies and stars, the movement of tectonic plates, the chemistry of cells, the biological complexity of photosynthesis, the migrating patterns of birds, fishes, turtles, and caribou. Creativity is also closely aligned with chaos and destruction as the universe unfolds on the edge of a knife.

Such a cosmological perspective is both ancient and modern—embedded in certain aspects of world philosophies and religions and revealed anew in the scientific story of the universe. Thus science along with philosophy and religion help us to recognize ourselves as participating in a larger integrated whole. In this spirit, images and metaphors from the wisdom traditions of the world religions and philosophies are woven into *Journey of the Universe*.

in a shared evolutionary story that respects differences. *Journey* is a multimedia project created over 10 years by Brian Thomas Swimme, John Grim, and me; it consists of an Emmy award–winning film, a book from Yale, a series of 20 conversations with scientists and environmentalists, and online courses. This project acknowledges that we humans are part of a vast unfolding universe, dwelling in a living Earth community, and ideally contributing to its continuity. *Journey* embraces an **anthropocosmic worldview** in which humans are seen as belonging to and dwelling within the cosmos and the Earth (Figure 7.5.1). It begins with the "great flaring forth" 14 billion years ago and traces the emergence of Earth, of life, and of humans. It concludes with our current ecological challenges.

Journey of the Universe thus weaves together scientific discoveries in astronomy, geology, and biology with humanistic insights concerning the nature of the universe. It is in the lineage of Thomas Berry's call for a "New Story." Berry felt we needed to bring science and the humanities together in an integrated cosmology that would guide humans into the next period of the flourishing of human-Earth relations. This perspective affirms that "the universe is a communion of subjects, not a collection of objects," as Thomas Berry often observed.

7.6 Principles, Strategies, and Tactics

Here are some suggestions, then, of principles, strategies, and tactics that the world's religions and environmental ethicists could promote toward the flourishing of people and planet in the face of rapid and relentless climate change. This section is adapted from an article I wrote in *Zygon* in 2015. First I explain two foundational principles—valuing nature and honoring humans. Then I explore two key strategies—thinking consequentially and integrating solutions. Finally I examine two interrelated tactics—restraint and law.

First foundational principle: valuing nature as source, not resource

Intrinsic value of nature We are moving from viewing nature simply as a resource for our own use to seeing it as the source of life and creativity. Instead of valuing nature from a utilitarian perspective, we are learning to appreciate it for its intrinsic beauty and complexity. As *Journey of the Universe* makes evident, Earth is a source of dynamic change and transformation, bringing forth life over billions of years of evolution. Participating in the flourishing of life's creativity is a major fulfillment of human destiny. Destroying that creativity is diminishing the possibility for life's continuity, as Thomas Berry noted in *The Dream of the Earth*.

Environmental degradation as an ethical issue Until recently environmental degradation was seen as an inevitable consequence of economic growth and industrial progress. This view is being called into question in many circles, especially those of ecological economists. To stem the tide of destruction will require a new economics and the extension of ethical concerns to nature as a whole and to individual species in particular. The role of humans in causing climate change through greenhouse gases

FIGURE 7.6.1 This photo shows the extraction of oil from the tar sands in Alberta, Canada, in 2008. Reproduced from Howl Arts Collective via Flickr.

is finally being acknowledged as ethically problematic. Our emissions (especially in developed countries) have adversely affected ecosystems, caused biodiversity loss, contributed to species extinction, and affected millions of people around the globe. There have been moral responses to this by the US Catholic Bishops in 2001 and the Canadian Conference of Catholic Bishops in 2006. Canadian Bishop Luc Bouchard's pastoral letter in 2009 is a unique example of a powerful critique of the problems caused by the extraction of oil in the tar sands in Alberta (Figure 7.6.1).

Many other bishops' conferences around the world have issued statements on the environment and climate change, calling for care for the poor and vulnerable, noting the need for a change in lifestyle among the wealthy, and holding corporations responsible for despoiling the

Earth. Pope Francis refers to several of these documents in his landmark encyclical on the environment, *Laudato Si'*, issued in 2015.

Second foundational principle: honoring humans—our rights and responsibilities

Environmental rights: present and future generations It is necessary to expand the notion of human rights to include environmental rights to a healthy atmosphere and biosphere for present and future generations. To do this, we need to consider the rights to information, public participation, and justice regarding environmental issues. This

Box 7.6.1 From a Pastoral Letter on Fossil Fuel Extraction as a Moral Problem

In 2009, Bishop Luc Bouchard of Alberta, Canada, issued a pastoral letter, The Integrity of Creation & the Athabasca Oilsands. *Here is an excerpt from his letter:*

The moral problem does not lie in government and industry's lack of a sincere desire to find a solution; the moral problem lies in their racing ahead and aggressively expanding the oilsands industry despite the fact that serious environmental problems remain unsolved after more than forty years of on-going research. The moral question has been left to market forces and self-regulation to resolve when what is urgently required is moral vision and leadership.

I am forced to conclude that the integrity of creation in the Athabasca oilsands is clearly being sacrificed for economic gain. The proposed future development of the oilsands constitutes a serious moral problem.

Environmentalists and members of First Nations and Metis communities who are challenging government and industry to adequately safeguard the air, water and boreal forest eco-systems of the Athabasca oilsands region present a very strong moral argument, which I support.

The present pace and scale of development in the Athabasca oilsands cannot be morally justified. Active steps to alleviate this environmental damage must be undertaken.

FIGURE 7.6.2 ***(above left)*** **In India, the Yamuna River is considered sacred.** Reproduced from Melenama via Flickr.

FIGURE 7.6.3 ***(above right)*** **But the Yamuna River is also polluted with sewage and trash. This view of the Yamuna River at Agra was taken in 2008 during a trash cleanup event.** Reproduced from India Water Portal via Flickr.

FIGURE 7.6.4 ***(right)*** **The Ganges is also both sacred and polluted. In this 2013 photo, pilgrims' offerings of flowers and coconuts float together with plastic trash on the surface of the river.** Photograph by Massimiliano Sticca via Flickr.

was set forth in the Aarhaus Convention in 1994, which called for access to information, participation in decision-making, and access to justice in environmental issues. But clearly those families and individuals who are exposed to pollution from petrochemical and coal power plants and those who are affected by mountaintop removal mining were never given information to ensure their health and safety or to guarantee their environmental rights. Faith-based religious initiatives in Appalachia, in Flint, Michigan, in Baltimore, and in Mississippi are trying to help such communities by calling for creation care and for environmental justice. Moreover, a landmark climate lawsuit, *Juliana v. United States*, brought by 21 young people from across the United States, is making its way through federal court. The suit alleges that the US government, through actions that cause climate change, has violated young people's constitutional rights to life, liberty, and property.

Box 7.6.2 Legal Personhood for Sacred Rivers

In India, a legal case on the rights of rivers suggests that new forms of Earth jurisprudence are emerging that are expanding the moral compass of the law to include nature and a sense of the sacred. Legal rights are often granted to entities and organizations that are not human individuals; in the United States, for example, corporations are considered legal persons. But recently, some nations, such as Bolivia, Ecuador, Australia, and New Zealand, have begun granting nature in general or specific natural entities legal personhood.

The state of Uttarakhand, India, contains part of the Himalayas and the headwaters of the Ganges River. In 2017, a high court there ruled that "the Rivers Ganga and Yamuna, all their tributaries, streams, every natural water flowing with flow continuously or intermittently of these rivers, are declared as juristic/legal persons/living entities having the status of a legal person with all corresponding rights, duties and liabilities of a living person." The court based its decision in part on the fact that these rivers are "sacred and revered . . . central to the existence of half the Indian population." Because environmental damage threatens "their very existence . . . [this] requires extraordinary measures to be taken to preserve and conserve Rivers Ganga and Yamuna" (Figures 7.6.2, 7.6.3, and 7.6.4).

The court's decision established the rivers as legal persons but as minors under the law, thereby recognizing that the rivers cannot speak for themselves. The court also designated specific positions in the Uttarakhand state government to act for the rivers. Though the ruling has been appealed and is still working its way through the courts, it shows not only how legal thought about the rights of nature is beginning to change, but also that religion and the sacredness of particular natural entities are central to that shift.

In 2011 the Forum on Religion and Ecology along with TERI University in Delhi and the Radha Raman temple in Vrindavan sponsored a conference in India titled Yamuna River: A Confluence of Waters, A Crisis of Need. It brought together scientists, hydrologists, political scientists, religious leaders, and scholars to find ways to meet the difficult challenges of pollution of this sacred river: fore.yale.edu/yamuna-river-conference/. The conference highlighted how climate change affects rivers in a variety of ways, including higher temperatures causing algae blooms and fish kills as well as unpredictable patterns of drought and flooding.

Environmental responsibilities: distributive justice With environmental rights come moral responsibilities toward those most vulnerable to the effects of climate change, such as the millions of impoverished people in the coastal region of Bangladesh, the thousands of African Americans in New Orleans after Hurricane Katrina, and those in Darfur and Syria suffering from climate-related drought and subsequent famine. The concept of distributive justice clearly requires further reflection regarding our moral obligation to people at a distance in space (in other countries) and time (in future generations).

As the oceans rise and their countries become endangered, the Alliance of Small Island States in the United Nations is considering suing developed countries for causing this catastrophe. Their citizens are becoming climate refugees; the population of Tuvalu is being relocated to New Zealand. Indigenous peoples in the Torres Strait of Australia have sued the government on the basis that climate change is threatening their traditional culture and religion. How many hundreds of thousands of people will have to be relocated from islands and coastal regions where most of the world's largest cities are located and a quarter of the world's population lives? Jakarta, a sinking city of over 10 million people on the world's most populous island, is already making plans to evacuate and move.

Many religious leaders are now speaking out on the need for climate justice, especially for the poor and vulnerable most affected by climate change. Rabbi Arthur Waskow of the Shalom Center in Philadelphia and Reverend Dr. Gerald Durley of Providence Missionary Baptist Church are leaders here, while United Church of Christ minister Jim Antal and Episcopal priest Margaret Bullitt-Jonas have written books on the topic (Figure 7.6.5). The Evangelical Environmental Network is also working on climate justice. A leading evangelical scientist, Katherine Hayhoe, has been speaking out on the importance of understanding the science and responding to our growing climate crisis.

First key strategy: thinking consequentially, short term and long term

Precautionary principle In his 1971 book *The Closing Circle*, biologist Barry Commoner made the commonsensical point that we ought to

FIGURE 7.6.5 Rev. Dr. Gerald L. Durley, Rev. Margaret Bullitt-Jonas, and Rev. Dr. Jim Antal. Photograph by Robert A. Jonas. Reproduced with permission.

stop pollution at its source. This can be seen as an early iteration of the precautionary principle or principle of prudence. We should invoke this principle as a means of stemming climate change. We need to suggest that rather than argue about some of the details of the science or ask for further studies, the precautionary principle requires us to act now. Future generations and the future of life depend on various kinds of preventive action. Cap-and-trade or a carbon tax are no doubt necessary economic incentives for change, but we need to develop a deeper sensibility regarding cutting back emissions at the source and seeing this as a moral responsibility. The Keep it in the Ground movement, for example, maintains that a viable ethical position is restraint in extracting fossil fuels in the first place.

Unintended consequences We must not only reduce emissions now, but also consider the long-term effects of our decisions. We know we are already compromising the quality of life for many people—including our children and grandchildren. The consequences of our actions, intentional and unintentional, need to become more visible. This is especially

Box 7.6.3 Responding to Climate Change Locally

Religious communities in many parts of the world are responding to the particular challenges climate change is bringing to their area. For example, the Higher Ground Initiative of Temple Solel, a Jewish synagogue in Hollywood, Florida, is confronting the problem of rising seas. Members of the synagogue educated themselves on sea level rise, investigated local areas that flood during very high spring tides called king tides, took action to bring attention to the issue, made efforts to reduce their synagogue's carbon footprint, and expanded their initiative to other Reform Jewish congregations.

There are many ways to take action on climate change. If you're involved in a religious community, find out if it has a climate change committee; if not, see if you can start one. Here are some resources to draw on:

- Interfaith Power and Light (IPL) leads religious communities' efforts to improve energy efficiency and conservation in the United States. IPL has worked for two decades to establish branches in over 40 states and focuses on several areas, including the reduction of carbon footprint in places of worship, educating congregants, environmental justice for the poor, liturgical renewal to include the environment, and work for policy changes in national and local governments: https://www.interfaithpowerandlight.org.
- The Shalom Center, based in Philadelphia, leads many Jewish environmental efforts: https://theshalomcenter.org.
- Eco-Justice Ministries works with a range of Christian denominations in the United States on greening churches, taking action on climate change, and transformational ministry: www.eco-justice.org.
- Earth Ministry undertakes "faithful advocacy" on environmental issues in Washington state, where the organization is based, as well as on climate change: https://earthministry.org.
- Green the Church leads African American Christian churches to become more sustainable, develop green theology, and advocate for political change: greenthechurch.org/.
- GreenFaith is an interfaith coalition for the environment that works with houses of worship, religious schools, and people of all faiths to help them become better environmental stewards: https://greenfaith.org.
- Interreligious Eco-Justice Network has been working on the intersection of ecological understanding and social justice for many years, focusing on key issues such as climate change and pollution: irejn.org.

true as the unintended outcomes of various proposed solutions to climate change are becoming evident. For example, geoengineering schemes, such as seeding the oceans with iron to increase phytoplankton and draw down carbon, may inadvertently disrupt the food web. A 2019 white paper by Gary Gardner and Forrest Clingerman highlights religious responses from Judaism, Christianity, Islam, Hinduism, and Buddhism to geoengineering. This report recognizes that many people feel geoengineering may be necessary to halt climate change, but they call for precaution in light of the unknown consequences of these procedures. This is an example of religions contributing an ethics of long-term thinking about the health and well-being of future generations beyond uncertain "technological fixes."

Second key strategy: integrating solutions—energy and technology

Renewable energy The development of safe renewable energies is of utmost importance as we shift from fossil fuels to energy from the sun, wind, water, and geothermal power. Indeed, many are suggesting we are in the midst of an energy revolution. While we have much of the technology to make this change, this shift needs to be scaled up so that it can be done without adversely affecting those most vulnerable. This will require making renewable energy economically viable and thus providing economic incentives and investing in more research and development. The shift from nonrenewable and polluting energy sources, such as coal and oil, to renewables is one of the largest transformations in human history, and is now a moral imperative. Fracking for natural gas is harming our ecosystems, polluting our waters, and causing social disruptions in the United States and around the world. Several European countries have outlawed fracking on environmental grounds.

Many religious communities, especially Native Americans in the United States and First Nations peoples in Canada, have rallied to stop pipelines, often joined by other religious communities. The most prominent example is the Lakota Sioux at Standing Rock in North Dakota and their many allies who tried to prevent a pipeline from passing under the Missouri River next to their reservation. This is an example of a precautionary principle being invoked to prevent pollution before it happens.

FIGURE 7.6.6 Stand with Standing Rock, November 14, 2016. Photograph by Leslie Peterson via Flickr.

The Lakota drew on their traditional belief that "water is life" and must not be put at risk of pollution. Native Americans and other Indigenous peoples embrace a cosmovision that considers all of life sacred, including the elements of earth, air, fire, and water (Figure 7.6.6). Humans are seen as kin to all other species who dwell in the living Earth community.

Technology transfer and efficiency Along with the large-scale move to renewable energy is an obligation to transfer appropriate technology to developing countries to assist with climate change mitigation and adaptation. As we improve alternative energy and green technology in the United States and the developed world, how can we find the economic means and political will to transfer this knowledge to developing countries? This is a justice issue, not simply an economic issue, as the developing world by and large does not have the capital to create or invest in these technologies without assistance. Large-scale funds need

FIGURE 7.6.7 Raising livestock on a large scale in factory farms like this one contributes to climate change—both because pigs and cows emit methane and because rain forests are destroyed to grow crops to feed these animals. Reproduced from Wikimedia Commons.

to be set aside to allow this to happen. Such help has been promised in the past but not delivered.

First tactic: ensuring restraint—curbing consumption and population

Consumption and affluence A key justice issue is that of overconsumption and the high levels of affluence in the developed world as factors that contribute to climate disruption. How can lifestyle change (using and consuming less) be seen as a moral issue? This will involve reexamining our carbon footprint, our building patterns, our transportation systems, our development plans, our clothing manufacturing, and most especially our agricultural processes, which depend on fossil fuels. The factory farming of animals and the destruction of rain forests to raise crops to feed animals is contributing to climate change (Figure 7.6.7). Many religious communities are suggesting that eating less meat will help reduce greenhouse gases. See, for example, CreatureKind: www.becreaturekind.org.

Population growth How can the difficult topic of population growth be raised as a moral issue in relation to global warming? The planet

clearly has limits to what it can support. By exploding from 2 billion to 7 billion people in one century, we have caused massive disruptions to Earth's ecosystems and natural cycles. While China adopted a national policy to control population, this still remains controversial in some quarters. However, as UN agencies have observed, educating women for jobs and empowering women by providing birth control and reproductive health care are assured means of population reduction. These need to be seen as moral rights that will ensure that children are wanted, nourished, educated, and cared for. We cannot avoid focusing on this issue in conjunction with consumption, for a person in the developed world will consume considerably more than a person in the developing world. Again, invoking the principles of justice and equity is critical.

Second tactic: creating law—global governance and global ethics

Global governance To be able to draft and enforce binding treaties on climate change, we need to ensure democratic participation, accountability, and transparency. This requires the development of a new stage of global governance that will be bound by international law and enforced by institutions such as the World Court and the United Nations. While we are a long way from such global governance, the foundations of such a system are being established. This is sorely needed as environmental problems such as climate change transcend national boundaries and thus call for international cooperation that is binding, both legally and ethically.

Global ethics The Earth Charter, a comprehensive global ethics document, was initiated by Mikhail Gorbachev and Maurice Strong, who chaired the UN Conference on Environment and Development (UNCED) held in Rio de Janeiro in 1992. They felt that an ethical document of principles was needed to adjudicate the contentious issues of environmental protection and economic development. An Earth Charter drafting committee was established with a broad spectrum of representatives; Earth Charter commissioners, prominent global citizens, were named from every continent; and an Earth Charter Initiative Secretariat was established at the University for Peace in Costa Rica. The Charter was

Box 7.6.4 From the Earth Charter

We stand at a critical moment in Earth's history, a time when humanity must choose its future. As the world becomes increasingly interdependent and fragile, the future at once holds great peril and great promise. To move forward we must recognize that in the midst of a magnificent diversity of cultures and life forms we are one human family and one Earth community with a common destiny. We must join together to bring forth a sustainable global society founded on respect for nature, universal human rights, economic justice, and a culture of peace. Towards this end, it is imperative that we, the peoples of Earth, declare our responsibility to one another, to the greater community of life, and to future generations.

drafted in the decade following the Earth Summit in 1992 and released at the Hague in 2000 with the assistance of the Dutch government. I was a member of the drafting committee of 25 people from around the world, representing key sectors such as politics, economics, education, and religion. The committee included a wide range of nationalities, of women, and of nongovernmental organizations.

Our question here is, How can the Earth Charter contribute to a more comprehensive ethical framework for envisioning solutions to climate change? The three sections of the Charter can be used as a context for refining moral responses to climate change. These sections include valuing (1) ecological integrity, (2) social and economic justice, and (3) democracy, nonviolence, and peace. This integrated framework of principles is critical to encouraging moral responses that are comprehensive enough to address the global nature of climate change and also to establish the conditions for the flourishing of local communities.

In addition, the 2010 Universal Declaration of the Rights of Mother Earth was drafted by Indigenous peoples at a gathering in Cochabamba, Bolivia. They contend that their rights and nature's rights have been violated in many parts of the world. The rights-based approach to nature may gain some traction in circles that hope to force action on climate change and other environmental issues. It may also be resisted by those who are hesitant to grant nature rights but nonetheless wish to address

climate disruption and the degradation of nature. It is increasingly clear, however, that a new Earth jurisprudence is needed. This is what Thomas Berry called for in a statement drafted as early as 2001 that was published in *Evening Thoughts*.

In this moment of great transition, science and religion need to work together as never before for the flourishing of the Earth community. Moral voices must respond to the "Cry of the Earth, the Cry of the Poor," as does the Papal Encyclical *Laudato Si'*. While the challenges are great, the call to create the foundations for an integral ecology, including respect for both people and the planet, is growing. As Pope Francis writes:

> The urgent challenge to protect our common home includes a concern to bring the whole human family together to seek a sustainable and integral development, for we know that things can change. . . . Humanity still has the ability to work together in building our common home. (*Laudato Si'*, Introduction, 13)

Supplementary Readings

Books and Articles on Climate Change, Religion, and Ecology

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Statements on Climate Change from the World's Religions

http://fore.yale.edu/climate-change/statements-from-world-religions/

Ecology and Justice Series from Orbis Books

https://www.orbisbooks.com/category-202/

Indigenous Environmental Network

http://www.ienearth.org

Journey of the Universe

Film, book, conversations: https://www.journeyoftheuniverse.org.

Massive Open Online Classes (MOOCs): https://www.coursera.org/specializations/journey-of-the-universe.

United Nations Environment Programme

Earth and Faith: A Book of Reflection for Action: https://wedocs.unep.org/bitstream/handle/20.500.11822/25988/Earth%20and%20Faith.pdf?sequence=1&isAllowed=y

Faith for Earth Initiative: https://www.unenvironment.org/about-un-environment/faith-earth-initiative.

Interfaith Rainforest Initiative: https://www.interfaithrainforest.org.

Interreligious Programs and Websites on Religion and Ecology

Blessed Tomorrow: https://blessedtomorrow.org.

Earth Ministry in Seattle: https://earthministry.org.

Faith in Place in Chicago: https://www.faithinplace.org.

Forum on Religion and Ecology at Yale: http://fore.yale.edu.

GreenFaith: https://greenfaith.org.

Interfaith Center on Corporate Responsibility: https://www.iccr.org.

Interfaith Power and Light: https://www.interfaithpowerandlight.org.

Interreligious Eco-Justice Network: https://irejn.org.

Parliament of the World's Religions Climate Commitments Project: https://parliamentofreligions.org/project-home/climate-commitments-project.

Denominational Websites on Climate Change

Catholic Climate Covenant: https://catholicclimatecovenant.org.

Evangelical Environmental Network: https://www.creationcare.org.

Franciscan Action Network: https://franciscanaction.org.

Global Catholic Climate Movement: https://catholicclimatemovement.global.

The Shalom Center: https://theshalomcenter.org.

Educational Programs in Religion and Ecology

Center for Earth Ethics at Union Theological Seminary: https://centerforearthethics.org.

Green Seminary Initiative: https://www.greenseminaries.org.

Yale Climate Connections: Faith & Ethics: http://www.yaleclimateconnections.org/topic/faith-ethics/.

Yale Divinity School MAR in Religion and Ecology: https://divinity.yale.edu/academics/degree-and-certificate-requirements/concentrated-master-arts-religion-mar/religion-and-ecology.

Yale School of Forestry and Environmental Studies and Yale Divinity School Joint MA in Religion and Ecology: http://fore.yale.edu/yale-ma/.

Climate Change Communications

Center for Climate Change Communications at George Mason University: http://www.climatechangecommunication.org.

Yale Center for Climate Change Communication: http://climatecommunication.yale.edu.

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7.1 Science and Religion: A New Alliance Needed

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CHAPTER 8

Communicating Climate Change Science

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Learning Objectives

1. Be able to list at least four terms that have different meanings for scientists and the public and provide a better choice for each of them.
2. Be able to explain at least four important scientific findings that illustrate our understanding of recently observed and predicted climate change.
3. Be able to describe for nonscientists at least four kinds of observational evidence that show that the global climate has recently experienced warming.
4. Be able to use stories, metaphors, and vivid language effectively to help explain the importance of addressing climate change.
5. Be able to have constructive and civil conversations about climate change with people who do not accept the fundamental findings of climate change science.

Overview

This chapter is divided into five sections, which can be thought of as five important steps on the path to becoming a skillful and effective communicator of climate change science:

8.1. Preparation—Preparing well is the first step to communicating well. Preparation includes knowing general principles of communication and having access to valuable resources. It also includes acquiring an adequate knowledge of the science of climate change.

8.2. Stories—Stories are a wonderful way to engage an audience. In this section, you will meet "Uncle Pete," a fictional character closely based on fact. Uncle Pete does not accept climate change science. Many people know a real person who strongly resembles Uncle Pete.

8.3. Metaphors—Metaphors and comparisons can be superb communication tools. In communicating the science of climate change,

powerful metaphors compare climate science with medical science and call carbon dioxide the steroids of our climate.

8.4. Language—Language is a critical aspect of communication. It is very important to match the language that you use to the audience you want to reach. Try to avoid depressing language and scientific jargon, and know the tricky words that have more than one meaning.

8.5. Solutions—Nobody wants to feel helpless. People should know the reasons for optimism. We have the tools to prevent the worst kinds of climate change. We urgently need to act.

8.1 Preparation

Preparing well is the first step to communicating well. Preparation includes knowing general principles of communication and having access to valuable resources. It also includes acquiring an adequate knowledge of the science of climate change.

Susan Joy Hassol is a communication expert who for more than 25 years has been my partner in communicating climate change science. The website https://www.climatecommunication.org contains detailed information about the key lessons we have learned. This is a website I strongly recommend to you. It is a rich resource for information on communicating climate change science. Here in 12 words is the guiding philosophy that underlies our approach to climate science communication: *Use simple clear messages, repeated often, by a variety of trusted messengers*.

Many people, when attempting to communicate complex subjects, typically fail to craft simple, clear messages and repeat them often. Instead, they overdo the level of detail, so people have difficulty sorting out what is most important. In short, the more you say, the less they hear. Climate scientists often fall into this trap when trying to explain what they have learned to the broad public. They know a lot, so they want to say a lot. That's a mistake. Think about the experts in various fields whom you may know, such as your doctor. He or she has spent many years learning a great deal about medical science, but only a very foolish doctor would try to tell you everything relevant to your health that medical science has discovered. Instead, a wise doctor speaks to you in simple clear terms.

I think that those who have studied this subject most seriously and carefully have now awakened to the complex challenges of communicating about climate change, when much more than the science is at issue. Our awareness now includes cultural and psychological issues.

FIGURE 8.1.1 Richard C. J. Somerville and the Dalai Lama speaking about climate change to a large audience on April 18, 2012, at UC San Diego. Reproduced with permission from Sylvia Bal Somerville.

Still, most people say they need more information about the science, so scientists and others are challenged to deliver scientific information in more accessible and effective ways. Much of what I summarize in this short chapter is based on the resources available on the website https://www.climatecommunication.org. This chapter reflects the ideas and recommendations on that website for combining accurate science with effective techniques for communicating with the public.

Trusted messengers can have an enormous impact and can motivate people to bring about change. Think of Mahatma Gandhi, or Nelson Mandela, or Martin Luther King Jr. Sharing a stage with colleagues at my university, UC San Diego, a few years ago in front of thousands of students, discussing climate change with the Dalai Lama, was a privilege for me and a memorable day in my life. You don't have to be a Tibetan Buddhist to understand that the Dalai Lama is respected and revered worldwide. When he speaks, millions listen. The Dalai Lama is an excellent example of a trusted messenger whose statements about climate change can profoundly affect public opinion worldwide. He and I are shown in Figure 8.1.1.

Some messengers have strong credibility with specific groups of people. For example, professor Katherine Hayhoe is a climate scientist who is also an evangelical Christian, and she is an especially effective communicator to her co-religionists because they share her convictions and values. The idea that humans should be faithful stewards of God's gift of a beautiful and valuable planet Earth to humankind—which is at

heart a moral and ethical concept—resonates with many evangelical Christians.

Climate change is much more than a scientific topic. I am convinced that confronting climate change is fundamentally a moral and ethical issue. It involves considerations of intergenerational equity. What do we owe to people who will come after us? Speaking as just one citizen of the Earth, I suggest that, at a minimum, we owe our descendants a planet that is as undamaged as the one we inherited from previous generations. It's also a matter of North-South equity. What do we in the rich nations owe to the billions of people now alive who do not yet enjoy what we would consider a bare minimum of rights and privileges? These include adequate food, access to clean water, decent health care, education, security, and, not least, the material comforts that come from a certain level of affordable energy. Our own prosperity has been built on having such energy, but we have used the atmosphere as a free dump for the waste products from our energy system, such as carbon dioxide (CO_2). We now realize these waste products can produce horrific side effects. And finally, what do we human beings owe to the natural world, now threatened with unprecedented levels of species extinctions?

Scientists and everybody else can improve their communication skills by considering their **audience**, knowing who the audience members are, and learning what they care most about. Why is climate change important to them? This approach to communication often means emphasizing impacts of climate change happening now, here in our own backyards, rather than impacts far away and in a distant future. It can also mean making connections between climate change and what people are experiencing in their daily lives, such as increases in extreme weather.

In addition to knowing your audience, it is important to know yourself. Analyze your own strengths and weaknesses as a climate change communicator, both in general terms and for each audience you face. Showing that you are interested in what your audience cares about, and showing that you are a warm, likable, knowledgeable, and trustworthy person, can make you a much more effective communicator. Seek feedback from your audience. Learn what others think of your abilities as a communicator of climate change science.

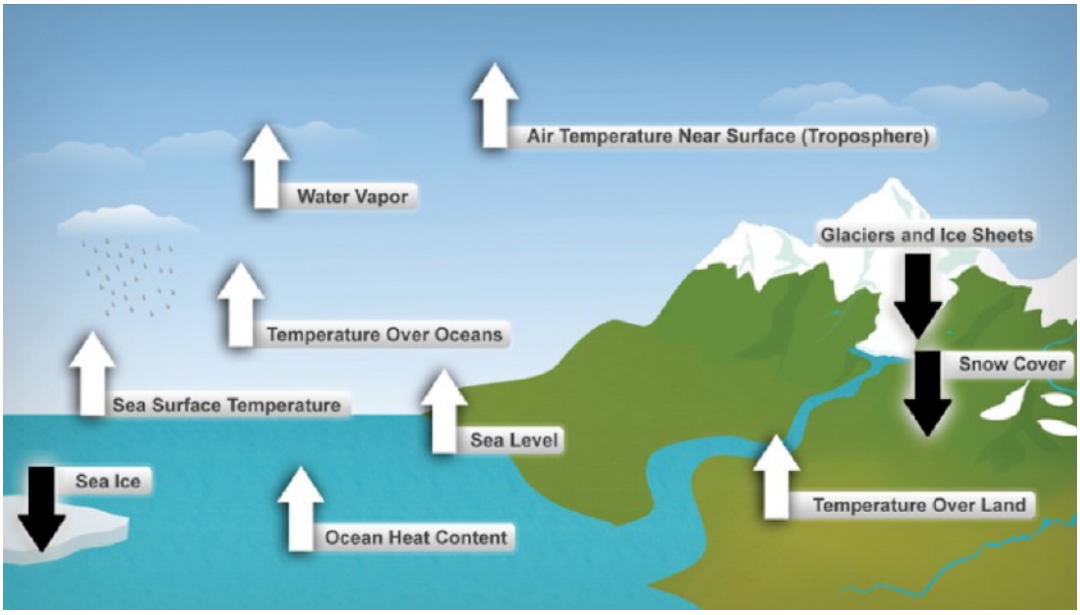

FIGURE 8.1.2 Ten different types of observations that contribute to the scientific evidence that the global climate is warming. White upward arrows indicate increasing quantities. Black downward arrows indicate decreasing quantities. From US Global Change Research Program. 2014.

Knowing your subject matter is crucial. Being well informed about the science of climate change is an obvious step in preparing to communicate it. For example, you can and should learn the most common myths and falsehoods about the science, and you can be prepared to refute them convincingly. Become something of an expert yourself first, at least in certain areas of climate change science, and only then try to communicate what you have learned. When answering a question, if you don't know the answer, say so. Don't guess. You're not expected to know everything.

Facts matter. Here are some facts: The world is warming. It's not a hoax. We measure it. The warming has not stopped. All the warmest years are recent years. The evidence for warming is not a weak thread. It's a strong rope. The atmosphere is warming. So is the ocean. Sea level is rising. Ice sheets and glaciers are shrinking. Rainfall patterns and severe weather events are changing. Climate change is real and serious. It's not a remote threat for the distant future. It's here and now. Figure 8.1.2 depicts the observational evidence that our climate is warming.

All ten of the illustrated changes are consistent with a warming climate. Climate science communicators should be familiar with these aspects of the findings of climate research, and they should know important details about how these observations are made and why they are trustworthy.

The best summary of climate change science is the assessment reports of the Intergovernmental Panel on Climate Change, or IPCC. Five such reports have been published between 1990 and 2013. They are published in hard copy by Cambridge University Press, and the more recent ones are also available free online at the IPCC website, https://www.ipcc.ch. These assessment reports are written by climate scientists and extensively reviewed. I'm an IPCC author. The most recent IPCC assessment report is the fifth. It was published in 2013. At this writing (2018), the sixth is in progress. We will consider the report of Working Group I of the IPCC, which covers the physical science of climate change. There are two additional working groups, devoted to topics such as climate change impacts, vulnerabilities, adaptation, and mitigation. The latest Working Group I IPCC assessment report is scientifically definitive, but it is long, about 1,500 pages, full of charts and graphs, and not easy reading. For this chapter, I've composed brief statements in plain English to summarize this IPCC report in only 12 points. These are scientific findings, well supported by extensive research and endorsed by every relevant major scientific organization in the world. The 12 points are shown in Figure 8.1.3 and listed here:

1. **It's warming.** We've just seen a summary of the many kinds of evidence for that.
2. **It's us.** We've done the detective work. It's not natural like ice ages. It's human-caused.
3. **It hasn't stopped.** The warming is continuing. The warmest years on record are recent years.
4. **The heat is mainly in the sea.** Over 90% of the heat added to the climate is in the oceans.
5. **Sea level is rising globally.** The rate of this rise is increasing. The rise is not uniform globally.
6. **Ice is melting.** Ice sheets on Greenland and Antarctica, as well as glaciers, are all shrinking.

7. **CO_2 absorbed by the oceans makes them more acidic.** That can affect the marine food chain.
8. **CO_2 amounts in the atmosphere are about 45% higher than in the 1800s, due to human actions.**
9. **The amount of CO_2 in the atmosphere now is the highest it has been in millions of years.**
10. **Cumulative emissions of CO_2 and other heat-trapping substances set the amount of warming.**
11. **Reducing emissions of CO_2 and other heat-trapping substances will limit the warming.**
12. **Climate change, because it takes so long for CO_2 amounts to decrease, will last for centuries.**

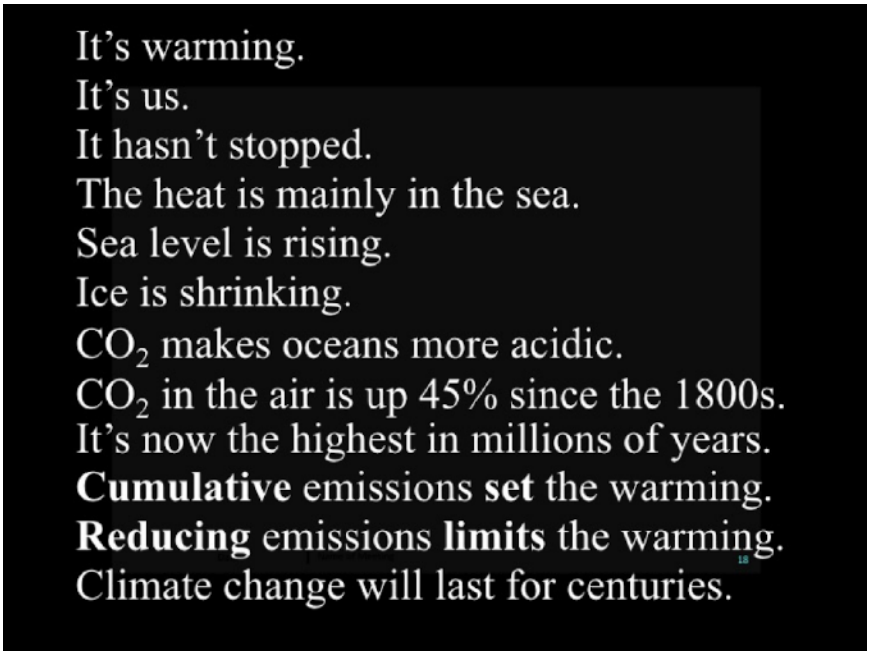

FIGURE 8.1.3 **My summary of the key results of the Working Group I (physical science) portion of the IPCC's Fifth Assessment Report, published in 2013. Climate science communicators should be able to explain these key points and the scientific evidence for them.** Image: R. C. J. Somerville.

8.2 Stories

Stories are a wonderful way to engage an audience. Scientists are widely admired, scientific research has clearly brought many benefits to humanity, and you might naively think that most people would be inclined to accept the main findings of climate science. Yet many people, including "Uncle Pete," a fictional character closely based on fact, strongly disagree with climate scientists. When Uncle Pete comes to dinner, he ruins the meal for everyone else by loudly proclaiming that climate scientists are dishonest or incompetent, and climate science is fraudulent or a hoax or simply incorrect. Pete insists on frequently repeating several climate myths and falsehoods, which he believes are true. He may have heard them on a talk radio show or seen them in some dark corner of the internet. Many people know a real person, perhaps a friend or colleague or family member, who closely resembles Uncle Pete.

Uncle Pete's myths and falsehoods include claims such as the world isn't warming; or the warming is natural and not human-caused; or volcanoes produce more carbon dioxide than people do. In a moment, I will explain why Uncle Pete's favorite and most frequently repeated claims are simply wrong. I don't have enough space to cover all of them, and I recommend the website https://skepticalscience.com for the rest of the story. That website is a collection of the most commonly heard climate myths, and why they are all dead wrong. Skepticalscience.com is a useful resource in refuting your own Uncle Pete. For up-to-date scientific information on climate change, I also highly recommend the website www.realclimate.org, which is run by excellent climate scientists. The main postings by these scientists on realclimate.org are usually outstanding, but the comments on the site by bloggers and other viewers vary greatly in quality.

Start with the myth that the warming we have observed in recent decades is natural and not human-caused. First, let's be clear that the

climate has indeed changed naturally in the past, with ice ages being an obvious example. But natural causes simply cannot explain the recent warming. How do we know that? It's much like the story of wildfires, which can be caused naturally, by lightning. But they can also be caused by people, either by carelessness or by arson. As you know, wildfire experts can investigate after a wildfire and can frequently determine exactly what caused it. They know how to do the detective work.

We climate scientists are good detectives too. We have discovered what paces the ice ages. It is the slow changes in the Earth's orbit around the sun, which affect how sunlight is distributed over the Earth's surface in the different seasons. Over many thousands of years, these effects are strong enough to trigger the transitions between ice ages and the warmer periods between them. However, over short time periods, such as decades, the orbital changes have much too small an effect to produce the observed large warming that has occurred in recent decades.

Through this kind of research, we scientists have also quantitatively ruled out all the other natural processes known to affect climate. For example, the sun powers the entire climate system, and the amount of energy given off by the sun does vary. The biggest variation that has been measured on decadal time scales is only about 0.1%, and that variation is due to the 11-year solar cycle, often called the sunspot cycle. We can measure this decadal-scale energy variability very accurately, and we can demonstrate convincingly that the measured changes are much too small to have caused the observed warming. As for the claim that the extra carbon dioxide added to the atmosphere by human activities is tiny compared with the amounts produced by volcanoes, that too fails quantitatively. Measurements show that human activities, mainly burning coal and oil and natural gas, produce about 100 times more carbon dioxide than volcanoes do.

Thus, we humans have taken over the dominant role of deciding what the climate in coming decades will be. We are no longer passive spectators in the global climate change pageant. We have become the primary actors. To climate scientists, whose goal is to discover the truth about climate change, it really doesn't matter whether or not some people find this discovery believable. Science is based on facts and

evidence, not on beliefs. Most people have a very vague conception of what science is and what scientists do. People often recall their high school chemistry course, for example, as a boring exercise in memorizing useless things, like the periodic table of chemical elements, and then forgetting them as soon as possible after the exam. Most people have never met a scientist. It's not just that people don't know elementary facts, such as that the Earth goes around the sun once a year. It is that they have no idea how such facts were discovered. There is nothing wrong with belief; indeed, it's important for people to believe that it is good to treat other people well. But in some domains, there is another way to find out what is true. That is to compare one's beliefs with facts and evidence. **Science** is the name we give to doing that.

Science provides extremely persuasive evidence that the heat-trapping atmospheric gases and particles produced by human activities such as fossil fuel burning are the main cause of the warming observed in recent decades. This aspect of climate science is very firmly established, going back to definitive laboratory experiments in the 1850s. Those scientific experiments showed clearly that carbon dioxide and other gases, present in small quantities in the atmosphere, have powerful heat-trapping properties. In recent decades, the fingerprint of the observed warming, such as how it varies with altitude and geography and season, matches the pattern that we expect from human activities adding heat-trapping gases to the atmosphere. We have found the enemy. He is us. Figure 8.2.1 symbolizes the profound and disturbing truth that we people are now the main actors in climate change. Our choices will determine the future climate. The destiny of the planet is indeed in our hands.

Here are some of Uncle Pete's favorite **myths** and falsehoods.

Uncle Pete asks, How can you forecast climate for a century if you can't even forecast the weather for next week? Answer: Climate is statistics, and that is much more predictable than daily weather, just as we can skillfully forecast mortality statistics for large populations, but not the lifetime of a specific person.

Pete claims that in the 1970s, climate scientists predicted global cooling. That's simply not true. We've checked. Global cooling was prominent in some media articles and popular books, but not in the

FIGURE 8.2.1 The warming climate observed in recent decades is not natural. Human activities, such as extensive use of fossil fuels, are causing it. We people are now the main actors in climate change. The destiny of the planet is in our hands. Reproduced from clipartimage.com.

scientific research publications of the 1970s. The great majority of climate scientists in the 1970s were already focused on warming.

Pete has heard about certain satellite data that seemed to show a lack of warming. We have known for many years now that those data were simply wrong. Measuring atmospheric temperatures from satellites is technically very difficult. It took time to learn how to do it right.

Pete says changes in the sun cause climate change. That is true for some past climate changes but not for the warming observed in recent decades. We measure the sun and its variability. The effects of the sun's changes in recent decades are tiny compared with effects caused by humans.

Pete claims that the atmospheric CO_2 amount increased from natural causes, like volcanoes. That's just plain wrong. It did not. We can measure volcanic emissions. We also measure human-caused emissions. Human activities produce about 100 times more CO_2 than volcanoes do.

Pete says errors in the Intergovernmental Panel on Climate Change (IPCC) reports show that the science is wrong. Not true. A few small mistakes did get into the reports, but none of them is important.

All of Uncle Pete's claims are simply not true. They are falsehoods, not facts.

There are similar convincing refutations of all the other common climate myths. That's why many studies have shown that about 97% of the climate scientists who are most active in publishing research on climate change agree that the observed recent warming is real and serious and overwhelmingly human-caused. Nevertheless, Uncle Pete remains unconvinced. He continues to repeat the myths. You might well ask, Why

is Uncle Pete so stubborn and so resistant to overwhelming scientific evidence? That's a very good question, and here is my answer.

For many skeptics or contrarians, like Pete, the climate change issue is not a science topic at all. For Pete, climate change is simply an opportunity for the government, and for liberals and environmentalists, to make rules and regulations, to interfere with markets, and to diminish the personal freedom of individuals. For Pete, climate change is just one more excuse for the authority of the state to control the lives of citizens. This view of Pete's has nothing to do with science, and no argument based only on science can change it. Uncle Pete, like some actual people I know, may seriously fear that the government will not only claim the right to decide what kind of car he will be allowed to drive, but will ultimately want to force him to limit his individual carbon footprint, that is, to ration his personal emissions of heat-trapping gases.

Uncle Pete invariably has a high opinion of the free market. He is confident that government actions, such as taxes and regulations, tend to hinder free markets and thus have the effect of limiting economic progress. He is also suspicious of subsidies for renewable energy. He is sure that renewables will never be feasible without big subsidies. Uncle Pete couches his opposition to carbon taxes or fees in statements such as "If you let people keep more of their money, they will invest it in the future." Once again, science is irrelevant here, and no claim that science has discovered or proven this or that fact will change Uncle Pete's mind.

Research showing that some 97% of active climate experts agree with the mainstream scientific consensus does not impress Uncle Pete. Instead, he is convinced that many climate falsehoods and climate myths are true. Uncle Pete may be a fictional character, but almost everybody seems to know people who closely resemble him. Some well-known public figures and some high officials in the government of the United States apparently agree with Uncle Pete. If you want to have any hope of changing the opinion of your own Uncle Pete, you need to understand why he rejects the science of climate change.

It's sad but true that most Americans have never met a scientist. Uncle Pete may have his own somewhat strange ideas about how science works and what scientists do. **Peer review**, the elaborate and thorough formal process by which other scientists carefully evaluate

new scientific research before it can be published in technical journals, carries no weight at all with Pete. In fact, he can easily imagine a corrupt and powerful scientific establishment, conspiring to deny research funding to scientists who disagree with prevailing opinions, and to prevent them from publishing. Pete likes to mention Galileo as an example of an outlier in science who turns out to have been correct. He forgets that real geniuses like Galileo are extremely rare and that almost everybody who considers himself a Galileo is very badly mistaken. Pete may cite past errors made by scientists as evidence that the scientific mainstream is indeed sometimes badly mistaken. Pete is very suspicious of us scientists, and he may think that government support of research in climate science is a waste of taxpayers' money.

Social science tells us that people tend to trust those who share their values and to distrust those who do not. We know that controversial issues, such as abortion and evolution and gun control, bitterly divide the United States, and we ought to realize that climate change is a very big issue for Uncle Pete. His natural distrust of academics and elites generally is increased if he thinks climate scientists are arrogant people who are scornful of his opinions, who mock his values, and who dismiss his most firmly held convictions.

I urge each of you to engage with the Uncle Pete whom you may know. Have a civil conversation. In his heart, Uncle Pete would probably admit that everybody is entitled to his own opinions, but not to his own facts. When it comes to facts, we scientists have the high ground. The world is warming. It's not a hoax. We measure it. The warming did not stop in 1998 or any other recent year. All the warmest years are recent years. The atmosphere is warming, and so is the ocean. Sea level is rising. Ice sheets and glaciers are shrinking. Rainfall patterns and severe weather events are changing. Climate change is real and serious, and it is happening here and now. It is definitely not caused by natural processes. Human activities are clearly the dominant cause of the climate changes we have observed in recent decades.

None of these facts tells us exactly what we should do about climate change. Science can inform wise policy, but it cannot decree or prescribe what the best policies will be. There is no silver bullet, but there is lots of silver buckshot. The main barrier to action is a lack of political will. In

deciding climate policy, science matters, but so do values, priorities, and political convictions. Given the same facts, different reasonable people can easily prefer different policies. For Uncle Pete, attacking climate science and scientists is simply a disguise for what really concerns him most, which is the prospect of liberals and environmentalists dominating policy, and of a government spinning out of control, a government that in Pete's view seizes power, limits freedoms, increases taxes, regulates markets, and diminishes prosperity.

We do not yet have national agreement on climate change. Despite the strong *scientific* consensus, climate change policy is contentious *politically*.

One option is to do nothing. Uncle Pete may well favor that option, because it appears to fit well with his sincere conviction that "if you let people keep more of their money, they will invest it in the future." On the option of doing nothing, I may be able to help Uncle Pete think a bit more clearly. I do not claim to be an expert on energy policy or taxes, but as a climate scientist, I can say something with very high confidence about what will happen if we do nothing. Deciding to do nothing about climate change is like deciding not to have serious elective surgery, such as declining a coronary artery bypass operation that your cardiologist recommends. The operation will involve risks and costs. But declining it will also involve risks and costs, including the risk of a fatal heart attack.

Sadly, most of us do not have enough conversations about climate change. The mainstream news media largely avoid the subject, and so do many politicians. Today the fact is that we—you and I and the other 7.7 billion living people (as of November 2018)—now have our hands on the thermostat that controls the climate of our children and grandchildren. A considerable portion of the carbon dioxide we emit will remain in the atmosphere for centuries and longer. Thus, it accumulates. There is a given allowed amount of CO_2 in the atmosphere that we must not exceed if we want to limit warming to any target we pick. Science can now provide fairly accurate estimates of that allowed amount. For the warming target of the Paris Agreement, signed by almost every country in the world in late 2015, we're already about halfway to that allowed amount of atmospheric CO_2, and we do not have much time left to bring global emissions to nearly zero. That's why it's urgent to drastically

FIGURE 8.2.2 The Earth is warming, just as surely as if it were immersed in a warm bath. Reproduced from Pixabay.

reduce global CO_2 emissions and to do it quickly before we exceed the allowed amount.

It's important to realize that once a political process such as the one at Paris in 2015 has occurred, and the world has agreed on a target of how much warming is to be allowed, science can then say approximately how much more CO_2 can be emitted to allow a reasonable probability of meeting the warming target. Given the warming target, the urgency of reducing emissions is thus based directly on the physics and chemistry of the climate system. It has nothing to do with politics or ideology, once the warming target has been agreed to.

Mother Nature, which we may use as one name for the physical climate system, reacts to the total amount of CO_2. The more carbon dioxide there is in the atmosphere, the greater the climate change will be. If we who are alive today do nothing about climate change, and if the world continues to use the atmosphere as a free dump for carbon dioxide and other waste products of an energy system based on fossil fuels, then we are effectively sentencing future generations to the consequences of a severely disrupted climate. Also, the disruption will not be brief. It will take many thousands of years for the climate to recover after we stop emitting CO_2. Thus, it's a long sentence. This is not a partisan opinion or a political statement. It is well-supported solid science.

Figure 8.2.2 illustrates the uncomfortable fact that the Earth is now warming, just as surely as if it were immersed in a warm bath. In fact, the Earth is surrounded by an atmosphere, which acts much like a warm

bath, and the atmosphere has been altered by human activities. As a result, the atmosphere now traps significantly more heat than it did in, say, 1800, before human activities adding heat-trapping substances to the atmosphere began to increase dramatically.

Military experts take this issue very seriously, and they have repeatedly characterized climate change as a threat multiplier. In the decades and centuries ahead, doing nothing would ensure that the world will inevitably see devastating climate change, including agricultural disasters on an immense scale and coastal cities abandoned worldwide because of sea level increases of many feet. If we do nothing, then because of devastating climate change, vast numbers of people will become environmental refugees, and we will see the destabilization of governments, especially in failed and failing states. In wealthy and powerful countries, like the United States, governments coping with severe climate change would surely have to act forcefully, including using emergency powers as in wartime, to preserve order and to minimize chaos and damage. Ironically, doing nothing at all about climate change, Uncle Pete's preferred policy, is thus likely to force governments to do exactly what Uncle Pete fears most: seize power and limit freedoms. Doing nothing, whether intentionally or by neglect, is a truly disastrous policy option.

In your civil and mutually respectful conversation with your own Uncle Pete, I hope you can help him think seriously about the prospect of such a horrible, but very preventable, future. We are at a critical crossroads. If the world decides very soon to act decisively, we still have time to reduce emissions rapidly and drastically. We still have a chance of limiting climate change to a tolerable level, a level that offers some realistic chances of successful adaptation. Our window of opportunity is still open. But it won't stay open much longer.

In my view, and that of many other climate scientists, we must act. We can't dither any longer. If Uncle Pete wants to avoid the government controlling his life and diminishing his freedom, as all of us do, then we all need to learn about and accept the science. We all need to take the threat of climate change seriously. We all must act wisely, and urgently, to minimize it. For me, the best reason for communicating climate change science widely and accurately is that doing so can inform people and increase the likelihood that the world will act promptly, wisely, and forcefully.

8.3 Metaphors

Metaphors can be superb communication tools. A **metaphor** compares one thing to another thing, often in a way that brings out hidden similarities or reveals unexpected resemblances that can aid our understanding. "We have our hands on the thermostat that controls future climate" is an effective metaphor because we are not used to thinking about thermostats and global climate together.

Here's another useful metaphor. Imagine you are watching a major-league professional baseball game. The slugger who is thought to be on performance-enhancing drugs hits a home run. Did the steroids cause it? Wrong question. You can't be sure they caused it, because he was already a big-league slugger when he was clean. And even with the drugs, he can still strike out now and then. But at the end of the season, you see in his statistics that he hit more homers than he used to. The drugs increase the odds of home runs. If baseball does not interest you, other sports can be equally effective vehicles for this metaphor. A bicycle racer on illegal drugs does not win every race, but his chances of winning are increased.

Climate is the statistics of weather, and CO_2 is the steroids of climate. The odds are higher now for all sorts of extreme weather because climate change has altered the environment in which all weather occurs. The entire hydrological cycle has sped up, there is more water vapor in the atmosphere, and so on. That's why observations show that more precipitation now falls in heavy precipitation events than was the case a few decades ago. That's also the reason for more high-temperature records being broken now than low-temperature records. After all, if the climate were not changing, neither warming nor cooling, but just randomly varying around a constant state, we would expect equal numbers of new high and low records to be set.

Figure 8.3.1 illustrates the catchy metaphor that carbon dioxide is

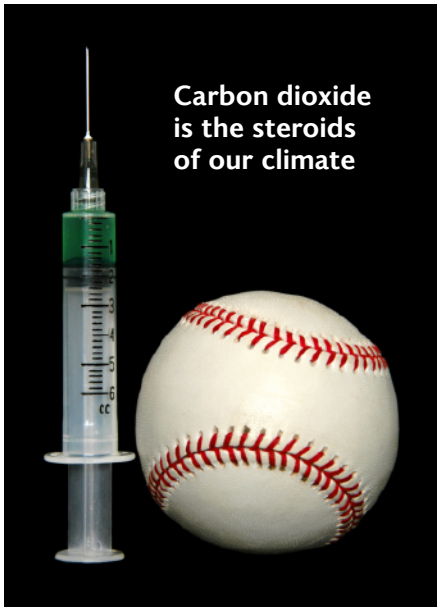

FIGURE 8.3.1 The catchy metaphor that carbon dioxide is the steroids of our climate is "sticky," meaning that it is effective and easy to remember. Adapted from Shutterstock.

the steroids of our climate. This metaphor is "sticky," meaning that it is effective and easy to remember. Climate is a subject in which statistics and probability play a key role. Climate change involves changes in the odds of many weather phenomena, such as heat waves and heavy precipitation events. Communicating the science of climate change is aided by using metaphors that are widely understood and easily remembered. Baseball fans understand that a player using performance-enhancing drugs such as steroids doesn't always hit home runs, but the drugs increase the odds of the player hitting home runs. A bicycle racer on illegal drugs does not win every race, but the drugs increase his chance of winning. In a similar way, adding heat-trapping substances such as carbon dioxide (CO_2) to the atmosphere increases the odds of heat waves and heavy precipitation events.

We climate scientists sometimes think of ourselves as planetary physicians. I had a fascinating experience not long ago. My regular doctor retired. I had to choose a new doctor. When we met for the first time, my new doctor said, "Sit down. Let me tell you how I practice medicine. First, I'm competent. I know what I'm doing. Second, I'm honest. If there's something I don't understand, I'll tell you. Third, I'm here only to advise you. *You* will make all the decisions."

I was impressed. No doctor had ever talked to me like that. We

climate scientists are planetary physicians. We are also competent and honest and here only to advise. We have learned many things about climate, but we still have a lot to learn. Like the findings of medical science, our understanding of climate, incomplete though it is, is already highly useful.

For example, the fundamental question—whether all of us, some 7.7 billion humans as of late 2018, have caused the world to warm up in recent decades—has already been answered. The answer is yes. We've settled that issue. At least, an overwhelming majority of the most active climate scientists involved in research consider it settled. Some other people may choose not to believe it. There are people, like Uncle Pete, who are unwilling to believe things that they wish were not true, or who just don't trust experts.

The public has come to respect medical science, however. Although there will always be gullible people, most of us know there's a difference between real experts and charlatans. Most people won't listen to, or act on, medical advice from a quack who can talk about medicine but who isn't really a physician. Everybody accepts this situation. Even the least enlightened members of Congress don't hold hearings to denounce modern medical science as a hoax. Yet, a few politicians and others do denounce climate science in exactly this way.

Medicine is different. At your annual checkup, if you're sensible, when the doctor tells you to lose weight and exercise more, you don't argue. You don't complain that medical science is imperfect and can't yet prevent cancer or cure AIDS. You don't label your doctor a radical alarmist. You know, and your doctor knows, that medical science, while imperfect and incomplete, is still good enough to provide advice well worth following.

Of course, some people just don't do what experts tell them. Not everybody takes the medications their doctor prescribes. "Noncompliance" by some patients can be a big problem for physicians. We should keep all this in perspective. Lest we fall into the trap of thinking that medical science is a perfect role model for us climate scientists who crave more public esteem, it is also good to remember that it took a long time for many medical results to acquire widespread acceptance. Some scientists in the 1930s already suspected that tobacco caused

cancer. The evidence was widely known to be strong by the 1960s. Yet the high-profile anti-tobacco lawsuits in the United States began only in the 1980s. Even today, many people still smoke.

The biggest single problem in human-caused climate change is carbon dioxide. We produce it when we burn oil and coal and natural gas to generate energy. It traps heat in the atmosphere, adding to the natural greenhouse effect and causing climate change. A few farseeing scientists realized more than a century ago that this might happen. Yet accurate measurements of carbon dioxide in the atmosphere began only in the late 1950s. Thus, we have known for only about half a century that the amount of atmospheric carbon dioxide is increasing. We ought to remember this half-century time scale when we get impatient about the slow pace of progress in action against human-caused climate change.

I would say that we scientists have known about the urgency of climate change for about 40 years. I have one especially important scientific research paper in mind, among many others. That paper, which is not very famous, is by Ulrich Siegenthaler and Hans Oeschger and was published in 1978 in the journal *Science*, which is often said to be the most prominent scientific journal.

The paper concluded that carbon dioxide emissions would have to peak and then quickly decline early in the current (twenty-first) century in order to limit global warming to moderate or tolerable levels. This 1978 result came from the simple models and the limited data available in the 1970s. We know much more today about the quantitative aspects of this prediction and many other details. However, the essential scientific foundation was already clear 40 years ago—or at least it was clear to two insightful Swiss scientists, Siegenthaler and Oeschger. That is the message I try to emphasize: the need to drastically reduce global heat-trapping gas and particle emissions is urgent, and the urgency is scientific, not political.

Incidentally, like many climate scientists, I don't fully approve of the catchy term "global warming," although I realize it's in the language to stay. It's an oversimplification. Climate isn't just temperature. Climate is a rich tapestry of interlinked phenomena, multifaceted and inherently complex. The important aspects of climate change are local, not global,

FIGURE 8.3.2 We climate scientists are planetary physicians. The decisions about caring for our patient, the Earth, will be made by its people and their governments. Climate science communicators must inform people and motivate them to act promptly, wisely, and forcefully. Reproduced from NASA.

and are not confined to warming. Global warming is just a symptom of planetary ill health, like a fever.

You and your physician both know that fever is important but not the whole story. At your annual checkup, you don't confine yourself to body temperature when discussing your health. Even the most ignorant patient realizes that measuring temperature alone doesn't enable the physician to diagnose an illness and prescribe treatment.

Instead, everybody knows that a body temperature only a few degrees above normal is a symptom that can indicate health problems that may have serious consequences, including death. Yet we still haven't educated most Americans to understand that a planetary fever of a few degrees can mean melting ice sheets, rising sea level, massive disruptions in water supply in the arid American west, increased risk of wildfires, killer heat waves, and stronger hurricanes on the Atlantic and Gulf coasts of the United States.

Figure 8.3.2 shows the Earth in space, beautiful and fragile and vulnerable. Climate change threatens the well-being of all its plants and animals, as well as that of its 7.7 billion human passengers. The most important function of climate scientists and climate science communication is to inform people and to motivate them to act promptly, wisely, and forcefully.

What can we say about hurricanes and their possible connection to an altered climate? The short answer is that you have to think about probabilities when you think about this connection. A warmer climate means that the strongest hurricanes may become even stronger, on

average. It does not mean we can definitely prove that any particular hurricane owes its strength to climate change, only that the odds of very strong hurricanes have gone up.

A hurricane is essentially just a heat engine with sea surface temperature as an approximate indicator of the fuel supply. The higher the temperature of the ocean surface, the more energy is available to power the hurricane. There is a critical sea surface temperature of about 80°F, below which hurricanes generally do not form. Because their destructive power increases as the sea surface temperature does, and especially because of the big recent increase in population and development in hurricane-prone areas in the United States, our vulnerability to hurricanes has increased strongly.

Scientists are cautious people, skeptical to a fault, fond of caveats, and not given to sweeping statements. We prefer to make claims only when we can back them up with solid data. We know that hurricanes are highly variable, no two are alike, and next year's hurricane season might be very different from this year's. It's our natural inclination to wait a few more years, observe more hurricanes, improve our theories and models, until we have an airtight case to present.

Nevertheless, the best current research tells us that the oceans have recently warmed substantially, that human activities are the primary cause of that warming, that an increase in the intensity of strong hurricanes is the expected result, and that we have indeed observed an increase in the numbers of the strongest hurricanes. No amount of waffling over probabilities and statistics can obscure these sobering results.

Many intelligent people still laugh at the small numbers we use and think a global warming of a few degrees is trivial. They may say that moving from a colder city to a warmer one involves a much greater warming and is actually quite pleasant. These people just don't grasp the crucial difference between local changes and global ones. They don't realize that when the climate of the entire planet changes by a few degrees, enormous changes happen. Going into an ice age, to pick one example, involves a global cooling of only a few degrees.

Some people really think that a rapidly warming climate is just a minor inconvenience that can be handled by air conditioning and other minor technological fixes. This massive degree of misunderstanding may

be due in part to a failure to educate people about science. It may also be the case that people have become confused by the widespread misperception that the science of climate change is immature, uncertain, characterized by raging controversy, and not to be trusted. An effective campaign of deliberate disinformation about climate science has helped spread this false impression.

Medical science has achieved a measure of pervasive respect that climate science can only envy. Journalists covering a medical discovery don't mistrust researchers and don't inevitably insist on hearing from "the opposing view." When reporting on research showing the need for Americans to eat more sensibly and be physically active, the media doesn't treat these advances in medical science in terms of a dispute. Journalists don't feel obliged to seek out medical contrarians "for balance."

There are many parallels between the climate change issue and medical topics. Maybe some can be useful in educating people and politicians. It has turned out to be frustratingly difficult to get people and their governments motivated to act to avert climate change. Yet people are intensely interested in threats to their own health. Many Americans have improved their health by making major changes in their personal lives, changes that are directly attributable to the results of medical science. Real progress has been made in making Americans, and their government, more aware of unhealthy behavior. The media, including public service advertising, together with organizations such as the American Medical Association and the American Cancer Society, have succeeded in raising many people's consciousness about health.

In climate change, the comparable scientific organizations have made very little progress in persuading people. In fact, most of the professional societies that scientists like me belong to exist mainly to serve the scientific community. They organize conferences of researchers. They publish highly technical journals that only scientists can read. These societies have low profiles and are essentially invisible to the public. Most of these societies have tiny budgets and devote very little effort to outreach of any kind. Many appear to be politically inactive or naive.

It is also true that some powerful segments of industry vigorously oppose efforts to act and to publicize the scientific facts about climate

change. However, business and industry are not monolithic in this respect. There are outstanding corporate champions of sound climate science, and we know that even the most retrograde segments of industry can change and become forces for progress, as notably happened in the ozone issue, for example. There, after it was scientifically proven that human-made chemicals were the culprit that caused the ozone hole, the industry that manufactured these chemicals changed its tune and developed safe substitutes for them. Governments and science and businesses cooperated, and humanity benefited.

In other cases, science and public concern have eventually triumphed over misguided opposition and propaganda. Numbers of smokers and deaths from smoking have been significantly reduced. Most Americans realize that smoking is dangerous and kills many thousands of people every year. They have learned this despite a highly professional and well-funded disinformation campaign mounted by portions of the tobacco industry.

Quitting smoking, like quitting using fossil fuels, is not easy to do, and in both cases the difficulty in quitting is immediate, while the most important benefits are all long-term.

The widespread public concern about the health consequences of smoking tobacco has led to political action, including warning labels on cigarettes, restrictions on advertising, and bans on sales to minors. The tobacco industry has repeatedly been defeated in court cases and has already paid large amounts of money as a result.

We see too the results of governments responding to public concern in the arena of promoting healthier food choices, including laws mandating truth in labeling and other actions to increase public awareness. These examples, and many more that could be cited, are direct results of medical science affecting public policy. People are persuaded that the science is right, and governments react to concern and pressure from citizens.

Science seems mysterious to many people, and it is not easy to penetrate the barriers of jargon and mathematics to explain the intricacies of computerized climate models or satellite climate measurements to a lay audience. Although very few people have a deep understanding of science or indeed any detailed familiarity with what researchers actually

do, the public generally respects scientists and has confidence in the validity of their results. In fact, polls consistently show that scientists are among the most widely admired people in our society.

Risk is an inevitable aspect of life. Medicine involves risk. People tend to be realistic about the consequences of serious medical problems. They know that a bypass operation is major surgery. They accept the cost and the risk, understanding clearly that doing nothing also entails real costs and dangerous risks. They don't expect that a simple bandage will cure a potentially fatal disease. As a climate scientist, I sometimes fear that we are wasting time arguing about which type of bandage is most attractive as a climate remedy, instead of facing the hard decisions, and the risks, that climate change demands of us.

You can't fool Mother Nature. The climate system responds to changes in the levels of heat-trapping gases. The climate system is indifferent to economic concerns, political considerations, or societal implications. The climate system does not care about the details of cap-and-trade agreements, and it knows nothing about diplomatic niceties like protocols and framework conventions. The amount of carbon dioxide in the atmosphere is what matters to climate.

The laws of atmospheric physics, unlike government reports, are absolutely immune from political tampering. If humanity insists on adding heat-trapping gases to the atmosphere, there will be consequences. That's just a fact. We scientists are busy researching the quantitative details, but we already know the big picture pretty well. If you see that a glib climate contrarian isn't at all worried about doubling the amount of carbon dioxide in the Earth's atmosphere, then start to think about tripling, quadrupling, and beyond. That is where we are headed, and our speed on this wrong road is actually still increasing. To have an effect, we simply must do more than make small token reductions in greenhouse gas emissions.

One of the towering heroes of climate science, my colleague at Scripps Institution of Oceanography and my friend, was Charles David Keeling, who died in June 2005 after nearly half a century of precisely measuring the amount of carbon dioxide in the global atmosphere. He was one of the greatest of planetary physicians. His legacy is summarized in a famous graph, the Keeling Curve, showing atmospheric

carbon dioxide inexorably increasing, decade after decade. Those data are rock solid, real science, unassailable.

In the 1950s, at about the same time that Keeling's measurements began, another renowned Scripps scientist, Roger Revelle, famously wrote that humanity is doing an inadvertent and unrepeatable geophysical experiment in moving so much carbon to the atmosphere so quickly. That perception, visionary at the time, seems obvious now.

What is still not obvious to many is that all of us are now engaged in a second global experiment, this time an educational and geopolitical one. We are going to find out whether humanity is going to take climate science seriously enough to act meaningfully, rather than just waiting around until nature ultimately proves that our climate model predictions were right.

In the end, our success or lack of it will be measured by whether we as a global society can change the Keeling Curve, bending it downwards, and whether we can stabilize the amount of carbon dioxide in our atmosphere in time to avoid the most dangerous climatic consequences. Whether that will turn out to be possible is not yet known. I hope so. I think it is the single most important question in planetary public health: armed with impeccable science, can humankind muster the wisdom and the will to make difficult changes? With many other medical decisions, the outcome is ultimately in the hands of the patient. In this case, it depends on all of humanity.

The biggest unknown about future climate is human behavior. Everything depends on what people and their governments do. For centuries, we humans were passive spectators at the global climate change pageant. Not any longer! We have become the dominant actors. You and I, and all 7.7 billion people who are alive today (late 2018), do indeed have our hands on the thermostat that will control the climate of our children and grandchildren. "The thermostat" is a powerful metaphor, illustrated in Figure 8.3.3. It is very useful in climate change science communication. People know that a household thermostat enables a person to control the temperature of the interior of a building. Yet many people do not realize that human activities are now a dominant factor in controlling climate change. We humans have caused the world to warm in recent decades. We human beings now have the power to limit the

FIGURE 8.3.3 We have our hands on the thermostat that will control the climate of our children and grandchildren. Reproduced from Fotosearch.

warming, to turn down the thermostat, and to avoid some of the most disruptive consequences of severe climate change. The big question is whether we together can muster the will to act promptly, wisely, and forcefully.

8.4 Language

Language is a critical aspect of all communication, written or oral, on every topic. When the topic is science, especially climate change science, some aspects of language become especially important. My first bit of language advice to anyone communicating about climate change science is to avoid the mistakes that climate scientists themselves often make. If you read enough research articles written by scientists, you are certain to discover that they tend to follow a peculiar format, one that is quasi-chronological. They typically start with background information, such as summarizing what previous research has been done on the particular topic being investigated. After that, the usual research paper moves on to an account of all the preparations that were made to start the research project being reported. Perhaps scientific instruments were procured or constructed, and then tested. Perhaps an expedition to a remote location had to be arranged. Perhaps computer programs had to be written and revised. Measurements or observations may have been taken, then processed and analyzed. At the end of this very long story, the authors present their results and conclusions.

Having read thousands of scientific research articles myself, I sometimes think that scientists force themselves to follow this structure, even though the way the research was actually carried out may have been very different. It has been said that making a scientific discovery and finding new knowledge is like climbing a treacherous mountain trail on a pitch-dark night. The climber stumbles and falls often, suffers many severe bruises from rocks and many sharp cuts from thorny plants, then is forced to turn back several times and try alternative routes, and finally reaches the top of the mountain, exhausted and in pain. Only then, as the sun comes up, is the climber able to see a smooth and gently sloping path, the route to success that should have been taken, a path that leads easily and painlessly from the bottom of the mountain to the top. When writing the article reporting the research, it is that smooth path that the

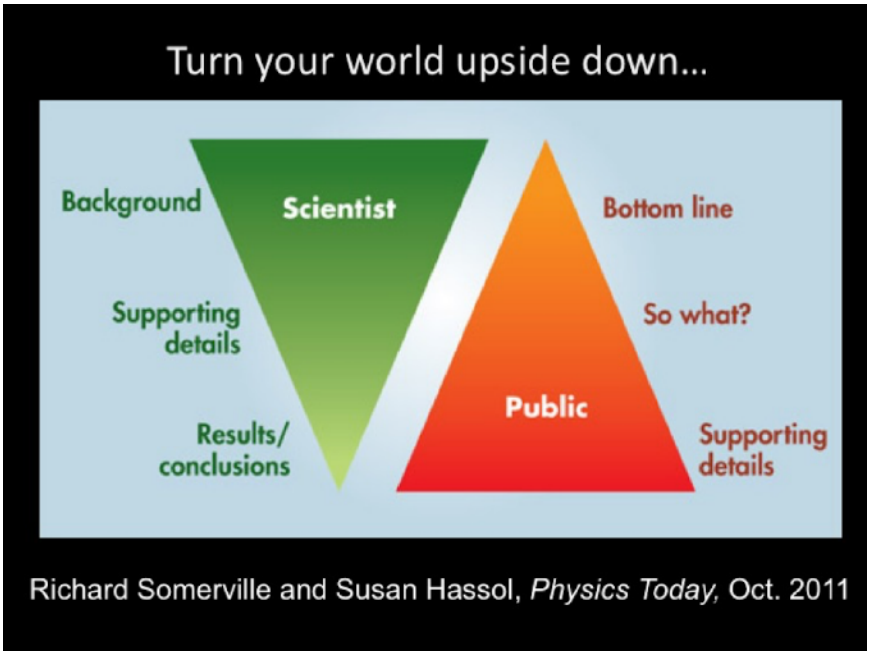

FIGURE 8.4.1 From Somerville and Hassol 2011.

scientist describes, starting with a calm and thorough search of previous work, then the making of orderly preparations for the research, and finally the logical carrying out of a swift and successful project, leading triumphantly to important new results. There is not a word about the long nightmare on the mountain and the many cuts and bruises endured on the route actually taken.

Don't follow the example of the scientist who communicates all the details and background first and then announces the results and conclusions at the end. In journalism, this sin is called "burying the lead." Reporters learn to compose a **lead**, the first sentence of a news story, in a way that conveys the main point of the story and also captures the reader's attention and motivates the reader to continue reading. We are speaking here of written stories and articles, but the point applies to oral presentations of all kinds too, including informal conversations. Figure 8.4.1 is taken from an article that my climate communication partner, Susan Joy Hassol, and I published, in which we urged climate change science communicators to start with the important result, not with background information. If a communicator has the scientist's habit

of giving a lot of unimportant details first, and the important main result last, we say, "Turn your world upside down." Everyone should remember, "Don't bury the lead."

Scientists in any specialty tend to speak to one another in a strange and private language that seems bizarre to nonscientists or even to scientists in other specialties. Jargon and mathematical terms are part of normal conversational usage for scientists. Words that are unfamiliar to the wider world should be avoided. They always have clear and simple substitutes. Rather than "anthropogenic," scientists could say "human-caused."

Be sure to use **units** that are familiar to your audience. Scientists everywhere use metric units in their work, and they often publish articles using these units. When speaking to or writing for a nonscientific audience in the United States, remember that metric units will be both unintelligible and frustrating to the audience. Instead, use feet and miles rather than meters and kilometers, use pounds instead of kilograms, and use degrees Fahrenheit rather than Celsius.

Scientific **jargon** refers to a type of language used by scientists in communicating efficiently and precisely with one another. Most scientists realize that jargon will not be understood by the public. However, there is an insidious trap involving common everyday terms that are not jargon, and that many people use, but that scientists use to mean something completely different from what everybody else means. There are hundreds of such terms, and they should be avoided by anyone wishing to communicate climate change science effectively.

Many climate scientists are shocked to learn that people misinterpret the term *positive feedback*, which scientists always use to mean a self-amplifying process. Here's an example: a warming Arctic causes less snow and ice, and so it makes the surface of the Earth darker. That darker surface is then less reflective, so it absorbs more sunlight, increasing the warming. This process is one of the main reasons why Alaska and other locations in the Arctic have warmed much more in recent years than the global average. For scientists, such a "positive feedback" increases global warming or climate change and thus is clearly bad. These scientists have temporarily forgotten that it is normal for people to be delighted when their boss praises their work, thus giving them "positive feedback"!

Terms that have different meanings for scientists and the public

Scientific term	Public meaning	Better choice
enhance	improve	intensify, increase
aerosol	spray can	tiny atmospheric particle
positive trend	good trend	upward trend
positive feedback	good response, praise	vicious cycle, self-reinforcing cycle
theory	hunch, speculation	scientific understanding
uncertainty	ignorance	range
error	mistake, wrong, incorrect	difference from exact true number
bias	distortion, political motive	offset from an observation
sign	indication, astrological sign	plus or minus sign
values	ethics, monetary value	numbers, quantity
manipulation	illicit tampering	scientific data processing
scheme	devious plot	systematic plan
anomaly	abnormal occurrence	change from long-term average

Richard C. J. Somerville and Susan Joy Hassol, *Physics Today*, Oct. 2011

FIGURE 8.4.2 **A sample of words that are not scientific jargon, but that are used differently by scientists and the public.** From Somerville and Hassol 2011.

Similarly, when human activities add heat-trapping gases to the atmosphere, climate scientists frequently refer to the consequence as an "enhanced greenhouse effect." They mean that the natural greenhouse effect is increased in strength, producing more warming in the atmosphere and causing climate change. In using *enhanced* to mean "intensified," these scientists overlook the everyday meaning of *enhanced*, which is "improved," as when attractive clothing or good health is said to enhance a person's appearance. Thus, just as in the case of *positive feedback*, scientists intend to describe something harmful and undesirable with the word *enhanced*, but their use of the term is confusing and creates misunderstanding because normally *enhanced* describes something beneficial and desirable. Figure 8.4.2 lists a few other terms that scientists often misuse, along with suggestions for improved communication of these concepts. There are many more such terms. Climate science communicators need to realize that such words should be avoided. They can always be replaced by better choices.

Much of my advice on language is not confined to this section but can be found throughout this chapter. I urge every climate change science communicator to compose messages that are simple and memorable, to repeat them often, and to partner with trusted messengers. I heartily endorse the use of metaphors and other vivid imagery. If climate change is very important to you, do not speak or write about it in dry and unemotional language that conveys boredom and resignation. Instead, let your passion show. Seize opportunities to learn from expert communicators and to get useful feedback from your audiences. Nobody is born knowing how to ski or play chess or drive a car. Like all these skills, communication skills can be taught, developed, practiced, and improved.

8.5 Solutions

When you communicate climate change science, be sure to include information on solutions. Nobody wants to hear about hopelessness, and in the case of climate change, there are many reasons to be hopeful. Climate change poses difficult problems and challenges, but there are lots of solutions that are both creative and practical and that can help solve the problems and overcome the challenges of climate change.

I think the main barriers to action today are not technical or financial. They are a lack of widespread political will and a lack of wise and inspiring political leadership. Science can help to inform policy, but only concerned people and responsive, capable governments can decide what policies are best, and then implement them.

In the United States today, we clearly do not yet have national agreement on climate change. Some people in the federal government sound just like Uncle Pete. Despite the strong *scientific* consensus, climate change is controversial *politically*. Incidentally, there are many lawyers in Congress, but as this is written (2018) only one member of Congress is a PhD scientist. Maybe that should change!

There is no silver bullet that solves all the challenges of climate change, but there is lots of silver buckshot, including increased energy efficiency and energy conservation and much more use of sun, wind, and water to provide the energy the world needs. These renewable resources are widely available now and already cost-competitive with fossil fuels. We have the technology. We lack the political will to act. At least, that has been true for decades, but there is evidence that a change is occurring now.

Faced with the very real threats of climate change, the nations of the world agreed in Paris in late 2015 to limit the warming to a specific maximum amount. That amount is 2°C, or 3.6°F, above the average global temperature in the early 1800s, before human activities began to have

a large effect. At the urging of the most vulnerable countries, delegates in Paris also agreed to "pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius," although it was widely understood that successfully meeting this aspirational goal would be much more difficult than meeting the 2.0°C target.

After Paris, is the glass half empty or half full? I am guardedly optimistic. I see many reasons for optimism, and I encourage all of you to learn about them and communicate them to your Uncle Pete and your audiences:

- World leaders are engaged; at least almost all of them are.
- Emissions of heat-trapping gases have begun to decline in some countries.
- Solar and wind energy have dropped drastically in price and continue to become cheaper.
- Renewable energy use in many countries is increasing rapidly.
- Many corporations are now acting to reduce emissions.
- States and localities are acting too.
- Many countries are showing rapid progress.

I'm also encouraged by recent polling that shows that in the United States, more people accept the science and are very concerned about global warming than was the case only a few years ago. However, when virtually the entire leadership of the Republican party in the United States rejects the findings of mainstream climate change science and considers climate change to be a hoax, we clearly have a long way to go. In the United States, climate change has become a very partisan issue.

Fortunately, it is quite possible to power the entire world on carbon-free energy. The technology is available today and continues to improve rapidly. In this country, even without decisive action by the federal government, I am guardedly optimistic. Figure 8.5.1 illustrates wind power. Wind and solar power are both already cheaper than fossil fuel power in many areas, even without subsidies and when the many hidden costs of fossil fuel power, such as health effects of air pollution, are not taken into account.

Market forces now favor carbon-free energy. Coal companies are

FIGURE 8.5.1 An array of wind turbines on a dike in The Netherlands. Renewable energy, typified by wind and solar power, is a key part of efforts to wean the world from fossil fuels. Reproduced with permission from Sylvia Bal Somerville.

going bankrupt. Renewable energy gets cheaper every year. Electric vehicles are happening fast. Much energy policy in the United States is set at state and local levels, not in Washington.

Uncle Pete needs to know that free-market, small-government mechanisms, ones he may prefer and approve of, such as revenue-neutral carbon fee-and-rebate plans, can work. Some have been advocated by leading conservatives, who argue that it is sensible insurance, hedging against climate change risk, whether one accepts climate science or not. Pete should study this approach. I urge you to study it and then talk about it to your Uncle Pete.

Leaving a healthy climate to your children and their descendants is a worthwhile goal, and a realistic one. It won't be easy, but it can be done.

We need to help people realize that not acting is also making a choice, one that commits future generations to serious climate change impacts. Research suggests that messages that may invoke fear or dismay are better received if they also include hopeful messages. Thus, we can improve the chances that the public will hear and accept the science if we include positive messages about our ability to solve the problem. For example, we can explain that future climate is in our hands; lower

emissions of heat-trapping gases will mean reduced climate change and less severe impacts. We can point out that addressing climate change wisely can yield a variety of benefits to the economy and quality of life. We can explain that acting sooner is preferable to delaying. We can all rise to the challenge of helping the public understand that science can illuminate the choices that we face.

Whether to act to limit global warming to tolerable levels should not depend on your politics. We have only one Earth. Everybody should want to avoid polluting and contaminating this magnificent world, and everybody should agree that we need to protect and preserve our amazing planet. Your policies and values and politics have a role to play in deciding which actions are best, but any rational policy begins by accepting the science.

The world needs to take firm action about the threat of human-caused climate change within the next decade. Research shows that global emissions of heat-trapping gases must peak and decline quickly—within a few years, not a few decades or centuries—if global warming is to be limited to a level that avoids severe climate disruption. Meanwhile, a well-funded and effective professional disinformation campaign has been successful in sowing confusion, and many people like Uncle Pete mistakenly think climate change science is unreliable or is controversial within the scientific expert community. Thus, an urgent task for us scientists and for all communicators of climate change science may be to give the public guidelines for recognizing and rejecting junk science and disinformation. If students today, who will be adults tomorrow, can understand and apply these guidelines, they may not need a detailed knowledge of climate change science. To that end, I offer the following six principles.

1. **The essential findings of mainstream climate change science are firm.** The world is warming. There are many kinds of evidence: air temperatures, ocean temperatures, melting ice, rising sea levels, and much more. Human activities are the main cause. The warming is not natural. It is not due to the sun, for example. We know this because we can measure the effect of human-made carbon dioxide and it is much stronger than that of changes in the sun, which we also measure.

2. **The greenhouse effect is well understood.** It is as real as gravity. The foundations of the science are more than 150 years old. Carbon dioxide in the atmosphere traps heat. We know that, because careful laboratory experiments prove it and theoretical physics explains it. We know carbon dioxide is increasing, because we measure it. We know the increase is due to human activities like burning fossil fuels, because we can analyze the chemical evidence for that.
3. **Our climate predictions are coming true.** Many observed climate changes, like rising sea level, are occurring at the high end of the predicted range. Some observed changes, like melting sea ice, are happening faster than the recently anticipated worst case. Unless humankind takes strong steps to halt and reverse the rapid global increase of fossil fuel use and the other activities that cause climate change, and does so in a very few years, severe climate change is inevitable. Urgent action is needed if global warming is to be limited to moderate levels.
4. **The climate change myths and falsehoods that Uncle Pete believes in have been refuted many times over.** The refutations are on many websites and in many books. For example, the mechanisms causing natural climate change like ice ages are irrelevant to the current warming. We know why ice ages come and go. That is due to changes in the Earth's orbit around the sun, changes that take thousands of years. The warming that is occurring now, over just a few decades, cannot possibly be caused by such slow-acting processes. However, it can be caused by human-made additions of heat-trapping substances to the atmosphere.
5. **Science has its own high standards.** Science does not mean unqualified people, who do not carry out scientific research, making unsubstantiated claims on television or the internet. Science means expert scientists doing research and publishing it in carefully reviewed research journals. Other scientists examine the research and repeat it and extend it. Valid results are confirmed, and wrong ones are exposed and abandoned. Science in the long run is

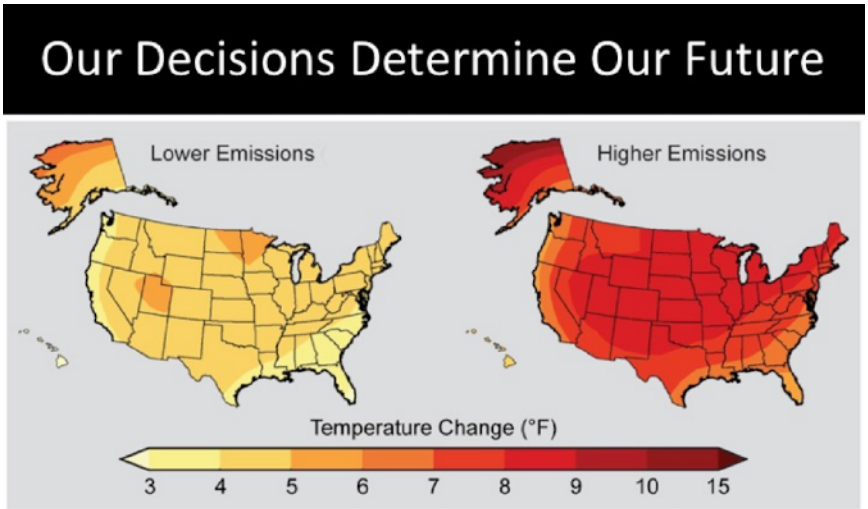

FIGURE 8.5.2 Reproduced from US Global Change Research Program. 2014.

self-correcting. People who are not experts, who are not trained and experienced in this field, who do not do research and publish it following standard scientific practice, are not doing science. When they claim that they are the real experts, they are not being truthful.

6. **The leading scientific organizations of the world, such as national academies of science and professional societies of scientists in fields relevant to climate change, have carefully examined the results of climate science and endorsed these results.** It is silly to imagine that thousands of climate scientists worldwide are engaged in a massive conspiracy to fool everybody. It is also silly to think that a few minor errors in the extensive IPCC reports can invalidate the reports. The first thing that the world needs to do to confront the challenge of climate change wisely is to learn about what science has discovered and accept it.

One last time: Always remember why we want to communicate climate change science. We want to inform people. We want to motivate them. We want them to act. The biggest unknown about future climate is human behavior. Figure 8.5.2 is a good illustration of the main take-home message from climate change science communication. These projections show that with lower global emissions of heat-trapping

gases—that's the map on the left—we can limit warming in the contiguous United States late in this century to about half of what it would be if we continue to rely on fossil fuels for the world's energy—that's the map on the right. The choice is up to us. Everything depends on what people and their governments do.

Supplementary Readings

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www.realclimate.org

www.richardsomerville.com

scrippsscholars.ucsd.edu/rsomerville

https://skepticalscience.com

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CHAPTER 9

Lessons from California

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Learning Objectives

1. Understand the historical foundation for California's climate policy. You will learn how local concerns—primarily air pollution in Southern California, but also public opposition to nuclear energy—built the institutional structures, technical capacity, and legal framework that the state later employed to tackle greenhouse gas emissions. You will also learn how a combination of public, legislative, and business support has maintained and extended California's climate policies.
2. Understand and identify the policy tools used to achieve cleaner air and a more energy-efficient economy. You will learn about the mix of regulatory, incentive-based, and market approaches that California has developed to reduce emissions and improve energy efficiency. You will also learn how the state has built on experience from elsewhere—for example, through designing a cap-and-trade system to avoid the problems experienced in Europe—and how it has responded to concerns about the equity and environmental justice impacts of climate policy tools.
3. Critically analyze the progress that California has made and the work that remains to be done. You will learn about the degree to which California has achieved its near-term objectives and the challenges that lie ahead as the state looks toward its goals for 2040 and beyond. You will be able to analyze why progress in some sectors has been rapid and identify the barriers that have hampered progress in other areas—particularly land use policies to reduce vehicle travel. You will also learn about the influence of California's policies beyond its boundaries and about how the state has served as a climate policy laboratory.

Overview

This chapter introduces the steps that one climate change leader, California, has taken to reduce its greenhouse gas (GHG) emissions across a wide range of economic activities. Given the magnitude of the climate change challenge, it's easy to conclude that brand-new or as-yet-undiscovered mitigation and adaptation policies will be needed. But California's experience shows that decades-old policies and programs designed to improve air quality and energy efficiency, as well as spur large-scale use of renewable power sources, can all be used to combat climate change. So, climate change policies are neither unknown nor untried; indeed, many of the required policies simply build on existing efforts that are widespread and well understood.

The chapter begins with some history, discussing how very poor air quality, especially in the Los Angeles basin, spurred activists, scientists, and policymakers to act. The chapter then focuses on California's innovative climate policies. We do not aim to provide a comprehensive guide to all of the state's efforts. Rather, we selectively review some of the most innovative and far-reaching policies, and chart the steady ratcheting up of its targets for greenhouse gas reductions and renewable energy. The first law explicitly requiring greenhouse gas reductions—anywhere in the country—targeted cars and other light-duty vehicles. The resulting regulations were adopted by 14 other states, accounting for almost 40% of US new vehicle sales. Later, the federal government worked with California to develop even more aggressive regulations. Thus, vehicle GHG emission standards were an early example of how California's policies could spur climate action beyond its boundaries.

Subsequent laws went beyond the transportation sector to require economy-wide greenhouse gas reductions. Most notably, Assembly Bill 32 (AB 32), the California Global Warming Solutions Act of 2006, set a target of reducing greenhouse gas emissions to 1990 levels by 2020, which in practice meant a reduction of 25% to 30% below business-as-usual emissions. A statewide vote highlighted the depth of California voters' support for climate policy; a ballot measure that would have effectively repealed AB 32 lost by more than 2 million votes.

Section 9.3 analyzes one of the centerpieces of California's plan to achieve the AB 32 target—cap and trade, which sets a limit on emissions and allows firms to trade emission allowances in order to reduce overall mitigation costs. California's experience with cap and trade has generally been a success. Emissions have fallen while the state's economy has prospered, and auctions of emissions permits have generated more than $10 billion for the state's Greenhouse Gas Reduction Fund.

Despite the high-profile nature of cap and trade, California has also relied on more traditional "command and control" regulations and performance standards, as well as other types of market instruments, to achieve its goals. The energy sector is a case in point. The state has continued to expand requirements for utilities to generate a certain portion of their electricity from renewables—by 2045, electricity must be 100% carbon free—and set energy efficiency standards. These energy gains have resulted in a state whose carbon footprint, in tons of CO_2 equivalent per capita, is much lower than that of the rest of the US, but still higher than the world average.

Section 9.5 discusses one area where the state's climate policies have had more limited results—encouraging more transit-oriented land use patterns that reduce vehicle travel and emissions from the transportation sector. The state has no authority over local land use decisions—that is, what gets built where. These decisions are jealously guarded by cities and counties as their own prerogative and determine whether and how far California residents have to drive.

In the final section, we'll go beyond AB 32, discussing how the state's targets have gradually increased in ambition. A 2016 law (SB 32) enshrines a target of reducing GHG emissions 40% below 1990 levels by 2030, and a subsequent executive order from the governor sets an even more ambitious goal of carbon neutrality by 2045. A key conclusion is that the politics of the state are favorable to climate policy. The lack of coal reserves and limited heavy industry, together with a business community that benefits from clean energy and environmental protection, have ensured that climate mitigation rests on a broad base of support.

9.1 Air Quality as the Genesis for Climate Policy

Urban smog in the Los Angeles basin is legendary. On many days, downtown skyscrapers and even the Hollywood sign blur into a dirty haze (Figure 9.1.1). Geography plays an important role; the San Gabriel Mountains create what is known as an inversion layer of warm air that traps the smog-laden cooler air below and prevents air pollution from dispersing. However, the region's air quality problems are rooted in the sheer number of cars and industrial pollution sources.

Southern California smog paradoxically laid the foundation for California's ambitious climate policy agenda and helped the state become one of the most energy efficient and least polluting in the country. The severity of air pollution forced a response that led to the creation of the institutional and legal framework that would later be harnessed in the fight against climate change.

A Dutch-American chemist, Arie Haagen-Smit, was the first to demonstrate, in the 1940s and 1950s, that Southern California smog was being caused by tailpipe emissions and smokestack gases. In 1968, Haagen-Smit became the first chair of the California Air Resources Board (CARB), a state agency that was created to help Californians address the problem of air pollution. Over the years, CARB developed and enforced air quality regulations, often acting earlier or more aggressively (sometimes both) than the federal government and other states. Indeed, California's tailpipe standards for automobiles, controlling hydrocarbons and carbon monoxide (CO), took effect in 1966—2 years before the first federal standards.

In the 1970s and earlier, officials in the Los Angeles basin issued many smog alerts when ozone concentrations reached 0.20 parts per million (ppm), warning residents to limit their physical exertion and sometimes even to stay indoors. Air quality staff recorded a maximum 1-hour ozone concentration of 0.58 ppm in 1970, nearly five times higher than the 0.12 ppm health-based standard that would be adopted later

FIGURE 9.1.1 Smog in downtown Los Angeles, circa 1995. California's experience since the 1940s in combating air pollution laid the groundwork for climate policy. Reproduced with permission from the Dorothy Peyton Gray Transportation Library and Archive at the Los Angeles County Metropolitan Transportation Authority.

that decade. As late as 1975, the South Coast Air Quality Management District issued smog alerts on 118 days. But air quality started getting better in the 1980s and has improved steadily ever since. By 1990, there were only 42 alerts, and there were none by 2000. These marked improvements came despite enormous population growth in the greater Los Angeles area, from around 10 million people in 1970 to around 17 million people in 2015.

One regulatory approach used by CARB and its federal counterparts in the 1970s and 1980s is known as **command and control**—the government commands firms and individuals to behave in a certain way, or to adopt a certain technology, and controls or monitors compliance. For example, bans on lead in gasoline, first implemented by CARB in 1992, 3 years in advance of the federal government, fall into this category. A closely related approach is called **performance standards**—the

government sets a limit on how much pollution can be produced for a given amount of activity but does not specify the precise technologies that must be used to achieve the standard. Auto tailpipe standards that dictate acceptable pollution releases in grams per mile are a good example of the performance standard approach that California has used.

Over the same period, California's environmental policy began to address broader questions of energy, normally using the same framework of command and control and performance standards. Through uniform building codes, appliance standards, and power plant requirements, the state steadily cranked down its per capita energy consumption and associated air emissions. While it's exceedingly difficult to show precisely how any particular environmental or energy policy affected pollution or consumption levels, many of California's trends (discussed in Section 9.4) are very encouraging.

9.2 California's Climate Legislation

California's recent wave of legislative efforts on climate change, summarized in Table 9.2.1, was built on the air quality and energy efficiency regulation described in the previous section and can be traced back to 2000. In a piece of legislation authored by state senator Byron Sher, California created the California Climate Action Registry to enable major sources of greenhouse gases to report their emissions and gain credit for "early action" to reduce CO_2 and other greenhouse gases. These efforts to collect baseline data helped build technical expertise, as California's regulators partnered with other regions, cities, states, and countries around the world to pool information and refine the methodologies for counting greenhouse gases.

Cleaner cars

The first major step toward regulating emissions, rather than just counting carbon, came in 2002, with the passage of a bill (AB 1493) from assembly member Fran Pavley to regulate the climate impact of motor vehicles. At the time, advocacy group Environmental Defense called it "the most important climate bill passed anywhere in the U.S. in the past two decades." Prior to the "Pavley bill," as it came to be known, emissions regulations for cars and light trucks had been limited to the pollutants that affect local air quality, such as carbon monoxide, oxides of nitrogen, and hydrocarbons. Carbon dioxide was not considered a "pollutant."

Car and light truck emissions are regulated by the Environmental Protection Agency (EPA). Because of long-standing smog in Southern California, however, California has a unique position under the federal Clean Air Act and can set its own, more stringent standards subject to a "waiver" from the EPA. Other states can follow California's stricter standards or default to the EPA rules. It was California's special status that the Pavley bill made use of, in order to add greenhouse gases to

TABLE 9.2.1 Major climate policy legislation in California

Year Enacted	*Bill*	*Key Provisions*
2000	SB 1771	Established the California Climate Action Registry to enable polluters to report their emissions
2002	AB 1493 (Pavley bill)	Required CARB to adopt regulations that achieve the "maximum feasible and cost-effective reduction of greenhouse gas emissions" from cars and light trucks
2002	SB 1078	Required 20% of retail electricity sales to come from renewables by 2017 (Renewables Portfolio Standard)
2006	AB 32 (California Global Warming Solutions Act of 2006)	Set target of reducing greenhouse gas emissions to 1990 levels by 2020, required CARB to develop a plan to achieve that target, and authorized the use of cap and trade
2008	SB 375 (Sustainable Communities and Climate Protection Act of 2008)	Required CARB to develop regional targets for greenhouse gas emissions and required regional agencies to develop integrated land use and transportation plans to achieve those targets
2011	SB 2-IX	Increased Renewables Portfolio Standard to 33% by 2020
2012	SB 535	Required at least 25% of cap-and-trade revenue in the Greenhouse Gas Reduction Fund to be spent on projects that benefit disadvantaged communities
2015	SB 350 (Clean Energy and Pollution Reduction Act of 2015)	Increased Renewables Portfolio Standard to 50% by 2030
2016	SB 32	Set target of reducing greenhouse gas emissions to 40% below 1990 levels by 2030
2016	AB 197	Required CARB to prioritize regulations that result in direct emission reductions (implicitly, command and control)
2017	AB 398	Extended cap-and-trade program through 2030
2017	AB 617	Required CARB to monitor and address local air pollution in the worst-affected communities, addressing some environmental justice concerns from cap and trade
2018	SB 100	Increased Renewables Portfolio Standard to 60% by 2030 and set goal of zero-carbon retail electricity by 2045

SOURCE: Adapted from California Air Resources Board. California Climate Change Legislation. https://www.climatechange.ca.gov/state/legislation.html.

the list of regulated pollutants. The Bush administration first delayed and then rejected California's waiver request, which would have allowed the new standards to take effect, but the waiver was quickly approved in 2009 once the Obama administration took office. Thus, while California continued to be at the forefront of national climate policy efforts, it could be most effective when its policies had the support of—or at least no opposition from—the federal government.

In what would become a common refrain for California's climate legislation, the Pavley bill did not set specific mandates for emission reductions. Instead, it required CARB to "develop and adopt regulations that achieve the maximum feasible and cost-effective reduction of GHG emissions from motor vehicles." Under the subsequent regulations, CARB required manufacturers to reduce per-mile emissions by about 30% by 2016, and by about 45% by 2020. Most of this reduction was to be achieved through improved fuel economy—for example, using turbochargers and more efficient transmissions in new cars—but the targets could also be satisfied through reductions in hydrofluorocarbon (HFC) emissions from air conditioners. HFCs are an important short-lived climate pollutant, as discussed in Chapter 15.

While the direct effect of the bill was limited to vehicles sold in California, 14 other states, accounting for almost 40% of US new vehicle sales, followed suit and adopted the Pavley standards, and several more were poised to do so. More importantly, the Obama administration later used them as the basis for even more aggressive federal regulations—negotiated together with California. Thus, California's law ended up influencing greenhouse gas limits for new vehicles for the entire United States. Without California's initiative, which demonstrated how ambitious reductions were technologically possible at a reasonable cost, federal regulation may well have been more limited.

Assembly Bill 32

While the Pavley standards were confined to the transportation sector, economy-wide greenhouse gas reduction goals followed soon after. An executive order from Governor Arnold Schwarzenegger set targets of returning to 2000 levels by 2010, to 1990 levels by 2020, and to 80% below 1990 levels by 2050—some of the most ambitious goals in the

FIGURE 9.2.1 Fran Pavley. As a state assembly member and senator, Fran Pavley authored several key pieces of climate legislation. Photograph by Jonathan Van Dyke, UCLA. Used by permission.

country. "I say the debate is over. We know the science. We see the threat, and we know the time for action is now," said the governor when signing the executive order.

Subsequent legislation gave the 2020 target the force of law and provided the mechanisms to achieve the emission reduction goal. Co-authored by Fran Pavley and Assembly Speaker Fabian Núñez, Assembly Bill 32 (AB 32), named the California Global Warming Solutions Act of 2006, was the centerpiece of the state's early climate change legislative efforts.

AB 32 is a short and simple bill, coming in at just 13 pages. (For comparison, the Waxman-Markey bill to introduce a federal cap-and-trade system, which passed the US House of Representatives but failed in the Senate, ran to more than 1,400 pages.) The main requirement of AB 32 was simply to return California's greenhouse gas emissions to 1990 levels by 2020, which in practice meant a reduction of 25% to 30% below business-as-usual emissions. The bill said very little about how to do that and did not even specify what "1990 levels" meant in terms of the number of tons of CO_2. The bill authorized, but did not mandate,

Box 9.2.1 Promoting Low-Carbon Fuels

The Low Carbon Fuel Standard (LCFS) is a good example of one of the hybrid policies pursued by CARB to achieve the AB 32 goal. Here, *hybrid* means that the LCFS combines regulations with market mechanisms to achieve its goal of reducing the carbon intensity of transportation fuels.

The initial LCFS regulation, adopted by CARB in 2009, required a 10% reduction in the greenhouse gas intensity of transport fuels by 2020. In 2018, the program was extended with a target of a 20% reduction by 2030. These targets are the heart of the regulatory portion of the standard.

The market mechanisms allow the targets to be met at lower cost and with increased flexibility. Oil companies that find it difficult or expensive to reduce carbon intensity can purchase credits from other fuel suppliers, such as electric utilities or biofuel producers.

The LCFS factors in the full life cycle emissions of different fuels. Those include emissions from oil extraction and refining, from combustion (burning) of the fuel in a motor vehicle, and from growing the raw materials for biofuels. For example, oil from the Canadian tar sands has a higher carbon intensity than conventional crude oil, while biofuels such as ethanol tend to have a lower carbon intensity, as does electricity.

a "market-based compliance mechanism" (that is, cap and trade) and more generally did not concern itself with the details of how to reduce greenhouse gas emissions.

Instead, the bill gave CARB responsibility for determining the 1990 baseline and developing a strategy to achieve the emission reduction target. The bill set a series of interim deadlines and specified objectives such as cost-effectiveness, technological feasibility, and equity. However, it said nothing about the types of regulations and other policies that should be implemented to meet the emissions goal.

CARB's blueprint to achieve the AB 32 goal is detailed in the Climate Change Scoping Plan, adopted in December 2008 after extensive technical analysis and public process and updated in 2014 and again in 2017. The first Scoping Plan set out both previously approved and new measures to reduce emissions by 174 million metric tons of CO_2 equivalent

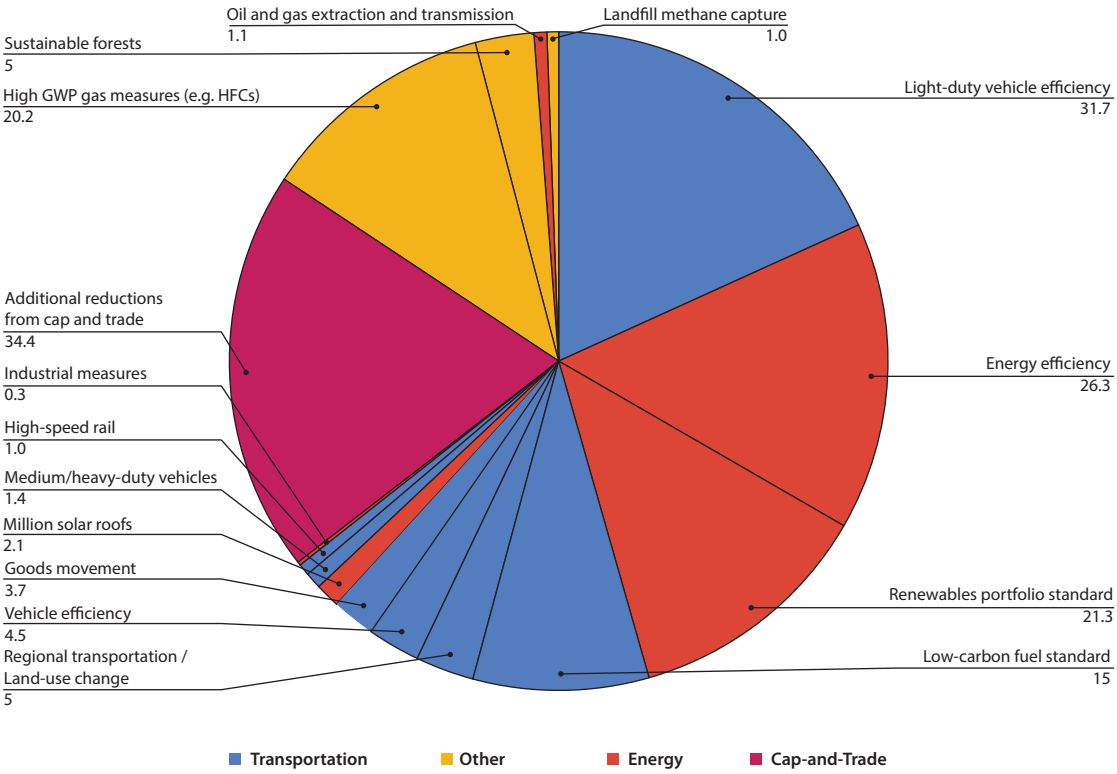


FIGURE 9.2.2 Planned sources of emission reductions in California's first Climate Change Scoping Plan. The reductions are those counted toward the 2020 target. Values indicate MMT CO_2e. Data from California Air Resources Board 2008.

(MMT CO_2e). The largest cuts (Figure 9.2.2) were to be achieved through the Pavley vehicle emissions standards; a new Low Carbon Fuel Standard (Box 9.2.1); energy efficiency regulations; requirements for 33% of electricity to come from renewable sources (the Renewables Portfolio Standard, or RPS, discussed in Section 9.4); and cap and trade, which is discussed in Section 9.3.

Leaving the details of how to achieve the AB 32 goal to a technocratic process within an existing regulatory agency brought many advantages. To some extent, it depoliticized decisions over specific emission reduction measures—in stark contrast to the federal Waxman-Markey proposal, which included intricate side deals negotiated with seemingly every affected industry. AB 32 allowed lawmakers to focus on the overall goal rather than the details of how it would be achieved. And it took

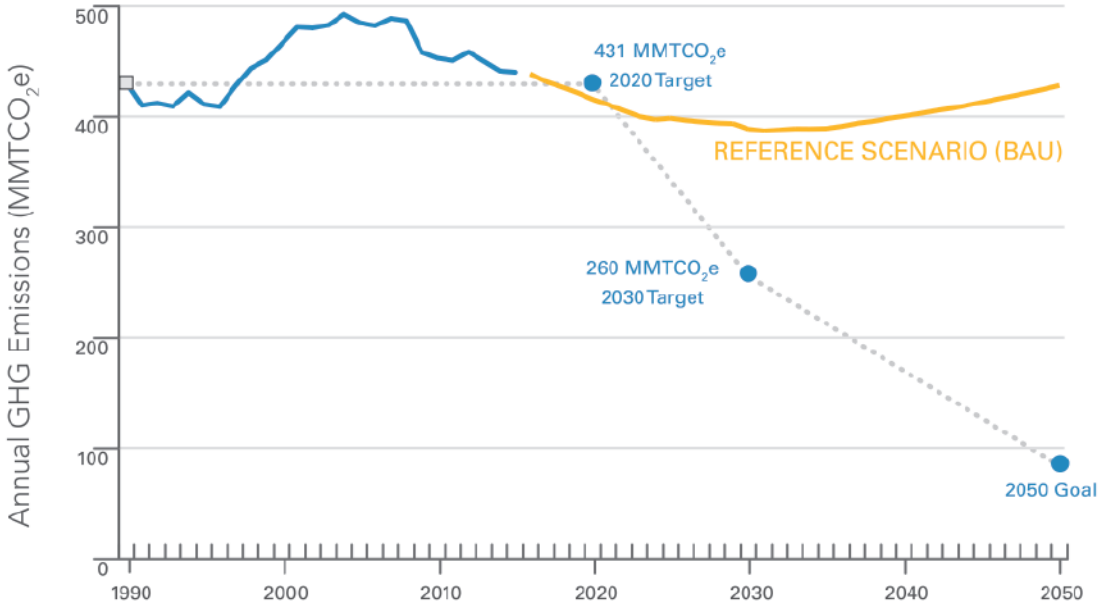


FIGURE 9.2.3 California emissions trends and targets. Reproduced with permission from the California Air Resources Board.

advantage of the institutional capacity of CARB, which as discussed in Section 9.1, had grown into one of the country's most technically adept regulators since the 1970s.

The successors to AB 32

More recent legislation has built on the foundation of AB 32. In particular, SB 32, enacted in 2016, ambitiously and vastly extends the state's targets beyond the 2020 horizon of AB 32, to enshrine a target of reducing emissions to 40% below 1990 levels by 2030. To the extent that AB 32 picked the low-hanging fruit, SB 32 represents an even greater commitment by the state. Most radically, outgoing Governor Jerry Brown issued an executive order in 2018 committing California to attain total, economy-wide carbon neutrality by 2045 and to achieve and maintain "net negative emissions" thereafter.

More-specific laws have also taken aim at specific sectors or focused on specific policies. The Sustainable Communities and Climate Protection Act of 2008 (SB 375) targets emission reductions from integrated

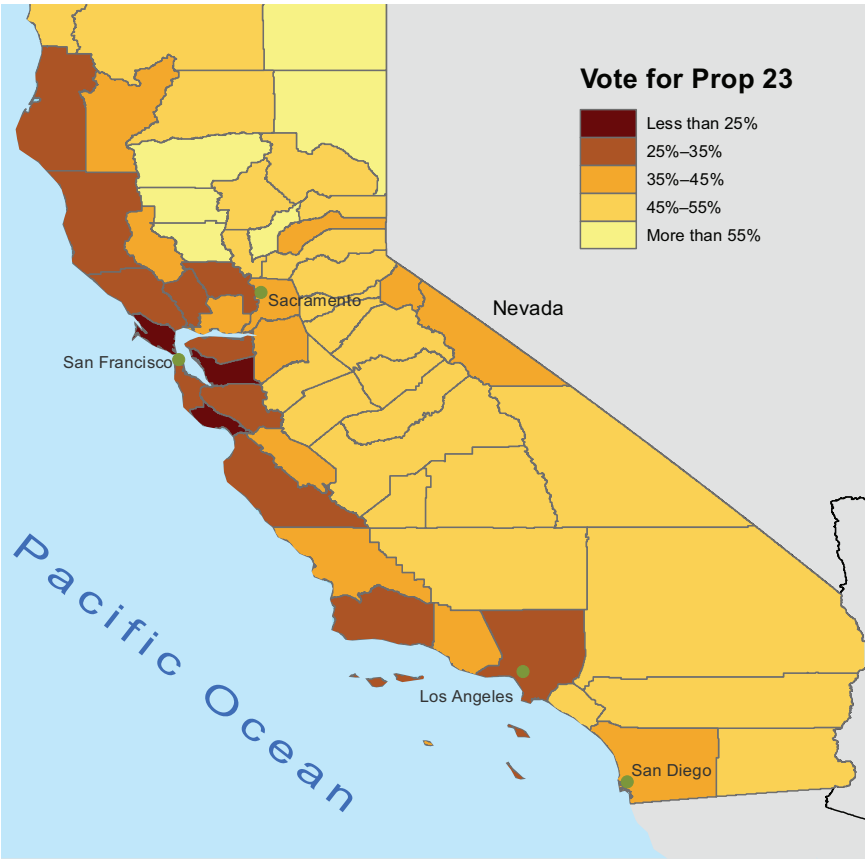


FIGURE 9.2.4 Voting patterns to suspend AB 32. The colors indicate the percentage in each county voting "Yes" on Proposition 23, which would have suspended and effectively repealed AB 32. Note that the support for suspension was strongest in the more remote northern and mountainous counties and was weakest on the coast, including in cities such as San Francisco and Los Angeles. Data from California Secretary of State. Map by Jesus Contreras, UC Santa Cruz.

transportation and land use planning; this effort is discussed in detail in Section 9.5. AB 398 extends the cap-and-trade program to 2030, and the accompanying AB 617 seeks to ensure that the benefits are distributed equitably throughout California (Section 9.3). Meanwhile, requirements for renewable energy have been ratcheting up (Section 9.4).

Thus, in the last two decades California's climate goals have become more ambitious. Not only have the targets been extended and deepened, but they go far beyond aspirational rhetoric and are accompanied

FIGURE 9.2.5 Anti–Proposition 23 campaign rally. The "No" campaign against AB 32 suspension focused on the fact that the initiative was backed by out-of-state oil companies such as Valero. This rally took place at UC Santa Barbara. Photograph by Ron V. Ocampo, The Bottom Line. Used by permission.

by extensive analysis and an effective implementation mechanism. The AB 32 target for 2020 seems likely to be achieved. By 2016, emissions had already fallen to below the required level (Figure 9.2.3), and so, provided that emissions do not tick up between 2017 and 2020, California will attain this major landmark.

California's steadily increasing commitments may seem inexorable, given the progressive political climate in the state and strong support from successive governors, the legislature, and the voters. Both AB 32 and the earlier Pavley clean-cars legislation were passed by a Democratic-controlled legislature, with support and leadership from Democratic and Republican governors, Gray Davis and Arnold Schwarzenegger. However, they did not become law in a political vacuum or in the absence of political opposition. The car industry vocally opposed the Pavley bill to limit emissions from motor vehicles, on the

grounds that it was a "veiled attack on California's family vehicles," such as SUVs and pickup trucks. AB 32 itself was the subject of a referendum (Proposition 23) in 2010, which would have effectively repealed the law by suspending its provisions until the statewide unemployment rate fell to 5.5% for a full year. (Rarely has statewide unemployment fallen that low for that long; at the time of the campaign, it was about 12%. Thus, "suspension" would have meant effective repeal.)

The Proposition 23 campaign, however, ended up highlighting the depth of California voters' support for climate policy and its air quality co-benefits. The anti–AB 32 measure lost by more than 2.2 million votes, with 38% in favor and 62% against (Figure 9.2.4). Campaign contributions from some mainly out-of-state oil companies were outweighed by pro–climate policy donations from individuals, nonprofit organizations, and labor unions. Many key organizations, including electric utilities, the California Chamber of Commerce, and oil companies such as Chevron, remained neutral or were opposed to the repeal measure. Partly, this broad support reflects California's low-carbon economy; indeed, "green jobs" were a key message of the "No on Proposition 23" campaign. But the referendum also reflected the political interests of many businesses, whose leaders evidently decided that energy conservation, low-carbon fuels, and CO_2 mitigation are the route to a profitable future.

9.3 The Cap-and-Trade Experiment

Cap and trade is one of the highest-profile features of California's emission reduction efforts. In the 2008 Scoping Plan, it accounted for 34.4 of the 174 MMT CO_2e of estimated reductions. These reductions would come about as cap and trade put a price on carbon, giving firms and individuals the financial incentive to reduce emissions. Just as importantly, cap and trade provided assurance that the AB 32 target would be met, assuming that the system functioned as intended. Should one of the other measures in the Scoping Plan fall short of expectations, cap and trade would soak up the shortfall.

During the debates over AB 32, cap and trade was a point of contention. From an economic point of view, cap and trade allows a given emission target to be achieved in the most efficient way possible (Chapters 11 and 12 for a more in-depth analysis). However, California was emerging from a bruising experience with a cap-and-trade program for a different pollutant—the RECLAIM program for nitrogen oxides in Southern California, which was partially suspended after permit prices rose from about $2,000 to more than $120,000 per ton during California's electricity crisis. Another set of concerns related to environmental justice. Because cap and trade does not specify where and how emissions will be reduced, it is possible for an inequitable outcome to occur, with middle-class, majority-white, higher-income communities benefiting the most.

Design of cap and trade in California

The compromise was for AB 32 to authorize, but not require, CARB to implement "market-based compliance mechanisms"—in other words, cap and trade. CARB ultimately opted to use this authority, and the detailed system design was informed by a market advisory committee of prominent academics, state and local officials, and other parties. However, most of the emission reductions in the Scoping Plan were to

be achieved through more-traditional command-and-control regulatory measures rather than the cap-and-trade system—effectively mandating many of the reductions that would have occurred anyway through the market-based approach of cap and trade. This hybrid system—part market based, part regulatory—may have reflected a lack of confidence in cap and trade, the political realities, and/or CARB's traditional regulatory expertise. In 2016, new legislation (AB 197) reaffirmed the role of command and control in California's climate policy.

When launched in 2013, the cap-and-trade system covered large electric power plants and industrial facilities. In 2015, it was extended to apply to fuel distributors, meaning that the heating and transportation sectors would be covered as well and that the program would encompass nearly 85% of California's emissions. Cap and trade for transportation does not mean that individual drivers need to buy and sell carbon allowances. Rather, this task is handled by fuel distributors, and the cost is passed on at the pump. In practice, cap and trade has added about 14 cents to a gallon of gasoline, providing a small incentive for drivers to choose more fuel-efficient cars and to drive less.

The *cap* in cap and trade refers to the limited number of emission allowances that are issued. One allowance gives the right to emit 1 ton of CO_2, and a polluter subject to the cap must purchase or otherwise obtain enough allowances to cover its emissions. The number of allowances issued by CARB each year is planned to gradually fall to 334 million in 2020—achieving the 2020 emissions goal, provided that sufficient emission reductions are also achieved by "non-capped" polluters, that is, those that remain outside the cap-and-trade system. These non-capped pollution sources include hydrofluorocarbons and other "super pollutants" (Chapter 15), emissions from agriculture and land use change, and methane emissions from the decomposition of organic waste in landfills.

CARB's decisions regarding the distribution of emission allowances internalized the lessons learned from problems with previous cap-and-trade programs, such as the European Union Emissions Trading Scheme (EU ETS) and the RECLAIM program for nitrogen oxides in Southern California. In particular, two innovations aimed to avoid the price volatility

experienced in Europe (where the prices of allowances have on occasion fallen to near zero) and in Southern California's RECLAIM program:

- An auction **reserve price**—this is the minimum price at which CARB will sell allowances. It started at $10 in November 2012 and rises each year at 5% plus inflation. The reserve price ensures that cap and trade will always provide a financial incentive to reduce emissions, and it avoids the risk that the price will fall to zero.
- An **allowance reserve** or "safety valve"—this is an extra pool of allowances that CARB only issues if the price rises above a given level.

Together, the reserve price and the allowance reserve make the price of carbon more predictable, enabling firms to plan their investments with greater confidence.

California's cap-and-trade experience

In general, California's experience with cap and trade has been a success and has avoided many of the pitfalls of trading programs in Europe and the northeastern US (Chapter 12). Emissions have fallen while the state's economy has prospered. The auction price has normally been slightly above the reserve price, and statewide emissions have declined along with the cap. Several major criticisms, however, remain.

One concern relates to the **reshuffling** of electricity contracts. That is, California's electric utilities have swapped out purchases of out-of-state coal-generated electricity in favor of cleaner sources elsewhere on the western electricity grid, which extends far beyond the state's borders. However, some of these coal-fired power stations have continued to sell electricity to consumers in other states, swapping out contracts in the opposite direction. Thus, while California reports lower emissions, the net reduction—considering emissions in other western states—is more limited. Coal plants simply sell their power to customers in Nevada, Arizona, or New Mexico instead.

Another concern for cap-and-trade integrity is **carbon offsets**. An offset is a certified emission reduction from a project that is not subject to the cap-and-trade program. In California, offsets allowed by CARB mainly come from forestry and agriculture, such as projects to reduce

methane emissions from flooded rice fields. Polluters can use an offset credit in place of an emission allowance. If all offsets were "real" and "additional," there would be no cause for concern, but in practice many offset projects may have been undertaken anyway.

A third potential challenge is the volume of allowances that firms have accumulated. More than 200 million allowances have been **banked**, or held by polluters for future use or sale. Such banking means that emissions are lower in the short term, but this practice may threaten the state's ability to achieve longer-term reductions.

A broader criticism of the cap-and-trade program relates to equity and environmental justice. As noted above, while cap and trade provides a price signal to reduce emissions and it limits overall emission levels, it does not prescribe *where* those reductions take place. In the first 3 years of California's trading program, some polluters increased emissions, while others reduced emissions. Those that increased emissions tended be located in places with more people of color, lower-income people, and other marginalized groups (although this analysis excludes emissions from transportation, which account for the majority of local air pollution impacts). This would not be a problem if the pollution were confined to CO_2 alone—while a major cause of climate change, CO_2 does not have any direct adverse health impacts. However, factories, power stations, and other sources of CO_2 also tend to emit other pollutants, such as sulfur dioxide and particulate matter, that do have health consequences for people nearby. At least in its early years, cap and trade seems to have done little to realize the hopes of improved air quality in the state's most vulnerable communities. Many of the co-pollutant reductions occurred out of state, as California's electric utilities reduced their purchases of imported coal-generated power, while in-state emissions saw more-limited changes and even increased in some places.

The equity situation may improve as the cap declines and polluters in all parts of the state begin to reduce their emissions. However, a more direct approach to address environmental justice concerns is to strengthen even further the regulation of local air pollution (where location matters) separately from greenhouse gas emissions (where the global concentration matters, not the location of the source). Indeed,

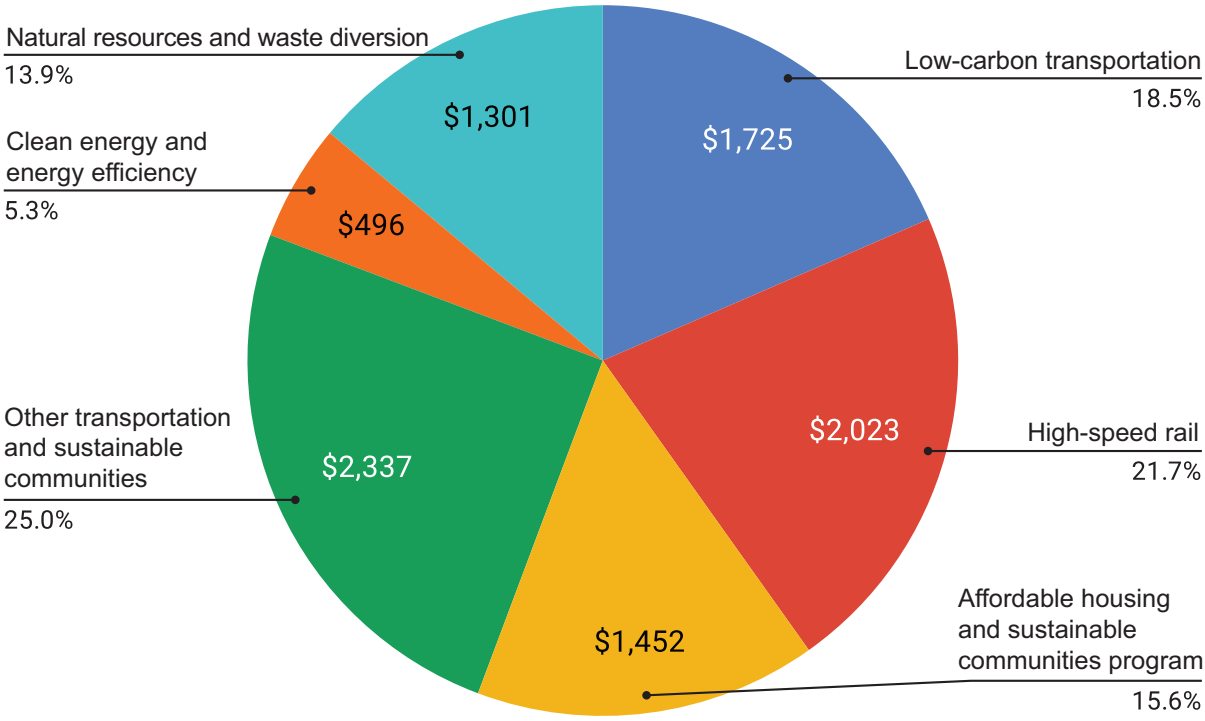


FIGURE 9.3.1 Use of revenues from cap and trade. Figures show appropriations from the Greenhouse Gas Reduction Fund ($ million) through fiscal year 2018–2019. Data from California Air Resources Board.

this direct approach was the tenor of the state legislature in Assembly Bill 617 (AB 617) in 2017, which was enacted as a parallel measure to the extension of the cap-and-trade system. AB 617 requires CARB and its local counterparts to implement additional air quality monitoring in heavily polluted communities, to accelerate the introduction of pollution control technologies, and to develop a statewide strategy to reduce local air pollution in the worst-affected communities.

Another positive contribution to equity—and to other state goals—comes from the revenue generated by auctioning a portion of the emission allowances. Through early 2019, the auctions have generated $10.3 billion for the state's Greenhouse Gas Reduction Fund. By law, at least 35% must be spent on projects that benefit and are located within (or, in a few cases, within a half mile of) low-income neighborhoods and disadvantaged communities that are disproportionately affected by pollution. Figure 9.3.1 shows how the money raised to date has been used. Some

projects focus on general emission reductions—for example, high-speed rail, encouraging housing close to public transit, water efficiency, and manure management. However, other projects specifically target low-income communities, such as the Low-Income Weatherization Program that funds energy-efficient appliances, new windows, water heaters, and other improvements that both reduce emissions and reduce household energy bills.

9.4 Energy

Many of California's climate policy efforts have been economy-wide—that is, they aim to reduce greenhouse gas emissions in many different sectors, such as industry, electricity generation, and transportation. However, legislators have also pursued more-focused efforts aimed at increasing energy efficiency and the use of renewable energy in the state. These efforts, which have led to California's having one of the least-carbon-intensive electricity supplies in the United States (Figure 9.4.1), date back to the 1970s, before climate change became a major issue. Instead, the original motivations included the oil crisis and fears over nuclear power.

To understand California's energy policy history, you have to understand the state's geography, its development history, and a little bit of its political culture. First, let's think about the geography. California is a large state in terms of land area—a state that's as big as many countries around the world. It has no coal, which has significantly influenced its energy pathway. Otherwise, however, it has an abundance of energy resources. It has a lot of oil, especially down in Southern California. It has a little bit of geothermal. Unlike the other western states or Appalachia, California has a large volume of water runoff from the Sierra Nevada, which has been tapped for hydroelectric potential. There's a lot of wind power, especially around Altamont Pass, near San Francisco, and down south in the Tehachapi Mountains, just north of Los Angeles. And California receives many hours of sunshine, with concomitant potential for solar power.

But renewable energy was not on the minds of energy planners around the middle of the twentieth century, when California's population and economy were rapidly growing. At the time, the assumption was that electricity generation capacity had to keep pace with population and economic growth—they were **coupled** together. Nuclear power was seen as the best way to scale up the supply to meet the

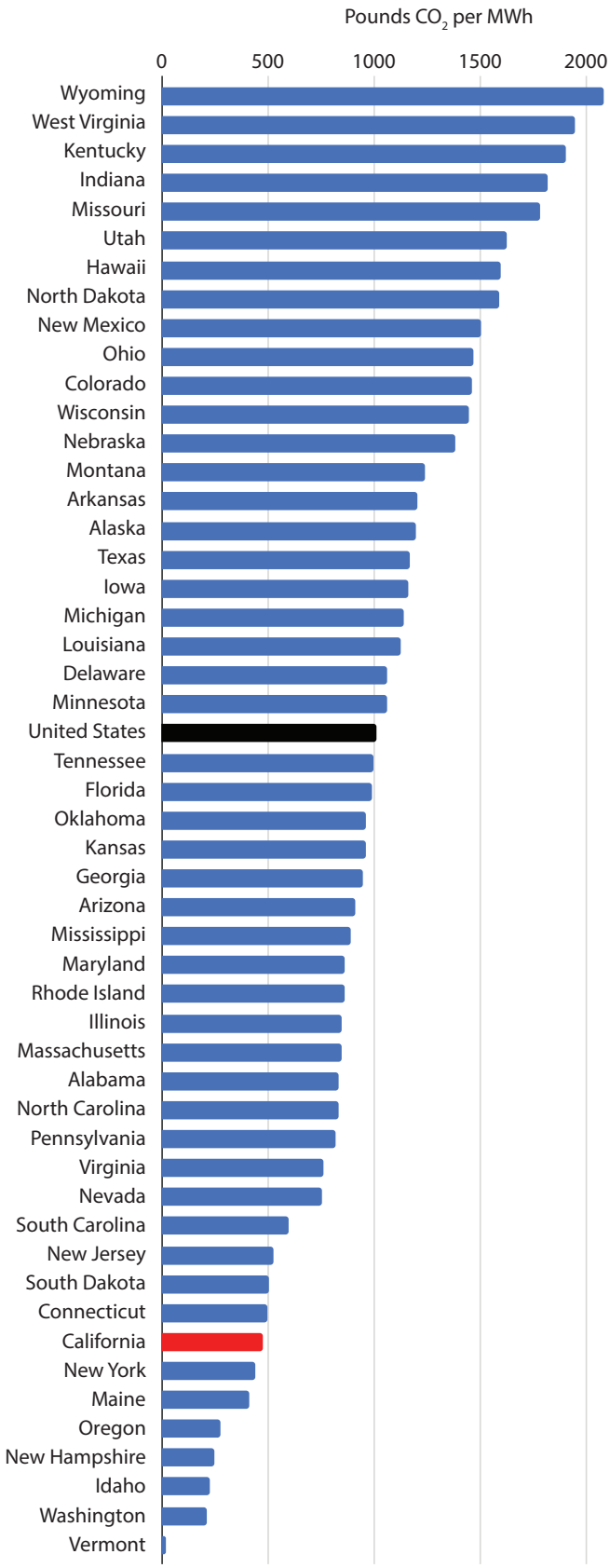


FIGURE 9.4.1 Electric power carbon intensity, by state, 2017. California has the eighth-least-carbon-intensive state power generation mix in the US. Most of the states that are less carbon intensive have much smaller populations and rely on hydroelectric or nuclear power. Data from US Energy Information Administration.

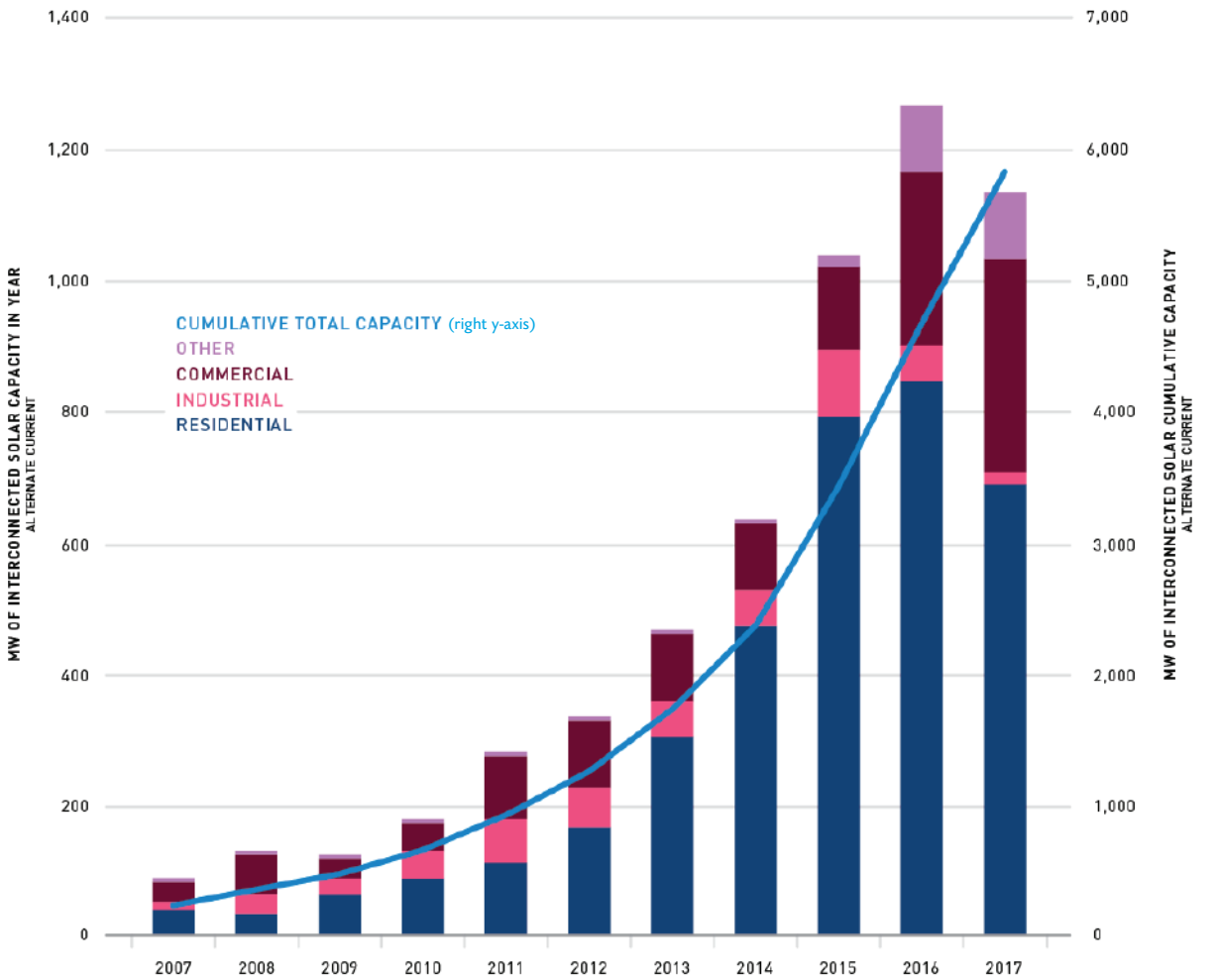
forecast demand; a series of planned nuclear plants on the coast from Southern California all the way up to the north would cool their reactors with the abundant waters of the Pacific. However, public opposition—partly due to the risks posed by earthquakes, and partly because of consciousness around the disposal of radioactive waste—frightened the public, prompting many to say, well, we don't want nuclear either. In 1976, state legislators placed a moratorium on new plants, pending a permanent solution to nuclear waste.

Energy planners were then faced with the dilemma of how to increase generation capacity without relying on nuclear, coal, or oil. Nuclear had been ruled out because of safety and waste concerns; the state had few reserves of coal; and oil, which in any case is a poor fuel for producing electricity, was in question following the embargo of 1973. Moreover, plentiful supplies of natural gas were not yet available in California.

In response, the legislature passed the Warren-Alquist Act in 1974 to create the California Energy Commission (CEC). While this might seem like a trivial move—yet another bureaucracy—the CEC created the framework to plan for energy in a comprehensive manner. The CEC preceded the federal Department of Energy (which was founded in 1977) and had the money and staff to plan in a systematic way, rather than lurching from one project to another.

Renewable energy was one area of policy that the CEC pushed forward, with large-scale wind energy projects as the initial focus. Subsequently, the state's Renewables Portfolio Standard (RPS) required utilities to source a certain proportion of retail sales of electricity from renewables. The first RPS, in 2002, was set at 20% by 2017. Over the years, the targets have ratcheted up, with a 2018 law setting an RPS of 60% by 2030 (Table 9.2.1). The same law sets a goal of carbon-free electricity by 2045, although the *carbon-free* definition encompasses several sources that do not qualify as "renewable" under the RPS, such as nuclear and large hydroelectric dams.

The state is already much of the way toward the 2030 and 2045 goals. On a sunny day—not too hot, not too cool—in March of 2017, 40% of the state's electricity was being generated by **utility-scale solar**, that is, large installations such as solar farms in the desert. Adding in



NEXT 10 CALIFORNIA GREEN INNOVATION INDEX. Note: The data set only includes interconnected solar PV Net Energy Metering (NEM) projects and presents the current "state of the world" in terms of how many interconnected solar PV projects and how many megawatts are installed in a given geographic area. Calculations based on "Application Approved Date." It does not include utility-scale solar installations.
Data Source: Currently Interconnected Data Set, California Solar Statistics. NEXT 10 / SF · CA · USA

FIGURE 9.4.2 **Interconnected solar in California. Through 2016, solar energy grew almost exponentially. In 2017, capacity reached almost 6,000 megawatts (MW), up from 228 MW just 10 years earlier. Residential rooftops account for most of the capacity.** Reproduced with permission from Next 10.

the solar panels that are dotting thousands and thousands of rooftops throughout California, that number came to about 50%. Figure 9.4.2 charts the dramatic growth in solar capacity, and Figure 9.4.3 illustrates the evolution of energy policy in California over the last 50 years.

Local governments, meanwhile, have been pushing forward with

FIGURE 9.4.3 Rancho Seco. The decommissioned Rancho Seco nuclear power plant in Sacramento County now hosts a solar farm and is under contract to the Golden 1 Center, the home of the Sacramento Kings. At full build-out, the facility will provide up to 100 MW of power, taking advantage of the transmission lines and other infrastructure built for the nuclear plant. Photograph by Hajhouse from Wikimedia Commons.

even more ambitious plans for renewable energy. **Community choice aggregation** (CCA) allows cities and counties to make energy supply decisions for their communities, taking over from investor-owned utilities. CCA programs have been launched in San Francisco, Los Angeles, and many other parts of the state and have normally aimed for higher shares of renewable power than the state-mandated minimums. Collectively, CCA programs are likely to mean that the targets in the state's RPS are exceeded by 9% in 2025, equivalent to 1–2 MMT CO_2e.

Less visible than wind turbines or solar panels, but just as effective in reducing carbon emissions, have been the CEC's efforts to promote energy efficiency. Partly, the CEC acted through direct regulation, setting efficiency standards for refrigerators and, later on, for such varied appliances as swimming pool heaters, furnaces, and computers. But the CEC and its partner agency, the Public Utilities Commission, also worked to transform the motives of utilities. Before, the more electricity they sold, the more money utilities made. They had a vested interest in encouraging profligacy. Under the state's new model, utilities were rewarded for weatherizing residences and commercial facilities and for promoting more-efficient heating and cooling equipment. In effect, utilities were allowed to charge ratepayers for not just megawatt hours, but **negawatts**, or negative watts—the energy savings from efficiency. This model of **decoupling** their profits from growth in energy consumption transformed the utilities overnight. Overnight, they became indifferent to sales—it was just as profitable for them to weatherize homes as to build new power plants.

Today, California ranks fiftieth among US states in per capita electricity consumption. The US per capita annual residential electricity consumption in 2011 was 4,566 kilowatt hours (kWh); California's was 2,346. Taking all consumption together (residential and commercial), the US per capita electricity consumption in 2016 was 11,634 kWh, but California's was only 6,536 kWh. Whether measuring just residential or all end use, the national average is almost twice that of California; a remarkable statistic, even accounting for California's mild climate—Californians use less air conditioning than residents of most other southern and western states. Most (64% in 2017) homes in California are heated with natural gas, a far more efficient form of home heating than electricity, and Californians also heat their water mostly with natural gas. Fully 14% of homes were not even heated in 2009. The state ranked thirtieth in its average annual per capita residential natural gas use in 2011.

9.5 The Land Use Problem

Shortly after AB 32 was passed, there was a growing realization that CARB had few tools to bring about emission reductions from regional land use planning and transit-oriented development patterns that reduce vehicle travel. Such plans would encourage denser, mixed-use development in urban centers and in other places well served by public transit, in contrast to the sprawl that has characterized much postwar development in California.

However, in considering land use planning, CARB ran up against the limits to its regulatory authority. While CARB had achieved success through command-and-control policies and performance standards such as the Pavley clean car standards, and through market-based approaches such as cap and trade, it had no authority over local land use decisions, which are jealously guarded by local governments—that is, cities and counties—as their own prerogative. And in contrast to out-of-state car manufacturers and oil companies, which had little clout with decisionmakers, local governments wielded substantial influence in the state legislature. Given that transportation accounts for more than 40% of California's greenhouse gas emissions, not including a further 7% from petroleum refining and hydrogen production, this was a major gap in the state's climate policy arsenal.

The legislative compromise was for CARB to set regional targets for emission reductions from the transportation sector but to avoid imposing any mandates on local governments. Senate Bill 375 (SB 375), the Sustainable Communities and Climate Protection Act of 2008, makes the state's 18 metropolitan planning organizations (MPOs)—regional agencies that plan for freeways and public transit expansions and make other large-scale transportation spending decisions—responsible for developing plans to meet these targets. Each MPO was asked to develop a sustainable communities strategy to demonstrate the combination of land use patterns and transportation policies that would allow it to meet

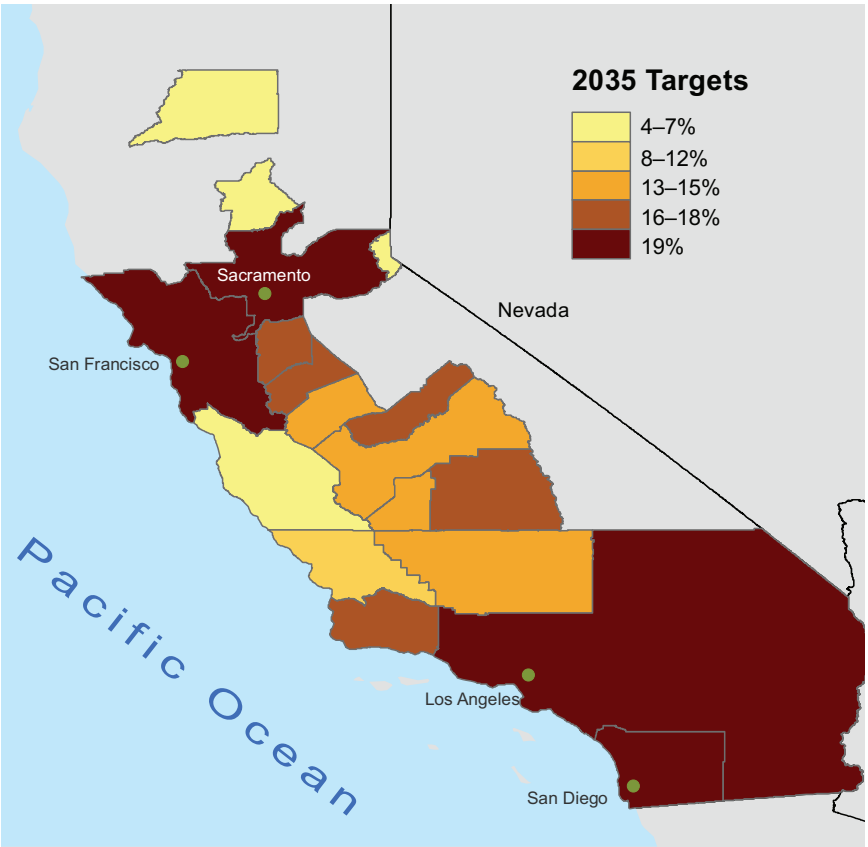


FIGURE 9.5.1 Regional greenhouse gas reduction targets. Targets refer to the reduction in per capita passenger vehicle emissions between 2005 and 2035, as adopted in 2018. The four largest regions (Southern California, San Francisco Bay Area, San Diego, and Sacramento) each have a 19% reduction target. Smaller regions have reduction targets ranging from 4% to 17%. Data from California Air Resources Board 2019. Map by Jesus Contreras, UC Santa Cruz.

its regional target. When it was passed, SB 375 was billed by Governor Schwarzenegger as the "nation's first law to control greenhouse gas emissions by curbing sprawl."

The process of setting the targets involved detailed modeling work and a negotiation between CARB and each metropolitan region. Some regions went beyond CARB's initial proposal, while other regions were more recalcitrant. The most recent (2018) round of targets call for reductions in per capita passenger vehicle emissions of 3% to 15% between 2005 and 2020, and 4% to 19% between 2005 and 2035. The

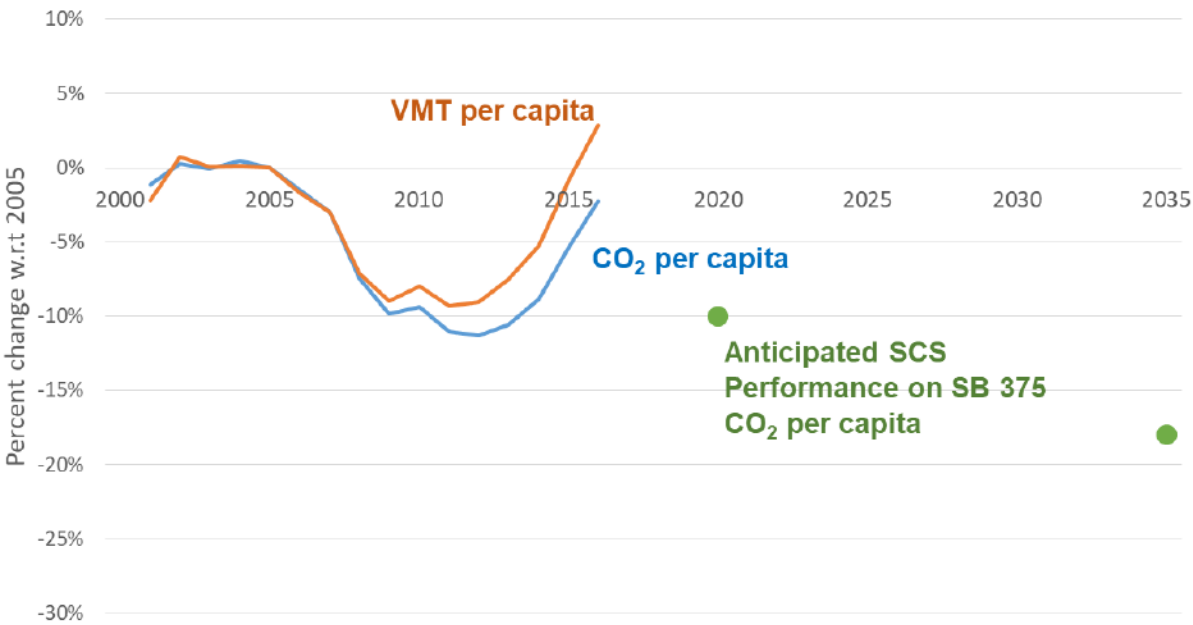


FIGURE 9.5.2 Vehicle travel and CO_2 trends in California. The orange line indicates vehicle miles traveled per person, and the blue line shows emissions from gasoline-fueled vehicles in California. The green dots indicate the modeled outcomes from the regional sustainable communities strategies, which, if current trends continue, will not be achieved. Reproduced with permission from California Air Resources Board 2018.

more limited reductions apply to smaller regions such as Monterey Bay and Shasta, while the most ambitious apply to the four largest metropolitan areas (Figure 9.5.1).

So far, SB 375 has led to incremental progress, but it is far from a revolution that is overturning entrenched patterns of urban sprawl. On the positive side, each region has developed a sustainable communities strategy that, according to its modeling, will meet its target. The law has changed the way that planning is done in many regions, leading to a greater emphasis on climate change and integration of transportation and land use planning efforts. And some regions have responded enthusiastically. In the San Francisco Bay Area, for example, regional agencies introduced a new grant program that rewards cities for building housing close to transit and implementing affordable housing policies.

Overall, however, Californians have increased their driving, meaning that fuel-efficiency gains from the Pavley clean car standards have been

outweighed by a greater number of miles driven (Figure 9.5.2). Transit ridership has declined in major metropolitan areas, and the proportion of funding dedicated to highways has changed little. There has been no dramatic shift in funding priorities toward public transportation, walking, and cycling. Overall, CARB's 2018 progress report finds that "California is not on track to meet greenhouse gas reductions expected under SB 375." The modeled reductions have yet to materialize in practice.

At root, SB 375 does not provide a way to coerce or incentivize recalcitrant cities into curbing car use through increasing densities and reducing parking next to transit. Cities still have incentives to be **free riders.** That is, city governments want tax revenue from car-oriented shopping centers and low-density, high-end housing within their own borders while relying on their neighboring cities to provide space for new housing next to transit. In contrast to the strong regulatory power that CARB wields in many other domains and the clear price signal provided by cap and trade, land use planning shows the limits of the state's climate policy power.

9.6 Conclusions and Outlook

California is one of the country's climate mitigation success stories. By many measures, it ranks among the least greenhouse-gas-intensive states in the US. On a per capita basis, only New York and Vermont rank lower, and the average Californian emits just 53% of the national average amount of greenhouse gases. California's large metropolitan regions also score well compared with their counterparts elsewhere. In popular perception, Los Angeles might be the poster child for unsustainable excess. But when measured by household greenhouse gas emissions per capita, the region is one of the greenest in the nation. San Diego, San Francisco, and San Jose claim the top three spots in one metropolitan-level ranking, while LA comes in at number five, after Providence, Rhode Island.

Most impressively, California's greenhouse gas reductions have not come at the expense of its economy. Figure 9.6.1 shows that the state's per capita GDP (roughly equivalent to average income) has grown even while emissions per capita have fallen. Indeed, some of the strongest supporters of AB 32 and other climate legislation have been clean energy firms and other businesses that see environmental protection as beneficial for the economy rather than a drag on performance.

California's success is partly an accident of geography. The largest cities lie near the coast where, for most of the year, homes achieve a pleasant temperature with neither air conditioning nor heating. About 40% of the state's electricity comes from low-carbon sources such as renewables, hydro, and nuclear—that is in part the result of deliberate policy, but also the product of federal subsidies for dams and the lack of large coal deposits in the state. Most of the remainder of the electricity is generated from natural gas.

Low emissions are also a product of a service-based economy with little heavy industry. California ranks among the lowest five states in terms of the emissions intensiveness of the economy, although this is

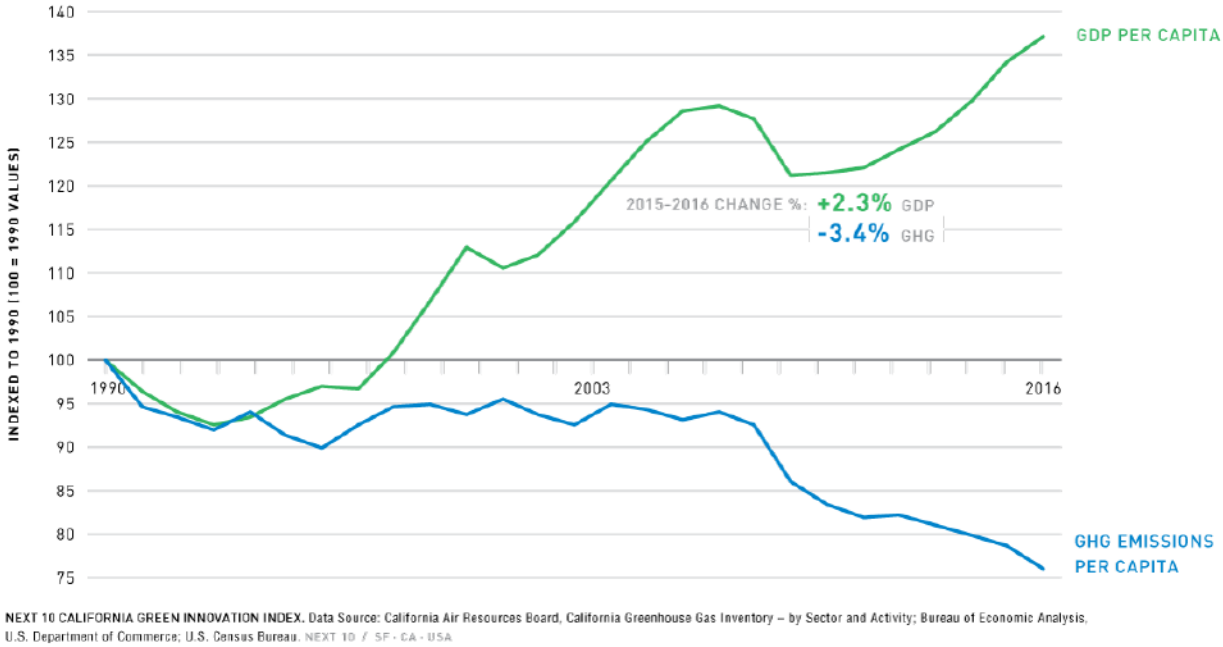


FIGURE 9.6.1 Greenhouse gas emissions and economic growth. Between 1990 and 2016, California's economy grew while greenhouse gas emissions declined in per capita terms, indicating that climate mitigation does not have to be at the expense of economic growth. Reproduced with permission from Next 10.

partially offset by "embedded" emissions in imported products, which, perhaps misleadingly, are not captured in the state's emissions inventory.

The nature of California's economy means that political support is easier to gather for wide-ranging climate change policy. In districts with low per capita emissions, politicians are more likely to support climate legislation. A reduction in power generation from coal, for example, will affect mining employment in neighboring states but cost few jobs in California. Fossil fuel extraction and automobile manufacturing are only minor players in California's economy. In contrast, sectors that would be harmed by climate change, such as agriculture and tourism, or that would benefit from efforts to reduce emissions, such as renewable energy technology, have a much larger presence on the West Coast. One of the main economic powerhouses of the state, the technology industry and associated venture capitalists centered in Silicon Valley, also tends to be a strong supporter of GHG mitigation. Energy costs for their

California operations are minimal (most server farms and data centers are located elsewhere), and many firms invest in innovations to improve energy efficiency or otherwise reduce emissions. Thus, California governors and legislators have shown a willingness to enact climate legislation far ahead of the federal government and most other states.

The political attitudes that favor climate change action in the state legislature and governor's office also permeate through many of the state's counties, cities, water and transit districts, and other local and regional agencies. Many officials, such as former San Francisco mayor and now California governor Gavin Newsom, have sought to portray themselves as leaders on climate policy—in part in an effort to pressure the federal government into action. San Francisco is rated the most progressive large city in the country, and Oakland the fourth.

The legacy of the air quality and energy efficiency programs from the 1970s and 1980s has also played a part. California regulators have been accustomed to taking action on air quality, renewable energy supply, and other environmental issues, which in other states might be left to the federal government. CARB, which has assumed the primary role in California's climate efforts, already had a depth of technical, regulatory, and legal expertise that positioned it well to respond to climate change policy imperatives.

What lies next for California? While the state is likely to achieve its 2020 goals, the 2040 target (a 40% reduction below 1990 levels) is much more ambitious, and the goal of carbon neutrality by 2045 even more so. Many of the low-hanging fruits (such as switching away from out-of-state coal generation) have already been picked. One key challenge is the number of "banked" allowances (Section 9.3) that may reduce the effectiveness of cap and trade in the future. Another is the stubborn resistance of the transportation sector, where vehicle travel has ticked up in recent years and local governments have been reluctant to implement the land use changes called for in regional plans. And a third is the federal government. While the Obama administration was largely supportive, the Trump administration has signaled that it will throw up roadblocks to the state's policies—for example, by threatening to revoke the waiver that California needs to enforce its more stringent clean car standards.

If California were an independent country, it would rank as the world's fifth-largest economy. This means that the action that California takes to reduce emissions is intrinsically important in terms of atmospheric carbon concentrations. Fundamentally, however, California's success should be measured not just by its ability to reduce in-state greenhouse gases, but also by its influence on energy efficiency and climate policy beyond the state's boundaries, in what is often called the "California effect." The Pavley clean car standards were adopted by 14 other states, accounting for almost 40% of US new vehicle sales, and ultimately by the federal government. Its cap-and-trade system has been joined by the Canadian province of Quebec, with the two governments holding joint auctions (although earlier plans for Ontario and several US states to join never materialized). And California's energy efficiency standards for everything from refrigerators to buildings have influenced policy elsewhere. Providing a laboratory to test and demonstrate the economic and technological feasibility of deep reductions in greenhouse gas emissions may be the state's most significant contribution to confronting global climate change.

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CHAPTER 10

The Paris Agreement and Its Implementation

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Learning Objectives

1. **Cite the importance of international agreements.**
   You will learn why effective action on climate change is unlikely to arise from countries and firms acting alone. From that understanding comes the need for cooperation and different strategies for achieving cooperation.

2. **Understand the history and implications of the Paris Agreement.**
   You will learn the basic history of attempts at international cooperation on climate change, starting with the negotiations leading to the 1992 Framework Convention on Climate Change followed by the 1997 Kyoto Protocol to that Convention. You will learn why those earlier efforts did not have much practical impact and then look at the process leading up to the Paris Agreement. There are many excellent resources online, including the texts of all these agreements at the Climate Change Secretariat (www.unfccc.int). There are also detailed articles on the diplomatic history in the sources section of this chapter. The learning emphasis in this chapter will be on the political forces that explain why these different types of agreements exist.

3. **Demonstrate the challenges to international agreements.**
   This chapter will offer many reasons to be optimistic about the future for the Paris Agreement—even as the United States under the Trump administration begins the process of withdrawal. Nonetheless, it is important to understand the fundamental challenges to any international agreement—in particular, challenges related to whether countries will honor their pledges, and whether their actions will lead others to do more. A key learning objective is to develop the skills critical to understanding when agreements will be implemented (and not), and what will happen as key provisions are not honored.

Overview

For nearly 30 years there have been international diplomatic talks on climate change. So far, those talks have had very little real impact on the emissions that cause climate warming. This chapter will explain why international cooperation is needed, along with different strategies for improving cooperation. Crucial to predicting the success or failure of cooperation is understanding the interests of countries and whether cooperation advances or undermines those interests. In general, the most ambitious agreements are those that will be seen by some countries as contrary to their interests, which is why there are so many bold statements and agreements to act on climate warming but little change in behavior. New technologies, which lower the cost of action, along with fuller political mobilization, can alter how countries calculate their interests and lead, over time, to more effective international cooperation. With this theory of change in mind, the chapter will explain why the Paris Agreement is widely expected to be more effective than earlier agreements—because Paris allows countries to tailor their commitments to what they are willing and able to implement and because the Paris process has mobilized substantial political and technological attention to the problem of climate warming and the challenge of reducing emissions. Nonetheless, none of the major Western countries that have been leaders on climate change are on track to meet the pledges they made under the Paris Agreement; worldwide, those pledges aren't nearly robust enough to stop warming at 2°C, a widely discussed goal. The political reality of climate change is that policy action is unlikely to come fast enough to halt warming soon, and thus societies will be forced to make massive adjustments to climate impacts.

10.1 Introduction

For decades, countries have not achieved much real cooperation on climate change, in part because there were too many players at the table and the interests of those players were divergent. Making complex deals has been exceedingly complex and vulnerable to vetoes by countries that abhorred cooperation on the issue. Diplomats have solved this problem by agreeing on what was agreeable, which usually meant broad, vaguely worded agreements that had little impact.

The Paris Agreement offers a new opportunity for serious efforts to achieve cooperation on climate change. Paris has set up a process through which national efforts become more transparent and may, over time, help governments achieve deeper cooperation. Although a global agreement, the Paris process also allows and encourages countries to work out solutions in smaller groups—often called **clubs** by scholars who study international cooperation. Those small-group "club" efforts can then deepen and diffuse more widely.

Paris creates an opportunity for doing better. That's because Paris has a much more flexible framework than those of past agreements, one that allows countries to set their own obligations according to what they are willing and able to implement.

Evaluating the Paris Agreement, which is the core topic of this chapter, requires understanding the incentives for countries to cooperate in the first place—the topic of Section 10.2. Failure to understand those incentives has led to many strategies for improving cooperation that, in practice, have not really worked. That reality is clear when looking at the full history of climate diplomacy, which is the subject of Section 10.3.

In Section 10.4 we explore how Paris might be different. One of the chief advantages of this new, more flexible approach to diplomacy is the ability to tailor diplomatic efforts around the countries that matter most and the countries that are most willing to take actions. (Those two groups are often not the same, which is one reason why effective

cooperation is so hard to craft. Often, the countries that are most willing to act account for only a small share of the global emissions.) For too long, diplomacy has focused mainly on global agreements, but it is extremely difficult to reach agreements that have meaningful content when every nation must participate and any nation can, in effect, veto the result. A new reality is emerging that emphasizes the benefits of making progress through smaller club groups of countries. This chapter will examine those benefits and also outline how such clubs could emerge.

Nearly all of the club literature has focused on clubs of sovereign nations. Research has revealed many of these climate-related clubs, and still more are forming. Arctic nations have a variety of clubs, notably the Arctic Council, through which they can cooperate. Forested nations have still other clubs. The European Union has become a club for advancing climate policy. The seven industrialized nations have their club, the G7, and the big economies of the world have yet another club with overlapping membership, the G20. In the run-up to Paris, the most important club was the bilateral effort of the US and China, which a year before Paris led to high-level pledges for emission controls that, in effect, defined what both countries would offer in Paris.

This approach of looking at national governments and international cooperation is often called **two-level bargaining** because what is possible at the international level is constrained by what is feasible for national governments (and vice versa). But this two-dimensional approach prizes the actions of the nation-state itself when, in fact, much of the real effort at cutting emissions and inventing new technologies happens along a third dimension—within the nation-state, especially within firms and industries. Where national governments are strong and consolidate power, this extra dimension may add little to our understanding of behavior. But in modern economies, national governments are relatively weak; by design, most political and economic behavior is devolved away from the state to other actors.

Finally, we look ahead at what needs to happen to turn the promise of the Paris framework into a reality. The list of needed actions is long—much longer than diplomats can reasonably achieve—and success is far from guaranteed. The chapter will help explore which of these

Paris implementation efforts are most important. Success will require a careful strategy that focuses inside the formal Paris framework, which is part of the United Nations (UN), for the kinds of activities that are feasible in that framework. At the same time, leaders will need to work in parallel but formally outside the Paris framework to do some of the things that will not be agreeable by all nations and therefore infeasible in a consensus-based UN-based process. Those areas of key leadership include demonstrating new technologies for deep decarbonization and also imposing penalties on jurisdictions that fail to make an effort.

10.2 Why Is International Cooperation Required?

Climate change politics, as currently structured, is not conducive to much cooperation. Because the pollutants that cause climate change mix across national borders in the atmosphere and because the economic effects of controlling those emissions are felt throughout the global economy, actions to protect the climate inherently involve the provision of what is often called a global **public good**. That is, a safe climate system is advantageous for everyone on the planet (to different degrees), but no party can be excluded from these benefits regardless of its own actions.

Public goods are typically underprovided in the absence of a well-organized government because each actor has an incentive to **free ride**—to gain a beneficial climate while failing to pay its share. It is perhaps especially likely that the world, as a whole, will underprovide global public goods because there is no well-organized and highly effective global government. Indeed, in areas where international governance is weakest—for example, fishing on the high seas—the incentives for free riding create strong incentives for each party to take what it wants. Often these outcomes are called a "tragedy of the commons" because even when each party would benefit from better management, narrow self-interest leads to the opposite outcome. In the area of climate change, these problems of free riding are worsened by the fact that leaders of states think that cutting emissions will make energy more expensive, adversely affecting national economic competitiveness.

The effects of this malign structure help explain why emissions, for all the talk about action on climate warming, keep rising. Figure 10.2.1, taken from the latest report from the Intergovernmental Panel on Climate Change (IPCC), shows emissions since 1970 for all the major warming gases. Since climate change has reliably been on the international agenda, starting in the early 1990s, emissions have kept on rising because even as awareness of the problem has grown, the incentives for individual countries to alter course have not much changed.

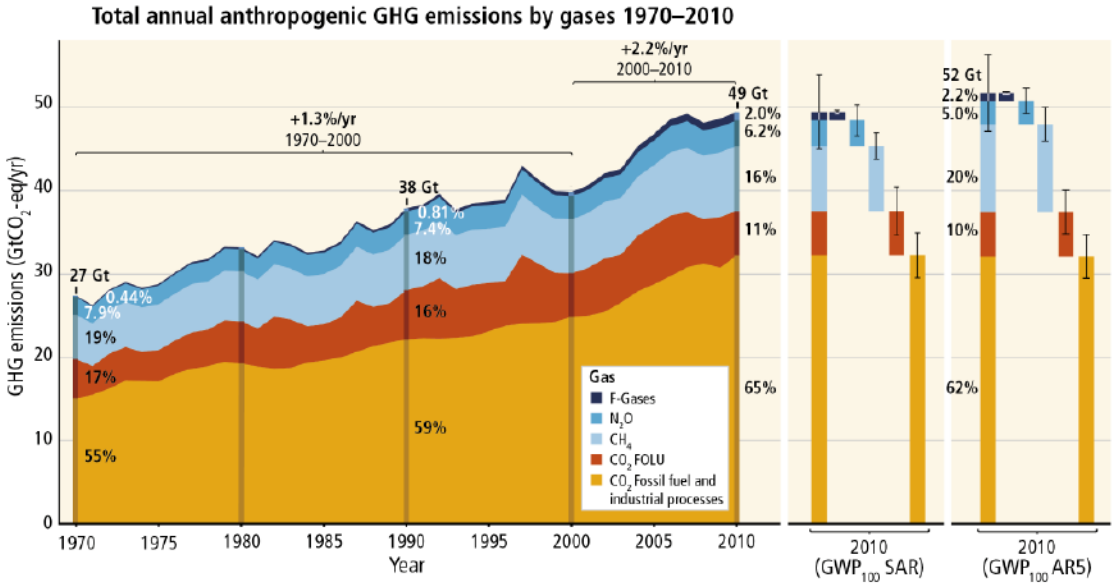

FIGURE 10.2.1 **Emissions of major warming gases. The chart shows emissions in common units (gigatons of CO_2 equivalents per year) by converting the different warming gases via "global warming potentials," a widely used method explained in Chapter 1. Emissions of CO_2 are further divided into those that come from burning fossil fuels (CO_2 energy), which are the majority, and those that emanate from industrial processes and changes in land use.** From IPCC 2014.

Global public goods are most easily provided when a single dominant country, or a small group, takes the lead. That mode of cooperation is why, after World War II, so many effective international institutions were created—from the World Bank to the International Monetary Fund and the General Agreement on Tariffs and Trade (GATT, a precursor to the World Trade Organization). One country was dominant—the United States—and it created public goods that benefitted most nations, including and especially the US. Even though the US often paid a disproportionate share of the cost of creating and sustaining these institutions, it also reaped a disproportionate share of the benefits.

In climate change today, however, no such dominant country or group exists that can readily solve the problem. The two largest emitters—China (23%) and the US (12%)—together account for only about one-third of world net emissions of warming gases (Box 10.2.1 for a note on data sources). Global public goods can emerge, as well, when a

Box 10.2.1 Emissions Data Sources

There are many different sources of data on emissions. I tend to rely heavily on the data set from EDGAR, the Electronic Data Gathering, Analysis, and Retrieval system of the US Securities and Exchange Commission (SEC), because it is regularly updated and includes not just emissions of CO_2 from burning fossil fuels but also (after a year or two delay) other emissions. Moreover, the latest IPCC assessment report, for which I was one of the convening lead authors, used principally that data set. In addition, for data on energy production and consumption—the main source of CO_2 and the largest source of greenhouse gas emissions—I find that the annual BP Statistical Review of World Energy is a reliable source.

global governing authority is already in place. Yet no such authority exists, although the Paris process or a successor to Paris may in time yield one.

Thus, because of the underlying structure of the problem itself, most states have strong incentives to avoid costly unilateral action, to wait for others to act, and to negotiate for self-interested advantages.

Political structure

Breaking the gridlock requires building international institutions that help promote **collaboration**.* Collaboration is the most encompassing concept to describe joint international action to achieve mutual gains. Collaboration can take many forms along a continuum from **coordination** to **cooperation**. In situations of *coordination*, agreements are self-enforcing: that is, once an agreement has been made, the parties do not have incentives to **defect** (fail to honor or withdraw from their commitments). For instance, once everyone in the US understands that Americans drive on the right-hand side of the road, no rational driver has an incentive to drive on the left; and vice versa for drivers in the UK. Agreements to use common frequencies and language (English) for

*The text that follows relies heavily on two main sources that are good introductions to the logic of collective action applied to climate change: Victor (2011) and Keohane and Victor (2016).

TABLE 10.2.1 Four basic structures: prospects and strategies for coordination and cooperation

	Potential joint gains are high.	*Potential joint gains are low.*
Agreements are not self-enforcing (cooperation is required for collaboration).	Possible cooperation with high rewards, but with dangers of defection that rise with the depth of cooperation	Little incentive to seek to cooperate, although shallowness of cooperation limits dangers of defection
Agreements are self-enforcing (coordination is sufficient for collaboration).	Likely coordination, with limited but realizable gains, often leaving potential gains "on the table"	Easy coordination, limited by the low level of potential gains

SOURCE: Keohane, R. O., and Victor, D. G. 2016, Cooperation and discord in global climate policy. Table 1. *Nature Climate Change* 6, 570–575. https://doi.org/10.1038/nclimate2937. Reproduced with permission of Springer Nature Publishing.

air traffic control provide another example—no pilot or airline wants to crash, so all, more or less, follow the rules. These kinds of agreements are quite rare in international politics. *Cooperation*, by contrast, is not self-enforcing. When one country lowers its trade and investment barriers, others may not automatically see a benefit in doing the same. The deep coordination needed between states to provide public goods has a similar structure.

Two variables largely determine the prospects for collaboration. The first, shown in the rows of Table 10.2.1, concerns cooperation and coordination: whether joint action is self-enforcing. The second major variable, shown in the columns of Table 10.2.1, refers to the degree to which the potential joint gains from collective action are high or low. Where joint gains are larger, there are stronger incentives for collaboration—even if it is costly and difficult to create effective systems for working together.

The most important and interesting cases are in the left-hand column, where the potential joint gains are high. In the upper left quadrant are the crucial situations where there are large potential gains from cooperation but strong incentives for parties to shirk from doing their share. Deep mitigation of climate-warming emissions is a good example. As the gains from joint action on this public good rise, so does the temptation to defect. Effective action on mitigation of climate change

requires policies and institutions that reduce that temptation. The essence of the global political challenge in addressing climate change is the creation, implementation, and maintenance of those policies and institutions.

In the lower left quadrant, coordination is sufficient to achieve joint gains. Often, diplomats shift problems from the difficult cooperation box, in which incentives to defect are high, to the much easier coordination box, which has low incentives to defect. Over the 60 years of international diplomacy on trade, for example, international agreements began by focusing on the highest tariffs whose reduction was clearly in the self-interest of countries and thus self-enforcing. As confidence grew, it became feasible to construct the World Trade Organization (WTO), with binding rules, adjudication, and enforcement mechanisms. The 1987 Montreal Protocol on Substances that Deplete the Ozone Layer began as a prime example of successful coordination in which countries adopted national policies whose benefits to the US, the European Union, and Japan exceeded the cost by a wide margin. Thus these countries paid a large share of the costs (which proved to be relatively small) and the whole planet reaped the benefits. Deeper cooperation followed later. However, this strategy of shifting hard problems to an easier structure comes with risks if collaboration remains shallow, enabling the parties to capture only a portion of the potential gains that could in principle be available.

The right-hand column is somewhat less interesting but parallel. The November 2014 US-China bilateral agreement on emissions and cooperative research exemplifies easy coordination (lower right). The US and China announced individual as well as joint efforts to address a global problem. In effect, they made pledges to each other for action that aligned with their self-interests and initially provided small joint gains. Many initiatives announced in Paris—such as on innovation, protection of forests, and regulation of potent short-lived climate pollutants—can also be seen as examples of relatively easy coordination. When such easy but shallow coordination is unsatisfactory to participants, they have incentives to press for deeper cooperation. Here, as elsewhere, cooperation derives not from harmony but from discovering areas of discord where additional collaboration—moving up and to the left on Table

10.2.1—would provide additional gains. Insofar as this logic applies, cooperation could arise from such coordination within small groups of countries and from other actors dissatisfied with the status quo. For example, the US-China accord of November 2014 was important in generating incentives for other countries to make meaningful pledges of action as part of the Paris process because it signaled to other countries that the two biggest emitters were beginning to tackle the problem.

In the upper right quadrant, cooperation is difficult and potential joint gains are low. In my previous research, I have argued that the Kyoto Protocol was an example of this kind of shallow dead-end cooperation—a topic I explore in more detail below.

The situations in Table 10.2.1 are stylized, but they help explain a key distinction in diplomacy: the difference between shallow coordination and deep cooperation. That distinction helps to explain why there has been massive diplomatic activity on climate change but little progress on the difficult task of cutting emissions.

The coordination-cooperation distinction also suggests how progress could be made on climate change. If the toughest problems are tackled first, deadlock is likely to result. Examples include the failed effort by governments to reach agreement on a meaningful new treaty at the Copenhagen Conference in 2009 to replace the original Kyoto Protocol. Too many issues with too many fissures of disagreement were packaged into an accord that required too many countries to consent before it could become law. It is crucial to move from shallow coordination toward deeper cooperation, while at the same time creating the conditions for favorable political coalitions within countries. Much of the enthusiasm around the larger role for bottom-up cooperation on climate change, as was on display in Paris, is rooted in this idea of building cooperation by working on smaller, easier problems where progress is feasible. Effective cooperation requires focusing on areas where agreement is feasible and then working to deepen and expand that cooperation into true collaboration over time. One of the many challenges in climate diplomacy is that that process of confidence building and learning is slow, whereas climate scientists, as outlined in other chapters of this book, are constantly warning that time is short.

10.3 A Brief History of Climate Diplomacy

We now have a simple tool for understanding the history of climate change diplomacy. Real solutions to the climate change problem would offer huge joint gains, but those solutions would require deep collaboration that could be, in reality or perception, contrary to the interests of important countries. Diplomats quickly learned that, and they focused mainly on producing agreements that aimed just at simple coordination with few joint gains. Put differently, the diplomats got good at crafting agreements that had little real impact on emissions and warming.

As the climate change issue emerged on the international agenda in the late 1980s, diplomats working on behalf of the dominant and most interested powers—the US and, increasingly, Europe, which about that time became the global leader on most international environmental issues—quickly sought centralized solutions in the form of a global and legal binding agreement. They worked within the only institution that stood ready to help broker global solutions, the United Nations (UN). A sign of their confidence is that it took less than 2 years from the start of negotiations early in 1991 until the finalization of the first global treaty on climate change: the 1992 **UN Framework Convention on Climate Change** (**UNFCCC**). That treaty had little real content—it was mostly an umbrella that committed the parties to share information, make efforts to reduce emissions, and attend future annual meetings for ongoing diplomacy.

The first formal follow-up meeting—known as the **Conference of the Parties** (**COP**), which convened in 1995 in Berlin with COP1—reached the conclusion that the UNFCCC by itself was inadequate. That conclusion launched a negotiating process that 2 years later begat the **Kyoto Protocol** of 1997. Formally a daughter of the UNFCCC, the Kyoto Protocol included a schedule of **targets and timetables** for the 38 advanced industrialized countries while imposing no emission control obligations on the rest of the world. By targets and timetables, I mean specific goals to reduce greenhouse gas emissions (the targets) by specific dates (the timetable).

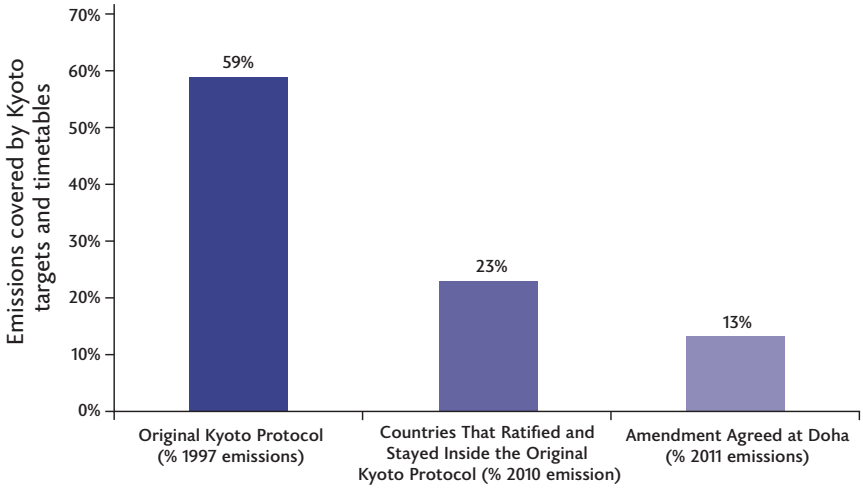

FIGURE 10.3.1 The declining impact of Kyoto. Data from Victor 2011.

In the years that followed, nearly all countries ratified the Kyoto Protocol because it did not require that they do much beyond what they would have done anyway—their diplomats ensured that schedule of targets and timetables mirrored what their countries were already on track to do. The one big exception was the US, where the economy in the late 1990s grew much more rapidly than expected (and with that growth came more emissions)—making it all but impossible to honor the Kyoto targets. The US never ratified the Kyoto Protocol, and when Canada (the largest commercial trading partner of the US) saw that, Canada withdrew as well.

Figure 10.3.1 shows how this Kyoto approach, over time, became increasingly irrelevant to solving the climate problem. The left bar shows the fraction of world emissions that were included in the Kyoto targets and timetables in the year 1997—when the Kyoto negotiations formally concluded. The middle bar shows the fraction of emissions covered by those targets and timetables in the year 2010—after many years when countries outside the Kyoto strictures (for example, China) saw extraordinary growth and two important countries that had been inside Kyoto (the US and Canada) exited. And the right bar shows the fraction of world emissions covered by Kyoto when the agreement was formally extended at the Conference of the Parties meeting in Doha in 2012. (At that extension point, the European Union agreed to continue, but Japan, under pressure

to end a deal that was seen by Japanese industry as unfair, did not.) Put differently, Kyoto became a club of the highly converted, committed countries. But with political and structural changes in the world economy, that club accounted for a shrinking share of the global problem.*

As the US failed to ratify Kyoto, some of the flaws in this system became apparent—in particular, the problem of rigid, binding targets and timetables when countries, for the most part, don't plan that way. New ideas surfaced, but none of them attracted much effort.

In 2001, just months after taking office, US President George W. Bush announced he would never submit the Kyoto Protocol for ratification; instead, his administration created a "coalition of willing supporters" of climate mitigation in an Asia-Pacific Partnership on Clean Development and Climate (APP). (The concept of a "coalition of the willing" was also how Bush's team described the other countries that joined the US reinvasion of Iraq. When the Iraq war proved a fiasco, the term, although informative, fell out of favor.) While the Bush team correctly diagnosed some of the failings of the Kyoto Protocol, their favored alternative fared no better. The Bush team did little to invest in their alternative vision, other than hold meetings and commission a few studies. Most other countries stayed married to Kyoto-style targets and timetables.

Even the cleverest diplomacy aimed at more effective top-down solutions could not mask the failure of the Kyoto approach. Despite massive diplomatic effort, emissions trajectories barely changed. The good news in all this is that failure came with a bang, and the shock helped open diplomacy to superior, alternative ideas.

The bang was the 2009 Copenhagen Conference—an event convened with the goal of crafting a successor to the Kyoto Protocol but ending with the parties unable even to negotiate a formal plan for further negotiations. Without top-down agreement, what was left in the wreckage of Copenhagen was a loose bottom-up process that encouraged nations to outline their own national plans. These pledges, updated and elaborated, would become the backbone of a new process set out in Paris.

The reasons for failure at Copenhagen were many, but the underlying forces at work were familiar.

*For more on these problems with Kyoto, see Victor (2001).

The first was political: the fragmentation of power and authority in the international system and the corresponding absence of a leader that could reliably impose order on actors with sharply divergent interests. Until the early 1990s, the US provided that function on most issues of economic and environmental organization. Since then, it has not played that role and no other actor has occupied that role, although the European Union has tried and China may yet step into that function. Europe, although increasingly unified at home on environmental issues, never had the power to convert its strong and growing environmental commitment into true global hegemonic leadership.

The second underlying force was cognitive: uncertainty about the cost and efficacy of reducing emissions through policy coordination. When the first global international agreement on climate change was penned—the UNFCCC in 1992—the joint obligations were so vague that the uncertainty in just how countries would cut emissions could be ignored. In a sprawling paragraph free of any definitive punctuation, Article 4.2 of the UNFCCC required industrialized countries to adopt policies to "demonstrate that developed countries are taking the lead in modifying longer-term trends in anthropogenic emissions. . . ." Diplomats did what diplomats did best—they found ways to agree even when the underlying facts and interests made detailed agreement impossible.

As pressure to take more serious actions mounted, no country or firm that took deep decarbonization of emissions seriously could identify exactly which behavioral, technological, and regulatory commitments would prove most effective. Indeed, the full text of the sprawling, punctuation-free paragraph in Article 4.2 made all commitments conditional upon technological, political, and other developments.* All this diplomatic artistry made it possible to ignore for years the key reality of climate cooperation: the challenge in collective action was not merely that countries had diverging interests, but that even those that wanted

*See the text of Article 4.2 that follows our earlier quotation, which includes this language: "taking into account the differences in these Parties' starting points and approaches, economic structures and resource bases, the need to maintain strong and sustainable economic growth, available technologies and other individual circumstances. . . ."

to act did not know which efforts would prove feasible, at what cost, and whether they would stay aligned with shifting national interests.

This veil of uncertainty about what true collaboration would cost—and how it would affect organized interest groups within countries—has exacerbated the bargaining problems that arose as diplomats tried to craft international agreements. Uncertainty made it hard for governments and firms to understand their interests, because nobody really knew when (and at what cost) big reductions in emissions would be feasible. Because climate diplomacy was focused on reaching agreements that looked, at least on paper, ambitious, it was convenient to skirt around some of the central challenges. The diplomats driving the process—a mantle that European diplomats increasingly took for themselves—focused less on grappling with uncertainty and more on making sure the whole treaty was **binding**, that is, that it represented a commitment that countries were expected to honor as a matter of international law. The pursuit of binding law was based on the theory that binding law would be more effective—because most countries take their international legal obligations seriously, and some even allow those commitments to be enforced through national and other courts. Ironically, the desire for binding law helped guarantee that the entire effort would fall far short. Binding law made governments focus on agreeing only to what they were sure they could honor, which led either to agreements that were designed to have little or no impact on behavior (Kyoto) or deadlock (Copenhagen).* What was different about the Paris process that followed was its explicit design to address these profound uncertainties in what countries were willing and able to implement.

*On countries taking their obligations seriously, see Chayes and Chayes (1998); it is a point underscored even in studies that are skeptical about the impact of international law (Goldsmith and Posner, 2006). On the trade-off between bindingness of commitments and depth, see Abbott and Snidal (2000). For the synthesis of these ideas, applied to climate, see Victor (2011).

10.4 The Promise of Paris

When the Copenhagen conference failed in 2009, it opened a vacuum. The eventual design of the Paris Agreement was the result of active efforts to fill that vacuum with new good ideas—including ideas that relied less on binding law and shifted to a more decentralized and flexible approach to bargaining.

At the core of the post-Copenhagen process was the idea that countries should set their own "pledges" for controlling emissions. In the run-up to Paris those pledges were called "Intended Nationally Determined Contributions" (INDCs), to indicate that these were pledges of what national governments *intended* to do and that these efforts were not centrally mandated but *nationally determined*. Once the Paris Agreement came into force, the "intended" was dropped and the pledges were simply called **Nationally Determined Contributions** (NDCs). The Paris process, by design, would begin with these NDCs that, over time, would be ratcheted tighter, and the overall progress of the system would be assessed.

The genius of this approach lay in its ability to engage many countries with diverse interests and capabilities. Before the Paris process, essentially all climate diplomacy focused on getting just the advanced industrialized countries to cut their emissions through binding accords, notably the Kyoto Protocol. Paris, by contrast, has the participation of almost every nation on the planet.

Several studies have tried to quantify the level of effort implied by different NDCs. While the results vary in detail, one pattern is most striking: the advanced industrialized countries are pledging the most. That's because these countries have the highest incomes and are most responsible for historical emissions. Moreover, from the beginning of climate change diplomacy in the late 1980s, these countries were expected to take the lead and do the most to control emissions. Across

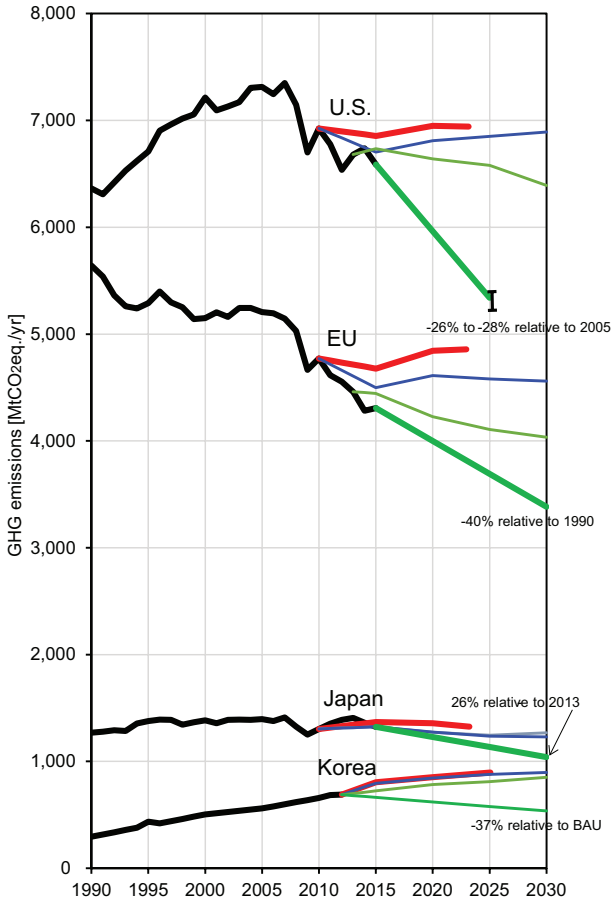

FIGURE 10.4.1 Progress by major industrialized countries in meeting their Paris pledges. Green lines show the path to the pledge. Red lines show business-as-usual trajectory without major new policies; blue and thin green lines show improved trajectories that depend on key policies, but none of the improved trajectories delivers the Paris pledge. Adapted from Victor et al. 2017.

the emerging and least developed countries, by contrast, the level of effort—measured as the cost of the pledged policies—is often low or zero. That's not because these countries are unconcerned about climate change but because they view climate policy efforts through the lens of other goals, such as cutting local air pollution and improving energy security. The other goals drive policy; protection for the climate is a **co-benefit**, that is, a side benefit that was not the main purpose behind the policy.

While the advanced countries have made bold pledges, a key challenge for the Paris process is that these nations are also falling short. As shown in Figure 10.4.1, all are bending their emission curves downward, but at a rate slower than needed to meet their NDCs.

The reasons for each country's troubles vary. In the US, massive efforts by the Obama administration were unlikely ever to add up to honoring the goal of cutting emissions 26% to 28% below 2005 levels by 2025. Even with heroic assumptions about improved technology costs and maximal sequestration from forestry mixed in, emissions would decline at most 23%. Under Trump, the gap in US compliance with its own target has widened modestly as the federal government has sought to reverse the Clean Power Plan, which would reduce CO_2 emissions from electricity generation, and other policies.

In Japan, where the economy is already extremely efficient, policymakers made pledges for still more emission reductions that far extend beyond what they can deliver at home. The EU also faces challenges in meeting its NDCs, although these are not as serious as those in Japan. The region's Emissions Trading Scheme (ETS) has capped emissions in the power and industrial sectors since 2005 and will assure that the EU will meet its goal of cutting greenhouse gas emissions in these covered sectors 40% by 2030. (Chapter 12 for an explanation of cap-and-trade schemes such as the ETS.) The big problem in Europe lies with the 60% of emissions that are outside the ETS—in the buildings, transport, agriculture, and waste sectors. Meanwhile, the share of EU emissions from agriculture, forestry, and land use is expected to double in the absence of additional mitigation that has been difficult to organize and implement. A shift to biomass for energy, for example, is merely moving emissions from the energy sector to land use without corresponding and sufficient mitigation in the latter.

These are serious problems, and the failures of leading countries to meet their pledges will lead many observers to declare Paris a failure. But a different reality is emerging—if the Paris framework works as designed, it will be able to adjust in response to new information about country performance. In theory, that performance includes undershooting and overshooting targets. But actually creating that kind of flexible framework will require fleshing out and completing many elements of

the Paris framework for which the Paris diplomats did not reach final agreements. Over the next two subsections we look closely at that—first at why Paris worked when other efforts have failed, and second on the long list of items left unfinished at Paris.

Turning the corner at Paris

Why did Paris work when almost everything before it failed? The central answer lies in a new style of international cooperation. Instead of setting commitments through centralized bargaining, the Paris approach sets countries free to make their own commitments—the NDCs.

The flexibility of this **pledge-and-review** system helped transform climate diplomacy from the gridlock and impotence of the past. That made it easier for national governments to tailor their commitments to what they know they can deliver at home. (Or, more precisely, the system lets them tailor commitments to what they think will be politically helpful in pushing for climate policy at home. As shown in Figure 10.4.1, many important countries are not on track to meet their pledges even as they undertake significant efforts to bend down their emissions curves.)

Most of the world's emissions come from countries that aren't worried (yet) about global climate change. Take China, the world's biggest emitter. Its leaders have learned more about the dangers of unchecked climate warming, and that has made the country a bit more willing to act. But the nation still has other much more pressing priorities—like clearing the urban air of smog. Or take India, another big emitter, which is also mainly focused on priorities other than global warming, such as making the nation's power grid more reliable. The pledging approach lets these countries offer packages of policies that align with their self-interests while also doing something to slow the growth of global climate pollution. When you look closely at the politics of the US, you see a similar story—outside the politically progressive coastal states, most of the nation is not seized by fear of global climate change.

Eventually a much more integrated global treaty will be needed to make major cuts in greenhouse gas emissions—one directly focused on the global goals. But the flexibility of a pledging system offers a way to get started and build confidence that, in time, will beget more

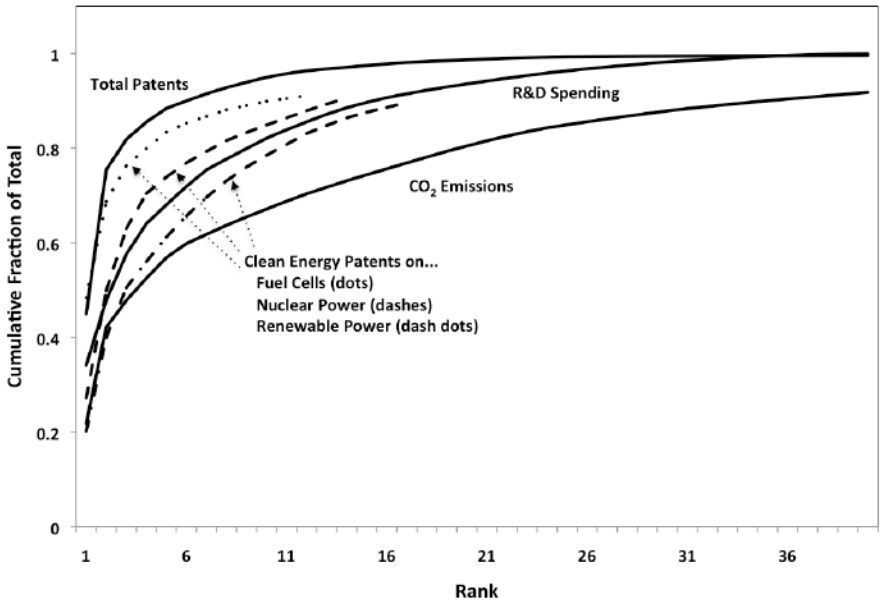

FIGURE 10.4.2 Rank order of global emissions, spending on energy-related R&D, and energy patents. Chart shows that the largest countries account for the vast majority of emissions and an even higher concentration of effort to control emissions. Data from Victor 2011.

confidence and a willingness to do more. This is the same theory—with a similar approach—that guided the creation of the highly effective system for international coordination of trade policy through the General Agreement on Tariffs and Trade (GATT) and, since 1995, the World Trade Organization (WTO). Trade diplomacy began in the 1940s with simple, self-enforcing agreements that aligned with national interests; through successive rounds of bargaining, those national policies were ratcheted forward and integrated. Easier problems were tackled first, building confidence that made it possible to tackle harder diplomatic challenges. The Paris Agreement moves the world in that direction.

In addition to flexible commitments, the Paris approach also envisioned a flexible geography for cooperation. Many diplomatic discussions would be universal—involving all nations. But some would not. The more countries try to achieve deep cooperation with large joint gains, as outlined in Table 10.2.1, the harder it will be to craft the deal. All else equal, that crafting process will be aided if countries can pick and choose their partners—turning a problem of highly complex negotiations

with nearly 200 countries into a much easier (but still difficult) task of working with a smaller club of the countries that matter most.

Figure 10.4.2 shows why this flexibility in the numbers of participating countries is so important. It shows a rank order plot for emissions of CO_2 (the most important long-term warming gas) as well as two key elements for addressing the climate problem—spending on energy-related research and development (R&D) and successful outputs from that spending: new patents on energy innovations. The biggest country for each line is shown on the left, with the rank of 1. Then the line accumulates with the first two countries (ranked 1 and 2) and so on. China accounts for about one-quarter of global emissions of warming gases (depending on the data set used for analysis). China and the second-largest country (the US) account for about two-fifths, and so on.

What is clear from Figure 10.4.2 is that there is massive inequality in the global system. A few countries account for most of the emissions and most of the effort. Politically, that inequality is potentially good news because it means that cooperation efforts can begin with just a few countries. The flexibility built into Paris allows and encourages these smaller climate clubs to form.

Challenges for putting Paris into practice

While reaching the Paris Agreement in 2015 was a huge accomplishment, that process left a long list of things undone. This is normal. The process of diplomacy often runs right to the deadline (and then some), agrees on what is essential, and leaves the rest to be filled in later (or never). When agreements are pretty simple, there isn't much filling in to do—for example, the UNFCCC was essentially complete when signed in 1992. The Kyoto Protocol, which was negotiated past its deadline (workers were removing the chairs from the conference hall when the diplomats finally declared their work done on December 11, 1997), left holes on important concepts such as accounting systems. It took another 4 years to fill in those holes.

Now that we have explored what makes for successful cooperation, we can explore how the post-Paris process may unfold—and we can also help identify some priorities for the process of filling out the details left unfinished in Paris.

First and most important is that the theory of cooperation that guides the Paris process is based on the idea that countries can best determine what they are willing and able to do—and those determinations will vary over time with changes in technology, interests, and knowledge. That theory of cooperation suggests that the process of making and adjusting pledges—the NDCs—is vital to the success of Paris. That's why the news that the advanced industrialized countries aren't on track to meet their pledges is so disturbing—because it is these countries that have the resources and motivation to lead in the effort to reduce global emissions.

It is crucial that leading governments—especially from the advanced industrialized countries that should be leading the efforts at cooperation—shift the conversation away from compliance with numerical targets and toward the level, quality, and transparency of *effort*. Because there are so many confounding factors that affect emissions—such as economic growth, shifts in political winds, and technology—a country might achieve its numerical target by sheer luck and with minimal effort. Conversely, a country may make major, costly efforts but still fail to achieve its targets if (for example) economic growth is more rapid than forecast or new technologies don't prove viable despite substantial investment. A flexible self-declaration approach to diplomacy ensures that leading countries keep their goals in line with what really matters: effort, or action. Europe, Japan, and the portions of the US that say they still honor their Paris pledges should begin the process of updating their goals to reflect the reality of what they are actually able to implement, even if that updating process reveals that real-world efforts fall short of fantasy-world goals. This process might also help provide cover for the Trump administration (or its successor) to reset the US national goal and rejoin the Paris Agreement fully.

Second, this pledge-driven process requires indicators and processes to make it easier to determine which national policy efforts are really working. The logic of decentralized self-declaration of commitments is partly rooted in the benefits of flexibility (as discussed above) and partly in the processes of learning that arise when there are large amounts of useful information on policy implementation available. That learning is partly technical—for example, if leaders in the process

of shifting power grids to renewables reveal information about what works, then followers can follow more quickly. Partly, the learning is about coalition formation. For example, environmental interest groups can gain information and examples that can make them more politically powerful by looking to the experiences in other markets where emission cuts have been successful.

So far, the picture on transparency is highly uneven. The NDCs for most countries are extremely short, and key assumptions that underlie the pledges are hard to pin down. Even the Obama administration, which initially vowed to set a high standard for transparency, did not disclose the crucial modeling assumptions it used to project future emissions. Transparency is vital to bottom-up diplomacy yet inconvenient for governments that are focused on always looking good.

Getting quick agreement on the right indicators and the best content for NDCs will be impossible within the formal UN-based Paris process because there are too many countries that don't want high levels of transparency and the accountability that would follow. A solution to this problem is for countries that are committed to cutting emissions to volunteer themselves for detailed mutual reviews of their policy efforts—much as China and the US did when they released in October 2016 mutual peer reviews of their efforts, under the G20, to reform fossil fuel subsidies. If a few leaders demonstrate how to reveal useful information about their policy pledges and how to do transparent reviews of that information, then the rest will follow.

Many theories of international bargaining view the climate change problem as provision of a global public good for which most countries have a strong incentive to defect. That view suggests the need for strict monitoring and enforcement procedures. Such procedures would be needed, according to this view, because countries would not be willing to adopt costly mitigation policies unless their economic competitors did the same. This "verification and enforcement" view of cooperation suggests that cooperation hinges on the ability to deter and punish defectors.

The theory of cooperation embodied in Paris is different. The Paris approach is based on the idea that, for now, the main impediment to cooperation is not knowing what to do—or how to demonstrate to others that each country has a reasonable plan of action in place. In some

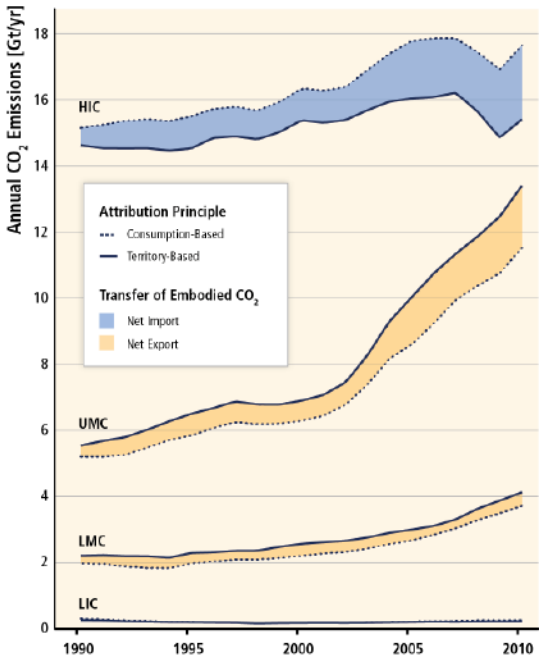

FIGURE 10.4.3 Global trade in embodied carbon between highly industrialized countries (HIC), upper middle income countries (UMC), lower middle income countries (LMC), and lowest income countries (LIC). The figure shows the different emissions statistics that are based on where products are produced (territory-based accounting) versus where they are ultimately consumed (consumption-based accounting). From IPCC 2014 and Victor et al. 2014.

of my research with Columbia Law School professor Charles Sabel, we call this "experimental governance" because it is based on the idea that countries and firms are running, in effect, experiments—learning what works and then selecting superior ideas for scaling up. According to this view of cooperation, which is embedded into the logic of Paris, what matters most right now is maximizing the number of experiments and creating an information-rich process to help everyone learn what works.

The genius of the system adopted in Paris is that it could radically increase the supply of this type of information. An effective information regime will lower the costs for crafting collective agreements. According to this view, the top priority over the next few years is to identify countries that are willing to show how to improve their NDCs.

Over time, it will be important as well to lay the foundation for a future verification and enforcement system—so that, as cooperation deepens, there aren't strong incentives for countries to avoid doing their fair share. One of the key elements in that will be dealing with trade effects, as shown in Figure 10.4.3. The figure shows the different emissions statistics that are based on where products are produced (using **territory-based accounting**) versus where they are ultimately

consumed (using **consumption-based accounting**). For example, when a ton of steel is produced in China and sent to the US where it is used to construct a bridge, the emissions associated with that production are assigned to China under territory-based accounting but to the US under consumption-based measurement. Nearly all emissions statistics today are territory based, which creates incentives for firms and consumers to select products made offshore and then import the products, avoiding the costly emission controls that would be needed if the product were made at home. Over time, those incentives also result in new investment shifting to offshore locations where pollution controls are more lax. These mismatched incentives also encourage offshore producers to avoid signing up to emission control policies lest they suffer an economic disadvantage. Fixing this problem will require adjustments at the border to compensate for the emissions embodied in traded products.

Third, the Paris process will move only as quickly as governments want to invest in deep decarbonization. Many governments are already making efforts because cutting emissions of warming gases overlaps with other goals, such as reducing air pollution or promoting energy security. That co-benefits approach to action can help get efforts under way, but they won't be enough to make the deep reductions in emissions needed to stop climate warming.

More political pressure will change how countries view their interests. Elsewhere in this volume you are reading about how interest groups can be mobilized and about how the spread of scientific information can help mobilize interest. All that is important, and there is something else that can help a lot as well: technological innovation.

Deep decarbonization of the economy implies a massive, transformative change—in particular, a transformation in how energy is produced and used. Figure 10.4.4 offers a sense of scale of the effort needed—the gray lines are published scenarios showing future emissions of greenhouse gases without significantly new policies, and the blue lines are scenarios consistent with stopping warming at about 2°C. There is a massive difference between the two, and studies that look into the details of these energy systems (and agriculture systems, for a fraction of world warming emissions comes from changes in how land is used)

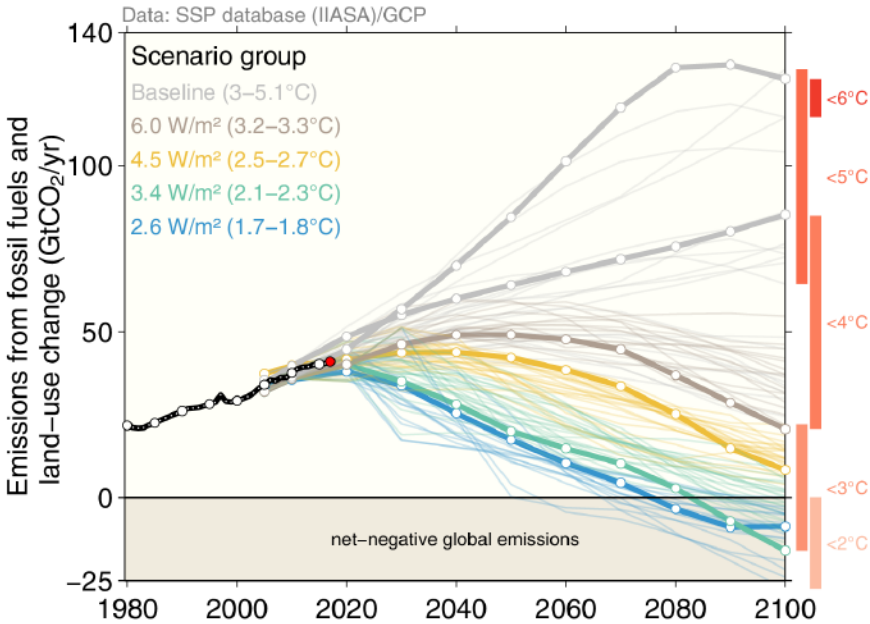

FIGURE 10.4.4 Different visions for future emissions. The chart shows published "baseline" scenarios, for which governments do not introduce significantly new policies (gray lines, for which the highest lines yield more than 6°C of warming). Deep emission controls (blue lines) are consistent with stopping warming at about 2°C above preindustrial levels, a widely discussed goal. Reproduced from the Global Carbon Project, CC BY 4.0 license.

suggest that the energy system of the future may not look anything like the system of today.

A central element to that transformation is innovation. New energy systems won't come into being entirely on their own—they require new ideas. And new ideas are, like a safe climate, a public good. They are available to everyone and can be excluded from none. Earlier in this chapter we learned that public goods require cooperation because countries and firms, if they think just about their narrow self-interest, won't do enough to deliver those public goods.

Innovation is a global public good—new ideas for new energy systems, as they appear, will be available to everyone. A key challenge in the Paris framework is to ensure there will be enough investment in these global public goods. Figure 10.4.5 is not encouraging—it shows public sector investment in energy-related research, development, and

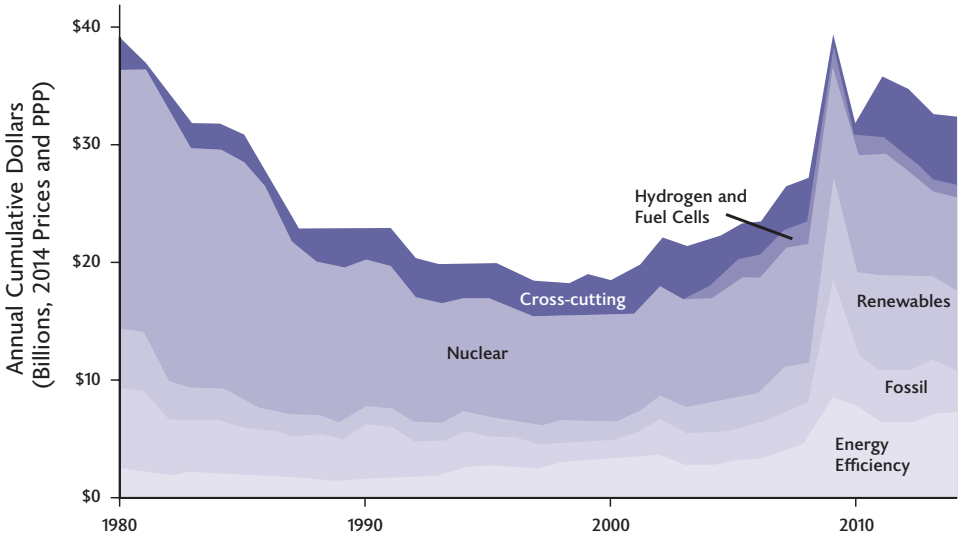

FIGURE 10.4.5 Public sector spending on energy-related research, development, and demonstration (RD&D). Data from the International Energy Agency.

demonstration (RD&D) for all the Western industrialized countries. (The data for these countries are relatively good, but this figure understates the world total investment, especially in recent years, because it excludes China.) Today, investment is barely back at the level of the late 1970s when the world was consumed with energy crises. The new energy crisis—the problem of carbon and other warming gases—requires a lot more effort.

On the first day of the conference that led to adoption of the Paris Agreement, nearly two dozen countries pledged to double their investment in public sector energy-related RD&D through a scheme known as Mission Innovation. Delivering on that mission is important not just for increasing the supply of new ideas from which real new decarbonized energy systems can emerge. It is also important politically because as the supply of new ideas for decarbonization rises, the cost of controlling emissions will go down. Less costly low-emission technologies will shift perceptions—away from the view that deep decarbonization is daunting and impossible, to the view that such decarbonization is feasible. That, along with new information about the harmful consequences of

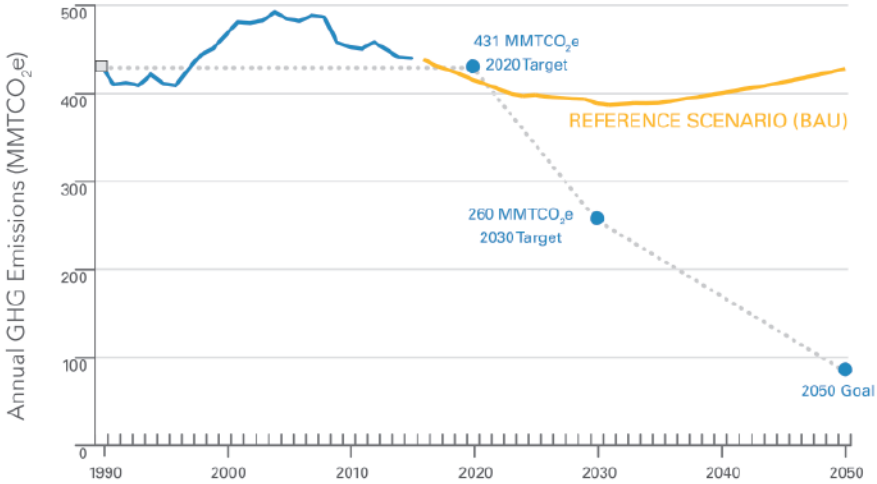

FIGURE 10.4.6 California's emissions trajectories and goals. Reproduced with permission from the California Air Resources Board.

unchecked climate change, will alter how countries evaluate their interests, will help interest groups that favor decarbonization get stronger, and will make governments more willing to act within the Paris framework (and within frameworks that emerge after Paris).

Fourth, the arguments made in this chapter suggest that a pledge-driven approach to cooperation is the best feasible strategy. But realism is needed about the rate at which experiments can be implemented, and lessons learned and diffused. Because more than two decades passed without a serious strategy for addressing the climate problem, there is a lot of catching up to do—even if the Paris process unfolds effectively.

The trajectory of emissions in the absence of climate stabilization policies, such as the trajectories in the gray lines of Figure 10.4.4, gives a sense of just how much remains to be done. There is a huge gap between baseline levels of emissions and what would be needed to stop warming at about 2°C. The Paris pledges might have closed that gap by perhaps one-third to one-half, but as noted earlier, even those pledges aren't being met by the countries that are expected to lead the global effort—the gap between emissions and stabilization that already existed in the Paris pledges is getting wider. Deeper pledges will be needed, although the feasibility of that effort to achieve greater ambition is hard

to assess. That reality suggests that the planet is likely to blow through the 2°C goal. New goals will be needed.

Fifth, and final, is the topic of leadership. There is much attention to the need for leadership, and the Paris process itself can't do much to create leaders. The pressure for leadership must come from within key jurisdictions—countries, states, groups of firms, and even cities.

California has been a reliable leader in this area and has set ambitious goals out to 2050, when the state expects to cut emissions 80% (Figure 10.4.6). Like all other leaders, California must grapple with the fact that leadership tends to come from economies that are already green and getting greener. Yet stopping global warming requires that the whole planet (especially the big emitters) get much greener. Leadership requires followership. The Paris process might help on that front by creating more focus on the lessons that leaders learn—and helping others internalize those lessons. But for that to work, leaders probably need to invest not just in good-looking activities at home but in creating the conditions to help generate followership.

10.5 Summary of Main Points

Paris was a huge step forward. But the framework remains young, incomplete, and fragile. In this chapter we have covered these main points:

- Failure to make progress on the climate problem is the result of many factors—each of which, on its own, could spell failure for international cooperation. The structure of the climate problem does not lend itself to effective national politics, because the costs for action are visible and up front while the benefits are diffused far into the future and global.
- There are many different strategies for achieving cooperation, but a central challenge is creating deep cooperation—that is, cooperation in which parties do more to address a global public good (protecting the atmosphere) than they would if they evaluated costs and benefits with reference just to themselves.
- The most important types of cooperation for climate change are those that create large joint gains and are not self-enforcing. As a general rule, self-enforcing agreements in the climate area have not involved much major change in behavior.
- The history of climate diplomacy involves many agreements that are largely self-enforcing but have little impact on emissions.
- The Paris Agreement may prove to be quite different because it sets up a process that requires countries to set their own commitments (pledges, known formally as NDCs) according to what they are willing and able to achieve. That process, in theory, allows more flexibility and can encourage greater experimentation.
- While promising, the Paris process left may key elements incomplete. Particularly important is a mechanism for checking on the quality and content of the national pledges—the NDCs.

- The engine for progress under the Paris Agreement will be leadership by jurisdictions that have a strong incentive or inclination to lead. The strategy of leadership requires a strategy of followership, since most of the world's emissions come from jurisdictions that won't be leaders.

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CHAPTER 11

Economics

Emissions, Impacts, and Policy

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Learning Objectives

1. Understand the mitigation challenge: What are we up against? In order to prevent more severe impacts from human-made climate change, we have to significantly reduce the emissions of greenhouse gases. In order to understand the magnitude of the problem, we will explore the sources of emissions historically and going forward.
2. Have a basic understanding of how economists think about climate change impacts: Climate scientists have developed advanced models of how the climate system functions and what the consequences of global warming are on the climate system. Economists have developed methods to help us quantify these impacts in welfare/monetary terms so one can compare the damages from climate change to the costs of preventing it by reducing emissions.
3. Have a basic understanding of the main policy options available: If we are to meet the ambitious emission reduction goals required to prevent significant climate change, policies will have to be put in place to reduce the growth and eventually the total amount of emissions. We will explore different approaches to doing so.

Overview

Climate change is the biggest environmental challenge of our and future generations. More humans currently live on the planet than ever before, and population growth is anticipated to continue throughout the remainder of this century. More people, whose incomes are rising because of economic growth, will demand more goods and services (for example, cars, air conditioning, televisions) as well as diets richer in protein. This drives the first challenge discussed in this chapter—the so-called mitigation challenge. In order to produce the goods, services, and foods that current and future humans will want to consume, one requires more inputs to production or much more efficient technology. Some of the inputs required are renewable (for example, lumber, fish, sunshine, wind), and others are nonrenewable (for example, coal,

natural gas, metals). The production of this portfolio of inputs is energy intensive and likely results in raised emissions of greenhouse gases. These emissions have been rising globally since the onset of the Industrial Revolution in the eighteenth century and, absent policy intervention, will continue to do so.

These rising emissions pose a challenge. If emissions continue in an unabated fashion, the planet will experience a significant degree of climate change. If we reduce, as has been argued by some noneconomists, emissions to zero, one will prevent a significant degree of climate change—but also possibly forgo many of the benefits derived from the consumption of goods that will not be consumed because of the policy. Economists argue that in order to find the efficient degree of emissions reduction, one should compare the costs of reducing emissions with the benefits of doing so. This is the backbone of a formal methodology called **benefit cost analysis**, which compares the full damages from additional climate change to the costs of reducing greenhouse gas emissions. In order to conduct such a benefit cost analysis, one clearly needs to have information on what it costs to reduce emissions and how big the damages from additional emissions leading to climate change are. In what follows, I discuss the emission reduction challenge and provide an overview of how economists attempt to quantify the damages from climate change in monetary terms.

The second part of the chapter assumes that we have decided as a society on how large emissions reductions should be. The question is how to get there? The problem here is challenging. First, I discuss this from a single country's perspective. The problem is similar to losing weight. If you step on the scale and decide that you need to lose 20 pounds, you have many ways to achieve this goal. You generally would like to choose the most efficient (for example, least painful) way to do so. Emissions reductions are similar. If we decided that we want to reduce our emissions by say 10%, we would want to achieve this in the most efficient or, as economists would say, "least cost" way. I outline the main approaches to reducing emissions and compare how efficient they are.

Now, let's complicate the problem. Since greenhouse gases are global pollutants, meaning their geographic source of origin does not

matter, each country needs to do its part. But how do we get each country to do the right thing? Again, turning to losing weight, this is similar to having your extended family decide that you will collectively lose a total of 200 pounds. Each member of your family has an incentive to free ride on others' weight loss, and your family will likely never achieve this common goal. This is essentially the problem behind the 2015 Paris Agreement, where all countries decided to jointly reduce emissions but each country is "doing its own reducing." Moreover, the Agreement does not contain significant penalties if a country fails to meet its emissions reduction plan. The chapter ends by briefly discussing the challenges of international cooperation in emissions reduction and the state of affairs. At the very end it lists a number of suggestions for accessible additional readings.

11.1 The Emissions Challenge

There are few machines that have had a bigger impact on human development than the steam engine. While the first steam engines go back to the first century AD, it was only in the 1700s that they were used in a production context. While at first they were used to pump water out of mines, by the late 1700s the Boulton-Watt engine was able to turn steam into rotative motion. This game-changing invention led to a massive increase in the demand for steam, which was most easily generated by combusting fossil fuels (for example, coal, gas, oil) and renewables (for example, biomass, wood). This invention was instrumental in kicking off the Industrial Revolution, which led to a massive expansion in the demand for fossil fuels. Further uses for fossil fuels came from the smelting of steel; the heating of homes, factories, and places of employment; and the arrival of the internal combustion engine, which enabled today's main modes of transportation.

Where do the emissions come from?

The inventions powered by fossil fuels led to the explosive growth in emissions of greenhouse gases that continues to the present day. Figure 11.1.1 displays the growth of CO_2 emissions from fossil fuel combustion since the 1700s. The world essentially went from negligible emissions to 35 billion tons of CO_2 in 2013. Most of this growth stems from the combustion of coal (solids), oil and its derivative products (liquids), and natural gas. There is a significant single use—the production of cement, which shows up in these graphs because the chemical process used to make cement generates CO_2 directly. Finally, when oil and gas are produced, some gas escapes and is not captured, for cost-effectiveness reasons, and is flared (burned) off.

Instead of looking at emissions trends by fuels, it is instructive to break down emissions by region. Figure 11.1.2 replicates Figure 11.1.1

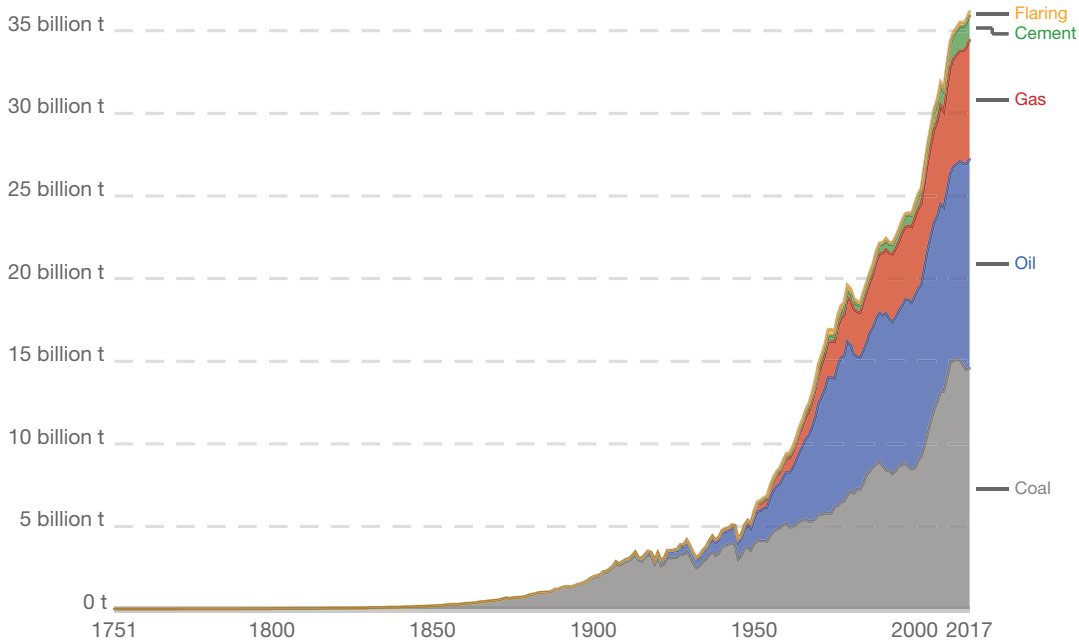

FIGURE 11.1.1 **Carbon dioxide emissions by fuel source globally from 1750 until 2014. Because of the long lifetime of CO_2 in the atmosphere, it is not the level of emissions in any given year, but the area under the curve that matters.** From Ritchie and Roser 2019.

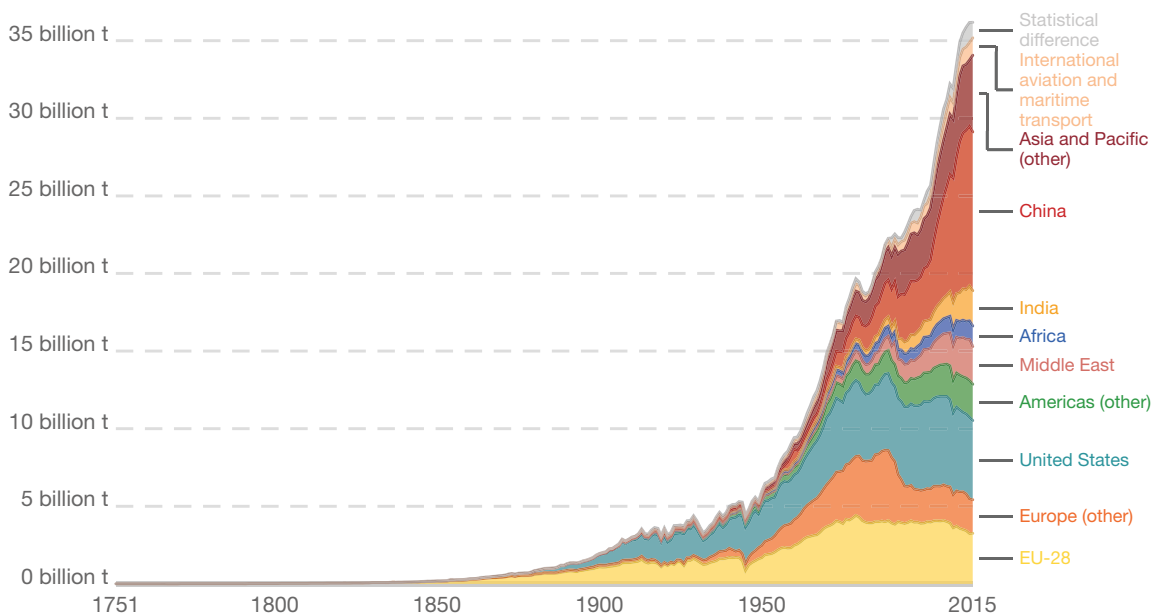

FIGURE 11.1.2 **Global emissions by world region. For the latter part of the twentieth century, the United States was the leading emitter, but it has recently been overtaken by the People's Republic of China.** From Ritchie and Roser 2019.

but indicates the source region of the emissions. Three things stand out from this figure. First, most of the emissions growth until the end of the twentieth century came from high-income countries, with the European Union (EU) and the United States being responsible for the lion's share of emissions. What we see in the twenty-first century, however, is that the most significant growth in emissions has come from lower- and middle-income countries. Most notably, China became the biggest emitter (in total, not per capita terms) early in the twenty-first century, and we are observing significant growth in India's emissions as well as those of the rest of Asia. Emissions in Europe and the United States have leveled off or stopped their significant growth path—for now.

What is driving emissions?

The question as to what is driving this growth is not as mysterious as one thinks. It has been formalized in what is called the **Kaya identity**. The identity states that CO_2 emissions can be expressed as a product of population, GDP per capita, energy intensity per unit of GDP, and carbon intensity (carbon per unit of energy consumed). It hence suggests that more populous, richer, more energy-intensive countries with a more carbon-intensive energy sector will have higher emissions. This is not rocket science and has been confirmed across countries through a variety of research efforts. As this chapter focuses on the economic aspects of climate change, taking a closer look at the income-emissions relationship is instructive. As China has a much larger population than the US, for example, a meaningful comparison here is to look at the relationship between per capita GDP in a common currency and emissions per capita. This gives us a snapshot of how average income and emissions correlate. Figure 11.1.3 plots this for the year 2016.

I find this figure enlightening. What we see here, albeit on a log-transformed scale, is that there is a strong positive relationship between per capita income and per capita emissions. Some sub-Saharan economies, such as Burundi, which are among the poorest in the world, have GDPs below $1,000 per person per year and per capita emissions below 0.1 tons per year. The world's richest countries—the United States, for example—have GDPs around $60,000 per person per year and have per

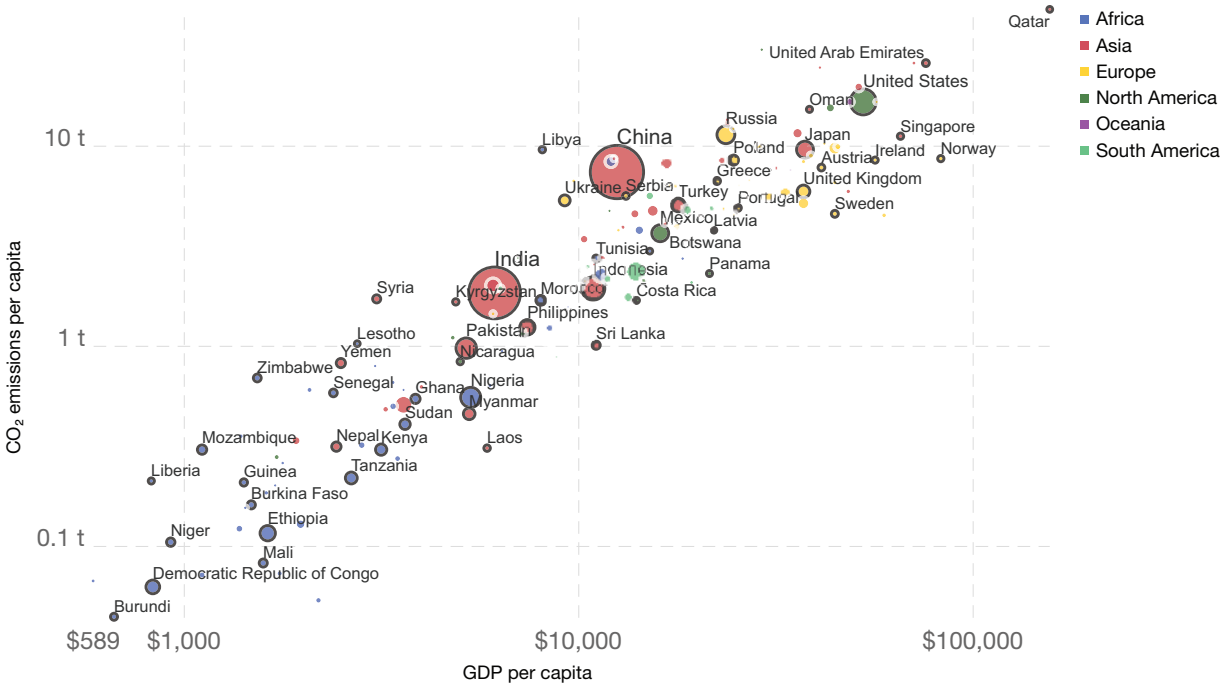

FIGURE 11.1.3 Per capita CO_2 emissions plotted against per capita GDP (the value of goods and services produced per person) across countries. The relationship is plotted on a log scale, which gives the illusion of a linear relationship between the two variables, when in fact the relationship looks more like the right part of a parabola. From Ritchie and Roser 2019.

capita emissions north of 10 tons per year. Yes. Almost 100 times the emissions per person of the world's poorest individuals.

While this graph is enlightening in the cross section, it is not surprising. Richer countries consume (and produce) more things and hence have higher emissions. This snapshot, by definition, ignores time. What if some or most of the bigger countries in the bottom left quadrant of Figure 11.1.3 migrate to the top right quadrant? Is this a bad thing? That depends on what you tend to worry about. The Kaya identity suggests that if you get richer, you emit more, which is intuitive. Also, as your economy becomes more carbon intensive—as many economies transitioning from an agrarian economy to an industrialized economy have—you emit more carbon. At least that is what the historical record suggests. One hope is that the amount of energy needed to produce a unit of output will go down as technology becomes more efficient. We

have observed this in many industries. One example is lightbulbs. Old incandescent lightbulbs used much more electricity and provided less light than new LED lightbulbs do.

One thing to wonder about, at least according to the Kaya identity, is whether rising incomes are a bad thing. If you were a development economist, you would be excited about rising incomes! Battling poverty is one of the main goals of development economists and practitioners. In fact, the first Millennium Development Goal (MDG) stated by the United Nations is to "eradicate extreme poverty and hunger." This has historically come at an environmental cost—a rise in greenhouse gas emissions. If you read down the list of the MDGs, the seventh MDG is to "ensure environmental sustainability." What this would suggest is that we are seeking a global transformation of human well-being, by eliminating suffering, all the while ensuring environmental sustainability. What this means is that we would like to move all countries to the right in Figure 11.1.3, while ensuring that countries currently low on the *y*-axis remain there and, at the same time, bring the countries in the top right quadrant down into the bottom right quadrant by reducing their emissions but preserving their wealth. This is clearly not a small task and will require a Herculean effort by politicians and researchers across the globe.

The global nature of current and future emissions

While it is easy to start thinking about what is happening in individual countries after seeing Figure 11.1.3, it is important to remember that greenhouse gases are largely global pollutants. A ton of CO_2 is roughly what you would emit by driving a Ford Mustang 5.0 (one cool car, especially the convertible) from San Francisco to Chicago. It does not matter whether that ton of CO_2 is emitted in California or China—it causes the same amount of damage. Hence the global climate responds to global emissions, regardless of where they stem from. There are numerous efforts under way to draw different scenarios of *global* emissions for the next 100 years. As you can imagine, predicting what will happen hundreds of years from now is extremely challenging. Imagine trying to predict today's economy and technology as a scientist living in the 1700s! These emissions scenarios are consistent with different versions of the Kaya identity. Figure 11.1.4 displays a set of future emissions scenarios.

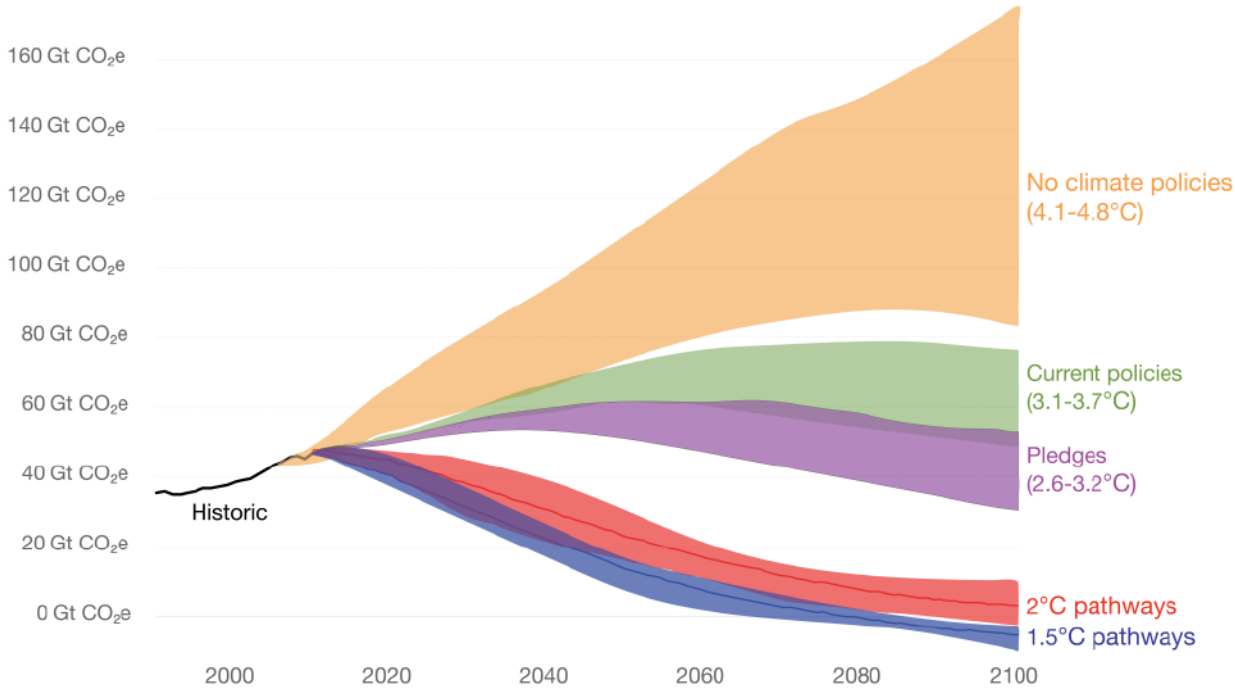

FIGURE 11.1.4 Possible scenarios of greenhouse gas emissions for the next 100 years. You can see that the scenario without climate policies is projected to cause significant warming, while the dark blue path is an extremely ambitious emissions scenario limiting warming to 1.5°C. From Ritchie and Roser 2019.

The top (peach-colored) band in Figure 11.1.4 displays a future where no climate policies are implemented—the status quo; the green trajectory shows a future where currently implemented climate policies are executed and adhered to. The purple band displays a future where all countries achieve their current targets/pledges set within the Paris Agreement. The red pathway corresponds to an aspirational goal of limiting emissions to a level where the global temperature only rises by 2°C above preindustrial levels. This would limit damages to avoid some extreme and worrisome effects. Finally, the blue trajectory is for an aspirational goal of limiting warming to 1.5°C. This scenario would require very urgent and rapid reduction in global greenhouse gas emissions. Figure 11.1.4 is just one example of a set of emissions scenarios produced in a very active academic literature. Of course, you and I could probably come up with alternate futures, which would look very different.

The emissions scenarios are used by physical climate scientists as

inputs into climate models (general circulation models, sometimes called global climate models [GCMs]). These models, as discussed in Chapter 1, translate changes in greenhouse gas emissions into impacts on physical dimensions of climate. These include, but are not limited to, surface temperature, precipitation, humidity, wind speeds, cloud formation, and sea level rise. These models hence produce different futures of planet Earth depending on what emissions pathway we follow. How big changes in the climate system will be depends critically on the emission path we will follow.

The Intergovernmental Panel on Climate Change (IPCC) generates the "official" climate scenarios, which are a synthesis of the mostly peer-reviewed scientific literature to date. Thousands of scientists review tens of thousands of published papers to synthesize our collective understanding of the current and future state of the climate system. Figure 11.1.5 displays the projections from their Fifth Assessment Report. There are different scenarios of climate change, called Representative Concentration Pathways (RCPs), which are simply worlds with different degrees of greenhouse gas concentrations. The graphs on the left display temperature change, precipitation change, and Arctic sea ice under RCP 2.6, which is consistent with warming of roughly 1°C over temperatures experienced in the late 1900s. Under this scenario the chance of exceeding 2°C is less than 33%. The graphs on the right show the same indicators (temperature, precipitation, and sea ice) under the high RCP 8.5 emissions scenario, for which temperatures are thought to continue increasing and reach about 4°C higher than late-twentieth-century levels (the likely range of outcomes for 2100 is 3°C to 5.5°C higher).*

The figure shows a number of interesting things. First off, the impacts on temperature are much more dire for the higher-emissions scenario (which is not that surprising) and for regions closer to the poles. Second, most climate models predict very similar increases in warming and distribution across space for temperature. The second row in Figure 11.1.5 indicates changes in precipitation. Two things stand

*Note that we keep on using °C, which is the unit used in most of the literature (water freezes at 0°C and boils at 100°C). If you like Fahrenheit better, multiply the degree Celsius figure by 9, then divide by 5, and add 32 to what you get.

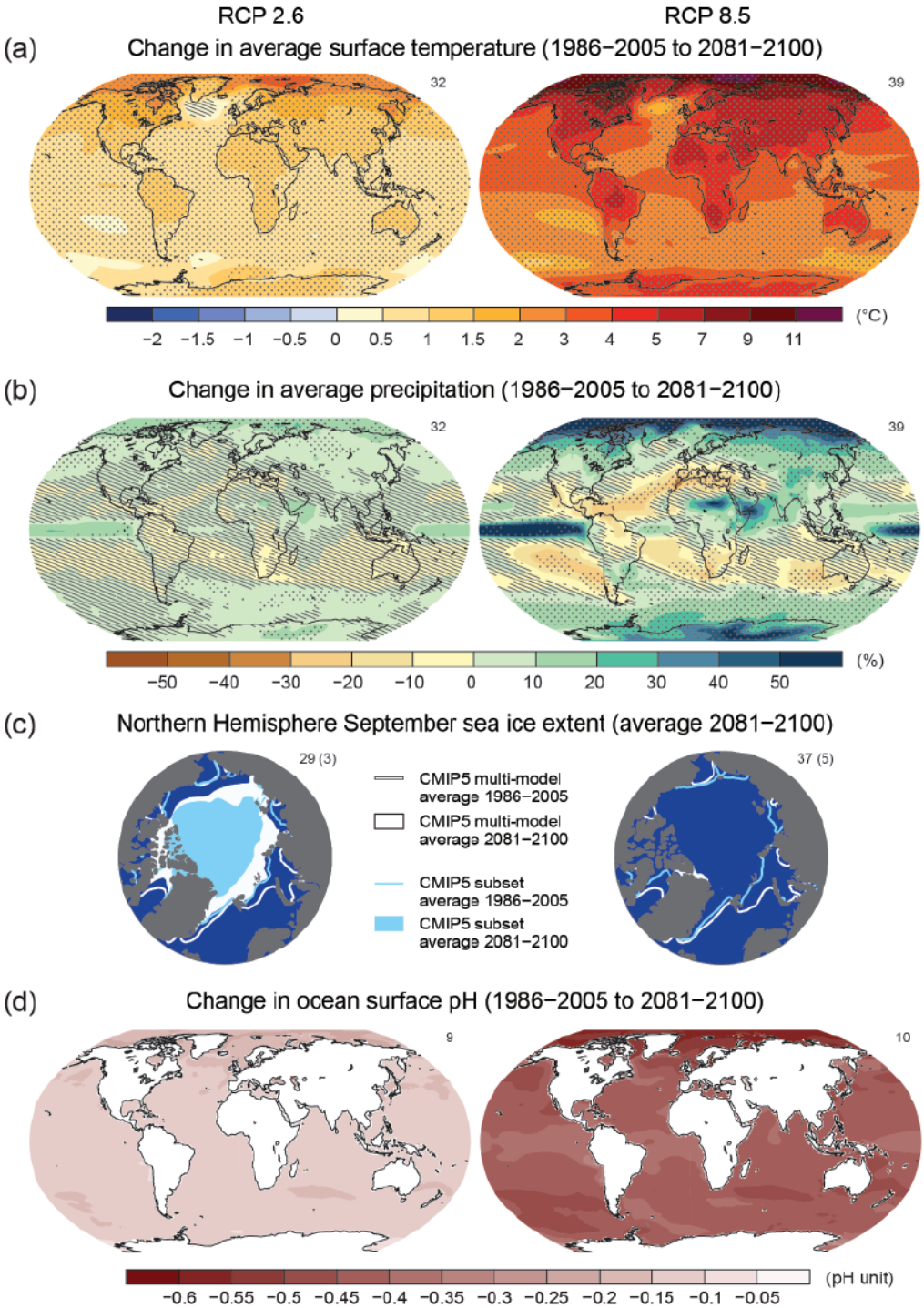

FIGURE 11.1.5 **Projected effects of climate change on temperature, precipitation, sea ice, and ocean acidity under lower (left) and higher (right) emissions scenarios.** From IPCC 2013.

out here. First, the high-emissions scenario has very different patterns of drying in different areas, and those with the largest decrease in precipitation include some of the major crop-producing regions in the world. Second, the model agreement is much lower, with different models predicting very different precipitation changes, making this one of the most important uncertainties in the climate literature. Especially if you are an agricultural economist like me! Crops need water to grow, and what and where to plant is one of the key decisions a farmer has to make. The more uncertainty there is in what your rainfall patterns look like, the harder it gets to make the best planting decisions. The third row shows Arctic sea ice under the two scenarios. It shows that under both scenarios, sea ice shrinks. Most notably it disappears under the RCP 8.5 scenario.

A pet peeve of mine is that funding agencies across the world have spent billions of dollars studying the physical aspects of climate change by collecting important data and supporting very complex computational models to study the future of the climate system. While this is clearly extremely important, much less attention (and, importantly, research funding) has been directed at studying the impacts of climate change on human and natural systems and translating these into monetary terms. Lack of funding notwithstanding, there has been a sparsely funded explosion in this literature recently, which led to the development of methods and insights that were not available as far back as 10 years. Much of this revolution in economics has been fueled by the availability of large data sets on the economy and detailed imagery data collected via high-resolution satellites.

11.2 Quantifying the Economic Impacts of Climate Change

History of climate damages

The first evidence of reflection on an impact of climate on human/economic activity goes back to Pythagoras' disciple Parmenides, who divided the world into five zones: one torrid, two temperate, and two frigid. The torrid zones (which we call the tropics today) he thought were too hot to be inhabited. Aristotle later agreed with this view, for both the torrid and the frigid zones (the poles). He believed that the only areas on Earth habitable by humans were located between the tropics and the Arctic and Antarctic Circles—the area where he lived. The French philosopher Montesquieu took a much more direct and controversial line on the causal relationship between climate and human ability, suggesting that humans from colder climates were physically superior, braver, more honest, and more clever. This clearly incorrect perspective on the cross-sectional influence of climate on human well-being lacked any sort of empirical basis and led to a long discussion around environmental determinism.

Economic damages from climate change—why is this so difficult?

The emergence of climate change as a field of study in the physical sciences in the late 1970s quickly led social scientists to think about what the possible consequences of a *changing* climate could be on economic sectors. This is a difficult problem, to say the least. Let's think about what one would like to know in order to make good policy. One would like to get *an estimate of the damage a ton of CO_2 (or another greenhouse gas) causes after it has been emitted*. Sounds simple, right? But this is where the heavy hand of physics presents the invisible hand of the marketplace with quite a challenge, which has to do with time and space.

First, CO_2, for example, is a long-lived gas. Once emitted, it stays in

the atmosphere for hundreds and possibly thousands of years. Hence it continues to produce warming for a long time. That tank of gas you burned through getting home for the holidays was turned into CO_2 molecules that your great-great-great-[…]-great-great grandchildren will feel the consequences of. This means in order to figure out what the damage of that ton emitted is, you need to figure out the consequences for the economy today, tomorrow, and the next few hundred years. This means you will have to put a dollar amount on the damages experienced by people (and critters and plants) living at the end of the century and beyond. We are again back to the problem of having to project the future state of the climate system and economy out hundreds of years.

The second challenge stems from the fact that the vast majority of greenhouse gases are global pollutants, as we discussed above. This means that the exact location of emissions is irrelevant to the damages they cause. Furthermore, one has to calculate the damages across the entire planet—not just at the point of emissions.

To summarize, so far the challenge seems pretty steep. You have to calculate global damages for the next few hundred years. But it gets harder when you contemplate the broad array of *economic sectors* that can be affected by climate change. The most obvious sector that will be affected by climate change is agriculture. Crops and animals largely live outside and exposed to the weather. If it gets hotter and drier, most plants and animals do not do as well. It has been shown, for example, that crop yields drop significantly if the number of days with temperatures above 30°C rises, as most climate models predict. Another sector affected by climate change is the energy sector. When it gets hotter, people who have air conditioners turn them on and increase their energy consumption—often significantly. They also heat less in the winter, which is a good thing.

But you can probably already see it. Quantifying what will happen to crops across the world as well as energy use in developed and developing countries everywhere over the next few centuries is a daunting task. If you take into account that there are many other aspects of human society that are affected by the climate, this task becomes even trickier. It has been shown that mortality, morbidity, crime, conflict, productivity,

water consumption, migration, spread of disease vectors, air pollution, happiness, cognitive performance, reproductive ability, and suicide are all affected by climate—worldwide. The studies showing this are not just telling stories but are using actually observed data to establish statistical links between weather/climate and these outcomes.

The damage function

As mentioned above, the literature examining this function linking climate to economic outcomes has exploded over the past decade. So let's take a look and examine what these studies do in practice. The next section draws heavily on an article I published in the *Journal of Economic Perspectives* in 2018 (listed in the Supplementary Readings section; it is a great, free resource written for a general audience).

Here is how economists have recently attempted to quantify the link between changes in climate and the consequent damages (and in a few cases the benefits). The mathematical relationship used to map changes in climate into damages is something fittingly called a **damage function**. This deserves some elaboration using an example. When you leave your apartment in the morning, you encounter the day's weather. If you live in sunny San Diego (like Professor Ramanathan, who is the brains and soul behind getting this book over the finish line), the weather you encounter is likely sunny and a pleasant 22°C. If you live in Northern Bavaria as I used to do, in the winter you will encounter a day close to −10°C with thick clouds. You can think of climate as the average weather over a long period of time. There are many different measures of climate that may be relevant to you. For example, you may be interested in what the average weather (climate) in a location is like in the summer. This is essentially how we pick vacation destinations! We look at average temperatures during the season we intend to visit a location. There is no guarantee that the weather when we actually travel will be what we anticipated, though. Often you will have traveled to the beach, expecting sunshine, and you just got unlucky and encountered rain and fog. This is weather.

So, if there is climate change, the average weather you will encounter will shift. For those of you who remember your statistics training, it is not just the average weather that shifts, but the whole distribution

(which in some places can be approximated by what is commonly referred to as a bell curve). For example, the average temperature may increase, but at the same time, the variability of weather may also increase. A shift in the average weather and possibly in its variability will lead to a higher frequency of "extreme events" such as heat waves and droughts. The issue is that these changes in weather—driven by climate change—affect outcomes of interest in unexpected ways. What I mean is that a 1°C increase in temperatures when it's cool outside could have a much smaller impact on, for example, crop yields and energy consumption than a 1°C increase when it's hot outside. Some important food crops, for example, have been shown to react very negatively to temperature increases above 30°C but do not care much if it gets a little bit warmer at 20°C.

Hence, what we are interested in is how individuals/crops/animals/plants respond to weather when the average weather (that is, climate) has changed in the long run. This response is likely different from the old response when the average weather had not changed. Let's use an example close to my heart to help us clarify our thinking. Historically, a really hot day in the San Francisco Bay Area would lead to increases in ice cream consumption and lots of whining. Since San Franciscans historically knew that these hot days were extremely rare, almost no houses or apartment buildings had air conditioners. If, however, San Franciscans learn that there is such a thing as climate change, and that their summers will resemble Palermo's unpleasant hot summers on average in the future, many will go ahead and install air conditioners.

Hence how the San Francisco hipsters react to a hot day after the climate has changed is different from how they would have reacted to the same hot day before climate change—because of the installation of "new gadgets," that is, air conditioners. The future under climate change will hence likely result in higher electricity consumption due to the installation of additional air conditioners, which consumers will pay money to install. Complaining will likely increase as well, since we Californians are a whiny bunch. But what about the people that already had air conditioners? The rational thing for them to do is to run their air conditioners more frequently. So what we end up with is air conditioners

new and old being run more frequently using electricity, which costs consumers money and results in higher emissions of greenhouse gases.

While qualitatively the above example makes a great deal of sense (at least to me), we need to quantify the impacts—meaning putting actual numbers to the problem of how much electricity consumption will change. This is done by statistically estimating the damage functions discussed above. The trick is that these damage functions need to be calculated for all (or at least for the most important) sectors sensitive to weather under climate change. These damage functions are key to making smart policy decisions and allow us to identify the sectors most vulnerable to a changing climate. So what do these damage functions used in policy analysis of the economic impacts of climate change look like—at least in our perfect ivory tower world? Figure 11.2.1 helps to fix ideas.

The top left panel of Figure 11.2.1 shows weather generated in a setting before climate change has occurred (light gray line) and one where the climate has changed (dark gray line). Here, we are only looking at changes in temperature. The post-climate-change temperature is warmer but also more variable. The top right panel of Figure 11.2.1 displays two damage functions (the smooth curves) that map weather into an outcome, in this case temperature into household electricity consumption (measured in kWh). The damage functions, as has been confirmed in many empirical settings, are highly nonlinear—they are not straight lines. When it is cold and temperatures rise, electricity consumption falls, as people heat less. When it is warm and temperature rises, electricity consumption increases, as people air-condition their homes.

Back to our San Francisco example, this response without any adaptation (the solid line) is relatively shallow, as few people have air conditioners. When the climate changes to become like that of Palermo, we assume that people eventually learn about this and will adapt. In this example they will do so by buying and using air conditioners, which changes the damage function to the dotted line. The response, especially at higher temperatures, is now much steeper, resulting in stronger post-adaptation increases in electricity consumption on a 1°C warmer day when it's warm outside.

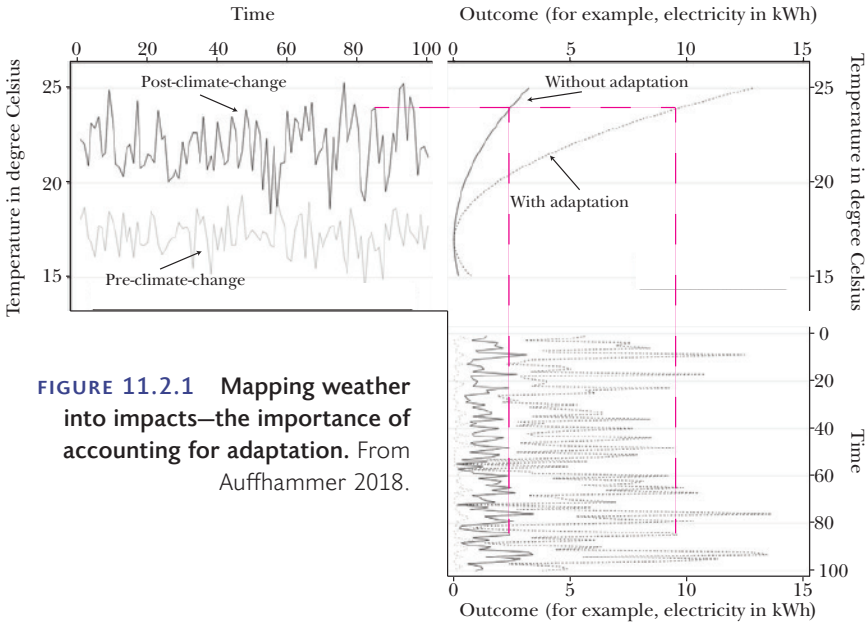

FIGURE 11.2.1 Mapping weather into impacts—the importance of accounting for adaptation. From Auffhammer 2018.

The impact of this can be seen in the bottom panel of Figure 11.2.1 very clearly. The solid light-gray series of *electricity consumption* shows consumption under the pre-climate-change weather with the no-adaptation response function. If the climate changes and we use the flatter (and wrong) pre-climate damage function, projected electricity consumption is the gray solid line. This is clearly incorrect, as one is using the right weather but the wrong response function. The correct response function is the dotted parabola, which results in the dark dotted time series of electricity consumption in the bottom panel. It is much higher and much more variable than the no-adaptation prediction. One way to think about this is by simulating weather impacts "with and without a climate adaptation response." Allowing for adaptation, in this example, leads to substantial changes in electricity consumption, which the damage function seeks to incorporate. This seems straightforward in the case of electricity consumption, since we know the likely adaptation technology and can observe how people use it in hotter areas. This is much more difficult for other sectors. Trying to estimate how crops will adapt, conflict will change, and species and disease vectors will adapt to climate change is very difficult. By that I mean you should contemplate working on these topics in your research!

TABLE 11.2.1 Coverage of the damage function literature, showing what we do and do not know about damage functions for different sectors of the economy and beyond

Sector	*Plausibly Causal Estimates*	*Adaptation Addressed*	*Global Coverage*
Agriculture	Yes	Yes	Yes
Forestry	No	No	No
Species loss	No	No	No
Sea-level rise	Yes	Yes	No
Energy	Yes	Yes	No
Human amenity	Yes	Maybe	No
Morbidity and mortality	Yes	Yes	Yes
Migration	Yes	No	No
Crime and conflict	Yes	No	Maybe
Productivity	Yes	No	No
Water consumption	No	No	No
Pollution	Yes	Maybe	No
Storms	Yes	Yes	No

SOURCE: Auffhammer, M. 2018. Quantifying economic damages from climate change. *Journal of Economic Perspectives* 32(4), 33–52. Table 1. https://doi.org/10.1257/jep.32.4.33.

Environmental economists have been preoccupied with developing statistical methods to estimate such damage functions from observed data on outcomes of interest. There are a number of great review papers, which discuss methods and results in greater detail and are included in the Supplementary Readings section. However, it is instructive to summarize where we are in terms of our understanding of damage functions and what is missing. Table 11.2.1 shows an overview of sectors and what we know about economic damages from climate change.

So much work to do!

What is obvious from Table 11.2.1 is that we know next to nothing about a number of important sectors. First off, the literature putting a value on the damages to so-called **non-market goods** is small to nonexistent. Non-market goods are things that improve our well-being but that are not typically traded in markets, such as biodiversity and clean air. An example helps to organize thoughts. If climate change wipes out a species,

say the bald eagle, is there an economic loss/damage? The answer is clearly yes. But what is the value of a bald eagle? Eagles are not traded in markets (unlike chickens—think Chicken McNuggets!). But just because you cannot buy an eagle in a store does not mean it does not have value.

Economists have developed a number of methods to value non-market commodities. One is to simply ask people how much they would be willing to pay in order to ensure that bald eagles are preserved—this method is called **contingent valuation**. You can then take these numbers, add them up across all people, and come up with a valuation. Often these numbers end up being unrealistically big. If you asked me what I would be willing to pay to preserve the bald eagle, I would probably say $200. If you asked me to pay up, I may have conveniently forgotten my wallet. Economists have developed methods to account for these issues, and contingent valuation has been used to assess damages from oil spills, for example. There are also other methods to value non-market commodities, such as the travel cost method that looks at how much people spend to go see a national park for example. You can in certain settings use this number as an approximation of the value people place on said national park. So yes, we need much more research on the value of biodiversity and non-market commodities, including exotic things like the nitrogen cycle.

The other thing that we know very little about is the damages incurred by extreme events. What is the damage caused by the West Antarctic Ice Sheet melting? What is the damage caused by the thermohaline conveyer belt, which is the ocean circulation that gives Europe its gentle climate, shutting down? These are events that we have not experienced in human history, so it is hard to determine what the damage from such an event would be. This is where we turn to "experts." We would call up world experts in ice sheet dynamics and sea level rise and ask how much sea level rise would be caused by the melting of the West Antarctic Ice Sheet. We would then talk to people who understand urban economies and come up with estimates of what it would cost to either protect or move certain coastal communities. Here we would have to rely on the assumption that experts actually know what they are talking about. In order to improve the quality of these expert assessments, we tend to not ask a single expert, but dozens or hundreds of them and average

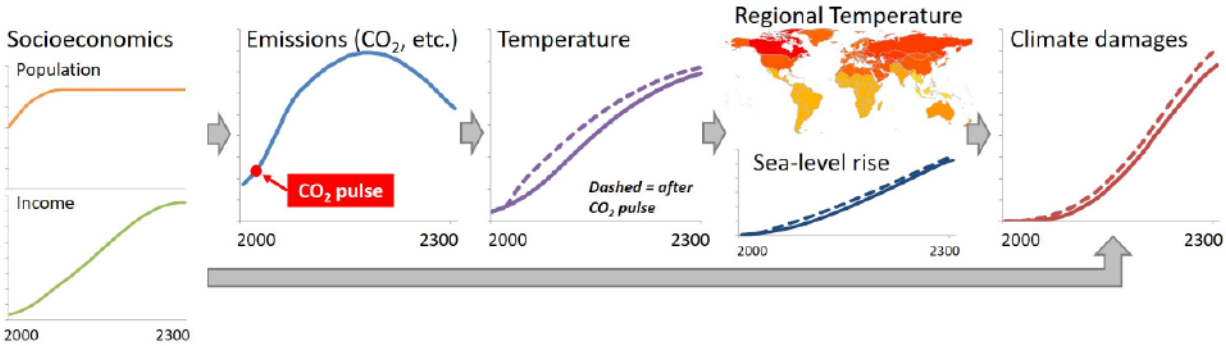

FIGURE 11.2.2 The social cost of carbon—what is needed to produce a number in one model? A lot. From Rose, Diaz, and Blanford 2017.

across their answers. That said, the economic damage from extreme events is hard to estimate, and much work needs to be done by credible academics to push the envelope of our understanding.

The social cost of carbon

Let's assume for a moment that you have done an amazing job (high fives!) and obtained a set of credible damage functions that satisfy the criteria set out above. What do you do with them? What you would want to do is calculate a number called the **social cost of carbon** (SCC). The social cost of carbon is maybe the most important number you have never heard of. The social cost of carbon is an estimate of the present value of the stream of global damages from one additional ton of CO_2 emitted at a point in time. In short, it represents the damage your ton of CO_2 will do to all sectors everywhere over its lifetime.

In order to calculate this number, the literature has employed what are called integrated assessment models, which integrate simple models of the economic and climate system, as illustrated in Figure 11.2.2. These models start with assumptions (sometimes referred to as socioeconomic scenarios) about the evolution of global, and in some cases regional, income and population over the next 300 (!) years. The models then translate economic activity into emissions of greenhouse gases, most notably CO_2, but in some cases other GHGs such as methane. (Methane is a short-lived but more potent greenhouse gas than CO_2. It comes from natural gas wells, fermentation processes, and the back

Box 11.2.1 What Is Discounting?

Discounting translates the value of future consumption into current-day dollars. You may value the consumption of a basket of goods valued at $10 that you get today more highly than the consumption of the same basket valued at $10 some 20 years from now. If you place a higher value on today's consumption than future consumption, and we want to figure out the value of your consumption stream over a long time period, we need to translate the value of that stream of future consumption into current-day value. This is called discounting. The discount rate is your personal "interest rate," and it reflects the relative value you place on current versus future consumption. The higher the discount rate, the less value you place on future consumption. This concept is central in evaluating the benefits and costs from doing something versus doing nothing about climate change, since the costs of doing something are largely incurred in the near term, but the benefits (avoided damages) come much later in time.

end of cattle.) These 300-year time paths of emissions are then fed into a very simple model of the global climate system, which translates emissions into surface temperature, precipitation, and sea level rise. These outputs are then fed to your amazing damage functions, which map the emissions path into economic damages. For example, a hotter state of Georgia due to climate change will likely use more electricity to cool the indoor environment. This is considered an economic damage. In order to calculate the effect that higher emissions have on outcomes of interest across many sectors of the economy, the integrated assessment model is run with and without one additional ton of CO_2. The time path of the difference in damages relative to the baseline represents the damages from that one ton for each year over the next 300 years. The stream of damages is then converted into a present value. This dollar amount is called the social cost of carbon and is measured in US dollars.

Some integrated assessment models are global and treat the world as a single region (for example, DICE by 2018 Nobel Laureate William Nordhaus), while others break out the world into very large regions

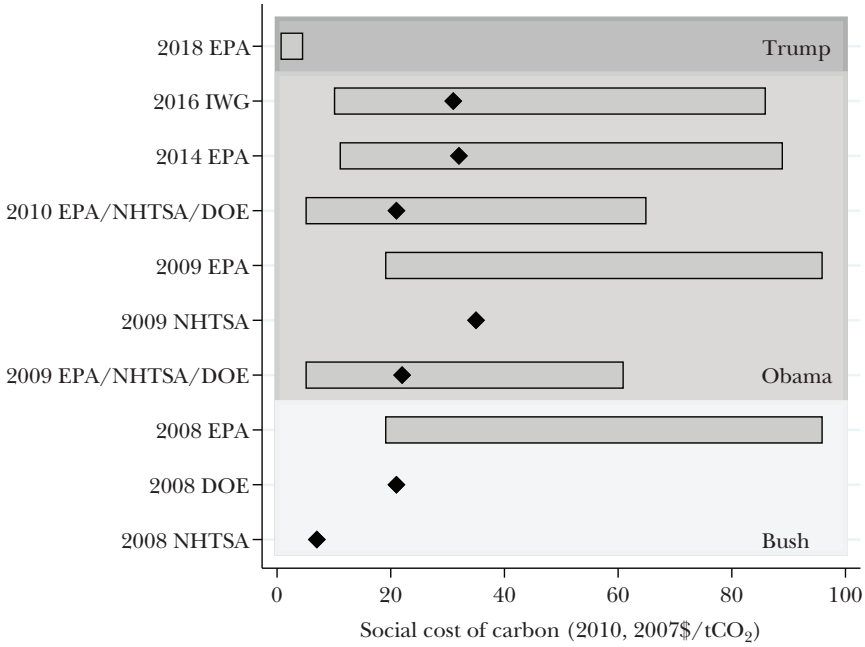

FIGURE 11.2.3 Sample of social cost of carbon (SCC) estimates used in federal rule making for three administrations. Estimates are in 2007 dollars for emissions of a ton of CO_2 in 2010. DOE—Department of Energy; EPA—Environmental Protection Agency; IWG—Interagency Working Group; NHTSA—National Highway Traffic Safety Administration. The black diamond indicates the "central estimate," if one was identified. The gray bars indicate selected upper and lower bounds used in regulatory analyses. From Auffhammer 2018.

(for example, PAGE by Chris Hope; FUND by David Anthoff and Richard Tol). In the case of models with regional resolution, damages are then aggregated across regions to calculate the *global* social cost of carbon. This number represents the damages caused globally over time by one additional ton of CO_2 emissions at a single point in time.

While there is not one official integrated assessment model that rules them all, the US federal government has attempted to estimate the social cost of carbon going back to the George W. Bush administration. Figure 11.2.3 shows a set of values used by the three last administrations in federal rule making. For comparability, the graphic shows values for 1 ton of CO_2 emitted in the year 2010 valued in 2007 US dollars.

In the early years of the Obama administration, the Interagency

TABLE 11.2.2 Social cost of carbon estimates by the Interagency Working Group

	Discount Rate and Statistic		
Year	*5% Average*	*3% Average*	*2.5% Average*
2015	$11	$36	$56
2020	$12	$42	$62
2025	$14	$46	$68
2030	$16	$50	$73
2035	$18	$55	$78
2040	$21	$60	$84
2045	$23	$64	$89
2050	$26	$69	$95

SOURCE: US EPA. 2016. The Social Cost of Carbon: Estimating the Benefits of Reducing Greenhouse Gas Emissions. https://19january2017snapshot.epa.gov/climatechange/social-cost-carbon_.html.

Working Group* embarked on an effort to calculate an official social cost of carbon. The approach adopted, which is described in detail in Greenstone, Kopits, and Wolverton (2013), was to essentially embark on the effort described by Figure 11.2.2: feed three integrated assessment models with a set of harmonized assumptions regarding the evolution of the economy and population, account for uncertainty, and provide a statistical distribution of the social cost of carbon across models. The most frequently cited number for the SCC was $42 per ton emitted in 2020 as measured in 2007. There were several updates to the social cost of carbon calculation, and the final available estimates are given in Table 11.2.2.

Table 11.2.2 displays the global SCC estimates using three different discount rates for emissions between 2015 out until the year 2050. Two

*The IWG was composed of members from the president's Council of Economic Advisers, Council on Environmental Quality, Department of Agriculture, Department of Commerce, Department of Energy, Department of the Interior, Department of Transportation, Department of the Treasury, Environmental Protection Agency, National Economic Council, Office of Management and Budget, and the Office of Science and Technology Policy. It was disbanded by President Trump.

things stand out from this table. First, columns 2–4 display the average SCC across simulations using three different discount rates. A higher discount rate (5%) puts a lower value on future damages and hence results in a lower SCC. A lower discount rate places a relatively higher value on future damages and hence results in a higher SCC.

Second, one notices that for any chosen discount rate, the SCC is higher the later emissions are made. For example, 1 ton of CO_2 emitted in 2020 using the 3% discount rate results in a $42 per ton SCC. A ton emitted in 2050, using the same discount rate, has an SCC of $69. This increase occurs for two reasons. First, as time goes on, the stock of CO_2 in the atmosphere is higher, as CO_2 accumulates over time. Hence, each additional ton emitted at a later point in time arrives in an atmosphere with a higher stock of CO_2 in it, adding additional warming into a more stressed system and leading to higher damages. Second, for some of the integrated assessment models used, damages are a function of income (for example, GDP). As the world grows richer over time, later emissions arrive in a wealthier world, resulting in higher damages. An easy way to think about this is, for example, higher incomes result in more valuable infrastructure, which may be negatively affected by changes in climate.

There is much work to do in order to properly quantify the damages from climate change, and the economic literature on the social cost of carbon is a good literature to follow. One specific effort, which is pushing the frontier of this literature, is the Climate Impact Lab. It is driven by a collaboration of the University of California, Berkeley; the University of Chicago; Rutgers University; and the Rhodium Group. They have an extensive website documenting their research at www.impactlab.org.

11.3 The Policy Challenge

In what follows, I discuss some economics of climate change policy and conclude by suggesting a path forward for international climate policy. A more extensive version of this discussion appears in Auffhammer et al. (2016).

Economic considerations when designing and evaluating climate policies

All undergraduate economics students are taught that under certain conditions, markets maximize social well-being and therefore do not require any government intervention—or even worse, government intervention can make society worse off! You may have heard this line of reasoning from some serious-looking people on the news networks. This is true for so-called perfectly competitive markets. It turns out, though, that perfectly competitive markets are about as abundant as panda bears. Many real-world markets do not satisfy the idealistic assumptions required, because of what we call market failures. There are numerous and well-studied types of market failures, but in the context of global climate change, two types of market failures reign supreme: **negative externalities** and **public goods**.

Negative externalities arise when individual agents do not internalize the full cost of their activities. In the absence of climate policy, individual consumers and firms do not pay for the negative effects of their greenhouse gas emissions on the environment and economy. This results in a larger than optimal amount of greenhouse gas emissions.

The second major market failure, public goods, arises when a good in question is **non-excludable** and **non-rival**. Non-excludability means that no one can be technically excluded from the consumption of the good (for example, national defense). Non-rivalry means that one agent's consumption does not diminish the amount of the good left over for

everyone else (for example, radio waves). If a good is *public*, it is both non-excludable and non-rival, and markets underprovide the good—and in some cases do not provide this good at all.

The public goods problem arises in two important ways in the context of global climate change. The first good related to global climate change that has public characteristics is emissions abatement. If one country (or state) abates its emissions, all other countries (or states) also benefit from the reduction and cannot be excluded from these benefits. This results in an underprovision of emissions reductions by individual countries, which is consistent with the outcome of the United Nations climate change conferences that have for the past 30 years not been able to come together with a binding treaty including all nations committing to anywhere near the optimal reductions in greenhouse gas emissions.

The second good related to global climate change that has public characteristics is innovation. If one private firm obtains a technological breakthrough in a renewable energy technology, unless intellectual property rights are well defined and enforced, other firms can copy the technology and capture some or all of the innovating firm's profits. This leads to an underinvestment in innovation.

Owing to market failures related to global climate change, well-designed government policy is important for addressing global climate change. In order to determine the optimal level of policy intervention when market failures exist, basic economic theory mandates that one compare the benefits from a proposed policy to its costs. Regulators in many places are mandated to calculate a ratio of the benefits to the costs (often referred to as the benefit-cost ratio) and only pass policies when this ratio is greater than one. In the case of climate change, calculating this ratio is especially complex, as damages occur globally and over a very long time horizon, while the costs of mitigation are incurred much earlier and in their majority by a small number of countries or regions. Hence localities often compare local benefits to local damages when deciding whether to pass climate policies. But fundamentally this is a global problem with a corresponding global benefit-cost ratio.

In addition, since the benefits and costs of climate change policy occur over a very long time horizon, the appropriate measure of

benefits is not the current benefits but rather the present discounted value of the entire stream of benefits over many years. Similarly, the appropriate measure of costs is not the current costs, but rather the present discounted value of the entire stream of costs over many years. Calculating the present discounted value of benefits and costs requires using an appropriate discount rate (Box 11.2.1). Moreover, since both investments in abatement technology and the damage from climate change are irreversible, there is a value to the option of waiting that should be accounted for when comparing benefits and costs. Estimating these benefits of greenhouse gas reductions is a complex undertaking.

While the social cost of carbon measures the marginal damage of emitting a ton of CO_2 equivalent (or the marginal benefit of avoiding its emission), there are significant other benefits to greenhouse gas reductions, which stem from the fact that the combustion of fossil fuels results in the emissions of greenhouse gases as well as other local and regional pollutants. There is a large literature on quantifying these **co-benefits** at the sectoral level. For many policies these co-benefits are a significant or in some cases the main portion of the benefits from greenhouse gas regulation. Importantly, the type and value of co-benefits from greenhouse gas regulation vary drastically across countries. For example, reducing the combustion of biofuels and fossil fuels not only has significant local impacts in terms of improved health, but also has large-scale positive impacts on local climate as black carbon is a highly potent, yet not long-lasting greenhouse gas (Chapter 15). The quantification of these local co-benefits through their direct pollution impacts on health and agriculture as well as their indirect climatic effect through black carbon and aerosols are an active area of research.

The direct and indirect benefits of climate policies in terms of their impact on human health are especially important as climate change is now considered the biggest global health threat of the twenty-first century. Over 150,000 deaths annually are attributed to ongoing climatic changes, and this toll is expected to grow by 250,000 additional deaths per year between 2030 and 2050, according to the World Health Organization.

Another challenge is to quantify the costs of greenhouse gas regulation, which in the economic literature is called the estimation of

abatement cost curves. In theory, each firm that reduces its emissions of greenhouse gases incurs a cost to do so. It can choose to reduce its emissions by producing less output, using new technology, or switching to lower-carbon-content inputs. A firm will compare the costs of the strategies. The least cost approach to reducing its emissions at each level of output is called the firm's abatement cost curve. Since much of this information is private to the firm, regulators can have a difficult time determining what the true costs of abatement for a firm are. Anticipating a new policy, firms have no incentive to reveal the true abatement cost, yet they have every incentive to exaggerate the costs of abatement. Hence, as the regulator attempts to determine the benefit-cost ratio, there is significant uncertainty about the cost component, and regulators often have to rely on simplistic engineering calculations or educated guessing.

In order to design an optimal global climate policy, two market failures have to be addressed simultaneously. First, from a global perspective, since there is no global police person monitoring and enforcing a possibly agreed-to climate policy by all countries, individual countries will underprovide abatement or simply not agree to follow or join an international agreement of cutbacks. This will lead to an ineffective global agreement on emissions reductions, which will fall short on what is required to stay under a maximum of 2°C warming. One example of this approach is the largely ineffective Kyoto Protocol; the reasons for its failure are discussed in Chapter 10. The subsequent Paris Agreement, under which individual countries proposed individual cutback plans up front, aimed to respond to some of Kyoto's failings. In order to work, a type of agreement such as Paris will need to rely on climate "clubs," which are regimes with small trade penalties on nonparticipants, to coordinate emissions reductions that are enforced with border tariffs (Chapter 10).

The second market failure that needs to be addressed is the general externality problem once countries have agreed to an emissions target. To reduce emissions to address the externality, there are two types of approaches: (1) **command and control** and (2) **incentive- or market-based approaches**. Command-and-control approaches come in three flavors generally. The first type is an emissions standard, which

simply prescribes how much each emitter can emit. The second is an input target, which prescribes which type of input to production an emitter has to use, for example, low-sulfur coal. Another example of an input target is a low carbon fuel standard. The third type is a technology standard, which prescribes a specific technology, for example, electric vehicles.

Incentive- and market-based approaches also come in three flavors. The first is an emissions fee/tax, which charges an emitter the marginal external cost and makes the emitter internalize this cost. Hence the emitter is paying for the full opportunity cost of its activity. The second is a cap-and-trade system, which caps the total amount of emissions and issues a right to pollute for each ton emitted, which can then be traded. This approach essentially places a price on carbon, as the permits have a price. The final incentive-based approach is subsidizing certain low-carbon technologies or fuels, which artificially lowers their price in the market and increases the incentive for adoption.

The advantages and disadvantages of command-and-control versus incentive- and market-based approaches are discussed in more detail in Chapter 12. In brief, however, in order to determine which policy should be used, two criteria are usually applied by economists for evaluating policy: **cost-effectiveness** and **efficiency**. For a given emission reduction, a policy is cost-effective if it achieves this reduction at least cost. A policy is efficient if it maximizes net benefits, or total benefits minus total costs. From an economy-wide perspective, cost-effectiveness and efficiency make sense, as one would not want to spend scarce resources on meeting policies in an unnecessarily costly manner. Policies that put a price on carbon—carbon taxes and cap and trade—have been shown to achieve this goal of efficiency time and time again. In contrast, command-and-control policies have been shown to be very costly ways of meeting a given emissions target.

One argument often raised in support of command-and-control standards is the fact that they are more fair or equitable than price-based policies. Under a standard, sources usually are subject to similar reduction targets, which is perceived to be fair. However, market-based policies can be made more equitable as they generate significant revenue, which can be redistributed to increase fairness, all while minimizing

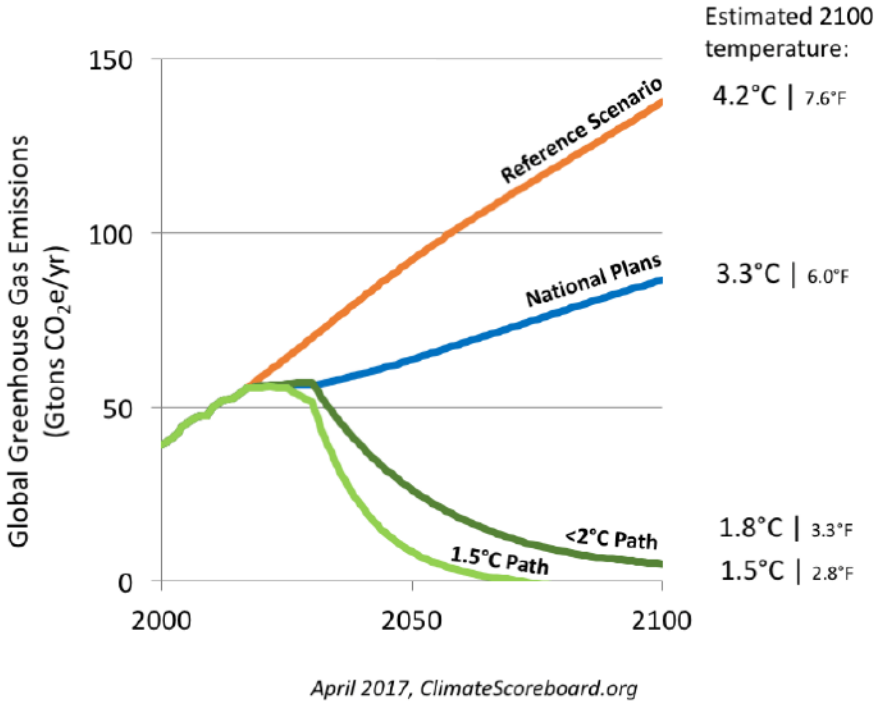

FIGURE 11.3.1 How much warming will we get for different policy scenarios? Reproduced with permission from Climate Interactive.

the cost of the emissions reductions. These revenues can also be used to address the innovation market failure, whereby tax revenue is used to enable research in promising future low-carbon technologies. One such example is research on carbon sequestration and storage, which carries a hefty price tag—in the billions of dollars for each experiment. Such large-scale projects are almost impossible to fund by the private sector and thus are likely to be a good place for the regulator to step in.

Where we are

Globally greenhouse gas emissions are the highest in human history. Atmospheric concentrations worldwide are the highest they have been in thousands of years. Human population and incomes continue to grow. There is a clear trade-off. Pulling humans out of poverty is an unambiguously good thing. But it comes at a tremendous cost to the global climate and ecosystem. I would like to close with Figure 11.3.1, which shows us how far we have to go.

Even though all but a single country have signed on to the Paris Agreement, even if every one meets its target, we fall significantly short of the 2°C target. There is a long way to go to solve this major problem. Smart implementation of cost-effective policies is the key to getting us even close to the 2°C goal. There are some small beacons of hope. The Kigali Amendment to the Montreal Protocol on Substances that Deplete the Ozone Layer (Chapter 15) has been an effective international agreement targeted at substances that deplete the ozone layer. The substances it covers suffer from the same externality and public goods problems as greenhouse gases do. Yet, it is effective. Some of that may have to do with the fact that the substances it controls (for example, hydrofluorocarbons) are very inexpensive and good alternatives exist. Carbon, in contrast, is everywhere and our economies have largely been built by injecting large quantities of it into the atmosphere.

The other beacon of hope is technology. Renewable energy sources such as wind and solar have come down in price in truly stunning ways and are now cheaper in many settings than natural gas and certainly coal. In order to truly decarbonize the electrical grid, we need to find cost-competitive electricity storage solutions (Chapter 13), as the production profile of renewables does not match the consumption profile. So the hope for the future is a combination of engineering genius, smart economics, and savvy policymakers. It's time for you to get to work!

Supplementary Readings

Auffhammer, M. 2018. Quantifying economic damages from climate change. *Journal of Economic Perspectives* 32(4), 33–52. https://doi.org/10.1257/jep.32.4.33.

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CHAPTER 12

Cost-Effective Climate Policies

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Learning Objectives

1. Identify policies that are market based versus command based in practice. What aspects of a particular environmental policy determine the kinds of change it will create?
2. Explain why command-based policies are not cost-effective. For any given command-based policy, be able to come up with examples of incentives that are missing or misplaced. Explain how a market-based policy could cost the same amount but accomplish a greater environmental goal.
3. Consider the role of consumer choice and behavior in the context of the two types of policy. Understand why command-based policies can sometimes be justified if consumers would otherwise make mistakes while shopping.

Overview

In practice, the control of greenhouse gas emissions takes one of two forms: market-based incentives (giving polluters a financial reason to cut back) and command-based regulation (requiring that emissions fall below a certain level, often through the use of specific technologies). Chapter 11 lays out the basic economic argument: command-based approaches often pick inefficient levels of emissions for a particular source, technologies that are not cost-effective, or both. Incentive-based approaches (most importantly, a carbon tax) place many sources of emissions and many different technologies on the same playing field, such that only the most cost-effective reductions in the most cost-effective sectors are employed. The overall strength of the incentive to reduce carbon emissions can be adjusted up and down by varying the level of the tax.

This chapter outlines the incentives created by different types of policies and uses examples of real policies around the world to show how close or how far we are from the economic goal of cost-effectiveness.

12.1 Incentives and the Source of Cost-Effectiveness

Understanding cost-effectiveness requires first that we understand the concept of an **externality**. The fundamental source of the climate problem in a market economy comes down to the idea of external cost. When you buy something in the market, you are paying for the labor, materials, capital, and technology that lie behind the final product. If in the process of making the product, or in the process of your using it, other people get hurt, an externality is created. The word comes from the idea that the damage is outside or "external to" the people buying and selling the product. For example, the tremendous damage that will be done to future generations as a result of climate change is external to the goals of many companies (profits) and consumers (individual well-being and low prices).

An important potential solution for externalities is to increase education and awareness of the problem (one of the goals of this book!). Companies could give up some of their profits, and consumers could cut back on some of the products they had been purchasing, in order to protect the climate for future generations. Indeed, some of the most profound changes to our society (in terms of the environment, but also much more broadly) have been led by exactly this sort of movement. How should we think about the need for policy, and about what type of policy is best? I would argue that the role for policy is twofold: (1) to create more, or faster, environmental change than is happening through current actions and (2) to accomplish the change in a way that minimizes cost to all parts of society. Achieving cost-effectiveness in an equitable way across society, and especially protecting the most vulnerable subgroups, requires careful consideration of policy design and the distribution of any revenues.

Cost-effectiveness

The key to understanding cost-effectiveness begins with a thought experiment. Imagine making a list of every opportunity available to reduce greenhouse gas emissions, being very specific. Next to each entry write down how many emissions are saved and what the activity will cost. The cost you enter for each item might not always be in dollars—sometimes it could be measured in terms of lost comfort, time, or convenience, for example. The list should be very specific: my walking to work instead of driving could involve a different cost (based on how far I live from my office, the local weather, how much I enjoy walking, and so on) than someone else's walking to work. Your list of possible actions to help solve climate change, therefore, should have a different entry for "walking to work" for every person and every day; sometimes it will be expensive or uncomfortable, and sometimes it will be cheap and easy. Similarly, the cost of installing solar panels rather than buying electricity from the grid can differ greatly based on geography and the type and angle of the roof on a house. Therefore, your list needs a different entry for "rooftop solar panels" for every house in the world.

Notice that your list should also contain many different entries for things that companies can do, along with the cost of those actions. Google's loss in profits (usually a good measure of cost for actions that companies take) from making its data centers carbon-free might be very different from Alcoa's loss in profits from making its aluminum-smelting plants carbon-free. The carbon savings are probably very different as well.

Next in the thought experiment, sort your entire list based on the lowest cost per ton of greenhouse gas emissions avoided. With a complete, sorted list in hand, achieving cost-effectiveness becomes quite easy: simply start at the top of the list, require each individual or company to complete the listed task, and continue down the list until the climate challenge is solved. This will change the environment for the better, using only the very cheapest items on the list (because you sorted it before deciding which actions to require). That's the definition of cost-effectiveness. If a government policymaker had access to the complete list and could enforce all the actions on it even when they occur inside people's homes, then the government could do very well on a cost-effectiveness goal even if using **command-based** rules (rules that

mandate particular technologies or actions). The government would be able to mandate each successive item until the carbon goal was reached.

As you have probably guessed, the problem in real life is that we cannot make, or even come close to approximating, this master list. There are simply too many actions and too many different people and companies involved to figure out something like who should and shouldn't be walking to work, which houses should have solar and which shouldn't, which companies need to go carbon-free or not, and so on.

Happily, a **market-based** policy such as a carbon tax is capable of letting individuals and businesses in the economy reveal their own places on the list. For example, if the government raises the price of emitting carbon dioxide, it will make gasoline more expensive and some people will start walking to work. The people who start walking to work happen to be exactly the same people who would appear near the top of your imaginary list! The people who keep driving, on the other hand, will be the ones farther down on your list, whose actions would be more costly.

In contrast, a command-based policy to require people to walk to work (for example, by taking away parking permits or license plates) could never fully distinguish between people in different places on the list. No matter how much information government tried to get, it would almost certainly still "scramble" the list, taking away parking permits or license plates from some people who find it very hard to walk to work, while accidentally leaving parking permits and license plates in place for other people who would be perfectly happy walking to work if they were asked to.

The fundamental difference between command-based and market-based policies is in how government chooses who has to take which actions, and in the likelihood that that choice matches up with the people and actions at the top of the hypothetical master list. Command-based policy, by its very nature, does the picking and choosing within the law itself—regulators perform often very complicated analyses to decide who should be subject to a rule and who should be exempt and which exact actions should be taken. While such analysis and detailed lawmaking can help get a little closer to matching the true list, there is simply not enough information available to do it very well.

Market-based policy, as championed by most economists, is easier

to create, easier to enforce, and better at matching the actions near the top of the cost-effectiveness list. Best of all, it can do this without even knowing which items are cheapest. Furthermore, it also adapts automatically as technology changes. For example, swapping my gasoline car for an electric car might be expensive and difficult for me right now but a much better choice for me in 5 years. A carbon tax would automatically incentivize my purchase of an electric car at the right time for me, and my neighbor's electric car at the right time for them.

There are several ways to create price signals to discourage greenhouse gas emissions, but the one we will consider in our examples is the simplest, and most economists would say best, market-based policy: a carbon tax. How does a carbon tax work? Most companies are very good at maximizing profits and minimizing taxes and so will be able to figure out which of their possible actions to reduce carbon emissions will be cheaper (and thus result in more profits) than paying the carbon tax. Likewise, individuals make many decisions every day to make their lives better (maximizing "utility," in the language of economics). A carbon tax creates a price signal that discourages people from buying products that are damaging to the climate and it incentivizes a whole series of small actions on energy conservation that, when taken together, can have a transformative effect on climate.

Individual choices and mistakes

The role of individual choices and actions in responding to a carbon tax raises an important potential problem with the policy: What happens when individuals can't figure out which actions will save them money? They might see a high price for a carbon-intense product on the shelf (the high price would be caused by the carbon tax) but just keep on buying it anyway because they don't know about alternatives with lower carbon intensity that are now cheaper than their old choice. Alternatively, someone could be attracted by a small subsidy on a carbon-free product but later find that using it costs them a huge amount in inconvenience and lost time.

Either of these two mistakes in decision-making could be corrected by a command-based policy that forces people to do items near the top of the cost-effectiveness list and prevents them from doing items that

are too far down on the list (and so are too expensive to be worthwhile). Such policy, of course, would be very difficult to write, since the correct decision could be different for different individuals. An impossibly large amount of data would be needed for the government to figure out the correct mandate for everyone. Finally, enforcement could be a problem because it is often impossible to observe everyone's actions carefully enough to ensure compliance.

An increasing amount of work is being done in economics to better understand when consumers make good decisions and when they might need intervention that helps guide them toward the right choice. For example, suppose a consumer sees two nearly identical twelve-packs of tennis balls next to each other on the shelf. Brand A has a price of $9: it costs the company $5 to make the tennis balls, it has to pay $3 in carbon taxes to the government, and it wants to keep $1 in profit. Brand B has a price of $7: it costs the company $6 to make the tennis balls in its carbon-free factory, and it also wants to keep $1 in profit.*

If the tennis balls are the same quality, we would expect the consumer to choose Brand B in order to save money. But, what if we observe that some (or even most) people are still buying Brand A?

Brand A was cheaper before the carbon tax, so maybe these people are just repeating habits from the past. Some authors have called this kind of mistake an "internality" (that is, losing money or utility because of an internal mistake) or referred to it as an issue of "inattention." Another reason we might see people staying with Brand A is that they don't know the two brands are the same quality and don't want to take a risk.

If the two brands of tennis balls are in fact identical in every way except for their carbon emissions, the government could fix any potential consumer mistakes by writing a command-based regulation to remove Brand A tennis balls from shelves, forcing people to make the correct choice. Under these circumstances, such a command-based rule would be more cost-effective than a carbon tax.

Of course, in the real world, the two brands might not be exactly the same quality. Furthermore, the aspects of quality that differ might

*Notice that the company's decision to build a carbon-free factory might have been prompted by the carbon tax. The incentives can operate simultaneously on both the consumer and producer sides.

matter more to some tennis players than others. If this is the case, then neither the command policy nor the carbon tax could produce exactly the right decisions. Some players should switch to Brand B to save money (and society would benefit because of the carbon reduction), while other players should stick with Brand A (because some aspect of quality is worth more to them than the $2 price difference).

In the application in Section 12.4 In Depth: Incentives in US Automobile Policy, we will consider the choice of which car to buy. This is a much more complex purchase decision than we make for a pack of tennis balls, and it is also much more consequential if a person makes a mistake and ends up regretting the choice.

12.2 Current Policy: Market-Based and Regulatory Examples

New regulations aimed at climate change are rapidly appearing in both small and large communities around the world. They include an incredible number and variety of command-based rules. Some of these rules ask for actions that are likely to be near the top of a cost-effectiveness list, while other command-based rules ask for actions that are quite expensive per ton of carbon saved. Simultaneously, an increasing number of market-based policies are being enacted in cities, states, and countries around the world. We now turn to two specific examples, first a command-based policy and then a market-based policy (in the form of a carbon tax), to think about how cost-effectiveness works in practice.

Lightbulbs

The old-fashioned incandescent lightbulb is still a staple in many homes, hungrily chewing up electricity and providing what many find to be a reliable and pleasantly colored source of light. Swapping out incandescent bulbs for energy-saving alternatives, such as the fluorescent or LED light sources pictured in Figure 12.2.1, is often a very cost-effective way of saving carbon. Remember, though, that the complete cost-effectiveness list has to be very specific: swapping each bulb is a separate activity and needs to be separately ranked. If such a master list existed, we would find that some old incandescent bulbs are very near the top—swapping them out could be done with very little cost and would offer lots of carbon savings. We would also find, however, that other individual bulbs, such as those that are rarely turned on or are very costly to swap, appear in entries toward the bottom of the cost-effectiveness list.

Many command-based policies have been enacted that force lightbulb swaps to occur as old bulbs burn out.* US law (specifically, Section

*The command-based rules apply only to new bulbs manufactured after a certain date, so they don't incentivize swaps before old bulbs burn out, which will also sometimes be cost-effective ways to save carbon.

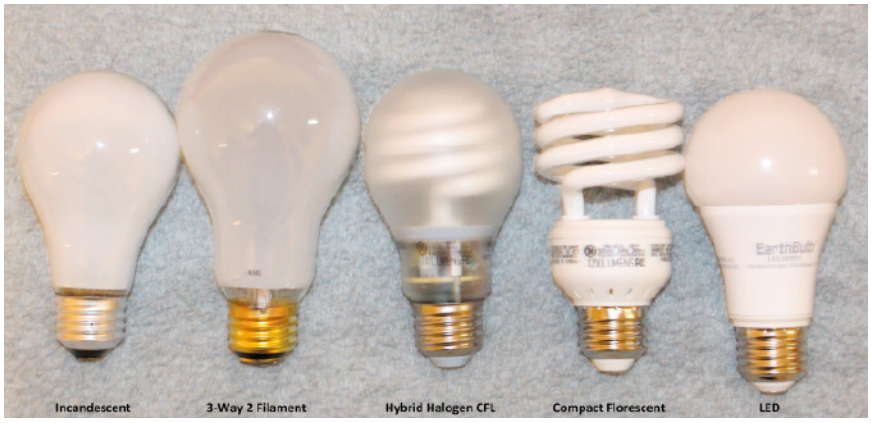

FIGURE 12.2.1 Lightbulb technology. The old-fashioned incandescent bulb is on the left. The energy-saving LED is on the right. Image by Mark Jurrens from Wikimedia Commons.

321 of the Energy Independence and Security Act of 2007) now requires that all new lightbulbs have a minimum amount of light output per watt of energy consumed, subject to a long list of exceptions. Here are some of the exceptions that lawmakers added: bulbs not intended for "general service," bulbs that have an odd-shaped base (in fact, anything other than a standard E26 screw base), bulbs that are very dim, bulbs that are very bright, bulbs that are not a standard size, and bulbs that don't operate on 110 volts AC. Why all the exceptions? When writing this rule, legislators no doubt realized that while lots of bulb replacements are excellent and cost-effective ways to save energy, they could at the same time accidentally be forcing other lightbulb replacements that wouldn't be saving much energy or that would be very high cost and so not worth the effort. For example, bulbs in medical equipment, movie projectors, and model train sets are all exempt from this particular command-based rule. These exemptions perhaps seem reasonable: the first two likely have very high-cost or no LED alternatives, and it is safe to assume the last one isn't a very large source of carbon emissions.

Now let's consider one of the other exemptions—lightbulbs inside refrigerators. These bulbs are not a standard size (usually smaller than a regular lightbulb), and so they are exempt from the rule. For some refrigerators, there are no fluorescent or LED options on the market, and so banning these bulbs would have meant very expensive retrofits,

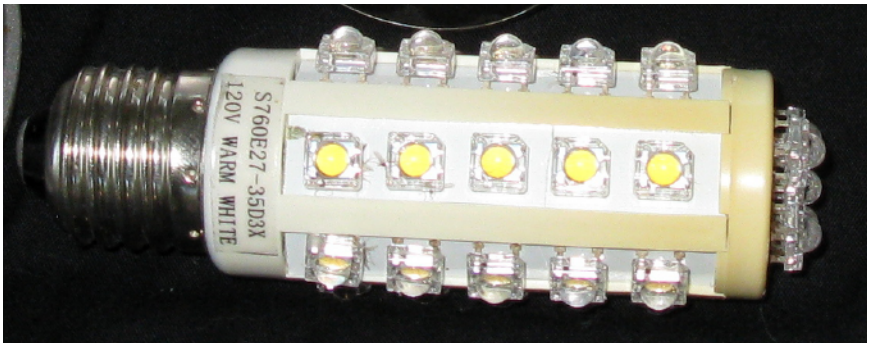

FIGURE 12.2.2 Appliance LED lightbulb. Image by Geoffrey Landis at English Wikipedia.

replacing entire refrigerators, or not being able to see which items are getting moldy. None of this is very appealing. However, what about refrigerators for which replacement LEDs are available (for example, the bulb in Figure 12.2.2)? Old-style incandescent refrigerator bulbs not only use a lot of electricity to make a little bit of light, they also add heat to the refrigerator. Many manufacturers of household refrigerators, and nearly all supermarkets (where the lights are on many hours a day), have already made the switch to LEDs for just this reason. Completely exempting replacement bulbs for old fridges, just to protect the few cases where no replacement is available, means missing out on many important, and very cost-effective, items on the master list.

We could perhaps write a more complicated command-based law to fix the refrigerator problem. It would need to have a precise list of exceptions to cover particular brands and models of refrigerator that have no available LED replacement, and the exception list should also get updated frequently as companies start to design different LED replacements and bring them to market. It is not just refrigerators, though. What about bulbs for other appliances, commercial lighting, and so on? You can see that it becomes almost impossible to write a command-based rule that correctly mandates cost-effective energy conservation for every size, shape, and application of lightbulb. Such complexity also dramatically increases the cost of enforcement.

Instead of trying to make the command-based regulation more complicated than it already is, economists would recommend a market-based

policy. Most simply, imagine a carbon tax that raises the price of electricity. Not only would every individual and company get a reward (a lower electric bill) for making a lightbulb swap, there would also be incentives for engineers to come up with LED replacements for all different sizes and shapes of bulb. For specific bulb replacements that are too expensive per unit of carbon saved, people would keep buying the incandescent version. No lengthy list of exceptions would be needed.

The carbon tax

In January 2019, the *Wall Street Journal* published a letter calling for a carbon tax to be imposed in the United States. The letter was signed by more than 3,000 economists, including nearly every former chair of the Council of Economic Advisors (both Democrats and Republicans), every former chair of the Federal Reserve, and almost every living Nobel Laureate in economics. In contrast to their deep disagreements on topics like minimum wages, budget deficits, and health care, there is an incredibly strong consensus among economists that we must tax carbon.

The *Wall Street Journal* letter lays out some of the key advantages of placing a tax on carbon, mostly along the lines of the arguments in Section 12.1 Incentives and the Source of Cost-Effectiveness. A carbon tax puts an incentive everywhere and on every action possible. Unlike command-based regulation, the incentive is also uniform across all actions: saving a ton of carbon by turning down an air conditioner is rewarded exactly the same as saving a ton of carbon through buying more efficient cars, lighting, or any other activity that emits greenhouse gases. It would take a near-infinite number of command-based regulations (plus an implausibly large enforcement effort to monitor people's everyday actions) in order to accomplish this without using a carbon tax.

At the same time a carbon tax incentivizes carbon savings, it also brings revenue in to the government. What the government should do with this money is a source of much debate. Some people advocate using the revenue to pay down the national debt, while others suggest it should be spent on education or health care, and still others think that the government should not spend the money at all, but should return it as a direct dividend check to each household. This last option

is recommended in the economists' letter and is perhaps the option most likely to be acceptable across different parts of the US political spectrum.

The British Columbia experience

It is something of a puzzle why most regulators remain reliant on command-based rules when economists agree that carbon taxes are simpler, are easier to enforce, and accomplish the environmental goal at much lower cost. Only a few jurisdictions around the world have implemented carbon taxation. The Canadian province of British Columbia is one prominent example and also represents the first significant carbon tax imposed anywhere in North America. British Columbia's carbon tax came into effect in 2008, giving us more than a decade of data that can be used to examine the impacts.

As with many environmental policies, British Columbia's carbon tax was phased in. The 2008 tax was set at $10 (Canadian dollars) per ton of carbon, with increases of $5 per ton per year until the tax reached $30 per ton in 2012. It has been held fixed since then, and the incentives are now felt in nearly every sector of the economy.* Even if a product or service does not produce any carbon emissions directly, there is almost always some fossil fuel being used somewhere along the way in production. Companies in British Columbia pass the carbon tax through each step of production, packaging, shipping, and so on until the final value shows up in the price tags seen by retail consumers.

The revenue from the carbon tax is returned to households, mostly in the form of tax cuts, rather than being used for increased government spending.** This has likely been an important factor in the public's growing acceptance of the tax. Low public opinion for the first several

*The most notable exemption in British Columbia is agriculture, which is allowed to use fossil fuel and to produce nonfossil greenhouse gas emissions such as methane without paying the tax. This type of exemption reduces cost-effectiveness: many farmers have actions they could take to reduce carbon emissions for less than $30 per ton, but they are not currently incentivized to do so.

**Many economists have studied the choice between (1) simple "dividend checks" and (2) reducing existing taxes (like sales taxes or income taxes) as a way to return carbon tax revenue to the people. Reducing existing taxes is more efficient, since most of the taxes we currently use to raise revenue cause unnecessary distortions in the economy.

TABLE 12.2.1 Translating British Columbia's $30 per ton carbon tax into fuel prices

Fuel Type	*Units for Tax*	*Tax Rate*	*Carbon Tax as a Percentage of Final Fuel Price*
Gasoline	$/gallon	$0.20	4.4%
Diesel	$/gallon	$0.23	5.1%
Propane	$/20-pound tank	$0.64	7.1%
Natural gas	$/MMBtu	$1.26	33.9%
Coal	$/ton	$48.60	54.7%

SOURCE: Adapted from Table 2 in Murray and Rivers (2015).

years of the tax, when people did not like seeing higher energy prices, gave way to popular support in more recent years as people realized their income and sales taxes were lower.

The goods that are most dramatically affected by a carbon tax are usually raw fossil fuels (for example, coal) and derivatives of fossil fuels (for example, gasoline). This makes sense: even though conserving a gallon of gasoline and buying a dog leash made in a solar-powered factory are both perfectly good ways to reduce your carbon footprint, and will both be incentivized by a carbon tax, saving the gallon of gasoline will be doing a lot more good for the climate. Table 12.2.1 shows how British Columbia's $30 carbon tax changed the price of fuels faced by consumers. A gallon of gasoline, for example, became 20 cents more expensive. Filling a typical 20-pound propane tank for a patio grill went up by 64 cents. These are relatively small percentage changes (4% and 7%, respectively) but enough to push people toward somewhat less wasteful habits.

Notice that the prices of natural gas and coal rose much more dramatically, by more than 30%. Much less of the cost of those fuels is related to refining and distribution, and so the raw carbon content ends up being a much larger component. These price changes are more likely to be felt by industry. Switching an industrial process from natural gas to solar, for example, became quite a lot more attractive after the carbon tax was implemented.

12.3 Cap and Trade

Many of the policies being undertaken around the world (Chapter 11) use another market-based approach—**cap and trade**. In this section, we focus on (1) why cap-and-trade policies are considered market based in terms of the tax-like incentives they create for climate action and (2) the main way they differ from a carbon tax.

Cap-and-trade policies tend to be fairly complex, first involving **allocation** of carbon permits of different vintages (that is, for use during different years). Companies that release greenhouse gases to the atmosphere (and sometimes also financial firms and energy traders) are then allowed to trade these permits with one another. The cap takes effect as companies must periodically "true up" by matching the number of permits they have in their possession with the number of tons of carbon equivalent they have released over a particular period (for example, during one calendar year). There are also rules that govern who can trade permits and when, as well as details to address companies that wish to borrow permits from the future or use permits from other countries or previous years.

The tax-like incentive provided by cap and trade

Return to the hypothetical list (sorted on cost-effectiveness) of all possible actions that lead toward a climate solution. A carbon tax encouraged people to undertake the cheapest, most cost-effective actions on the list because doing the action would be cheaper than paying the tax. In theory, cap and trade can create exactly the same incentive. Because the permits have value, companies should embed the value of carbon permits (that they could have sold if they had shut down their factories or power plants, for example) into their products' price tags. This works in exactly the same way as the tennis ball manufacturer in the previous section embedded its carbon tax payment into the price of its product.

One potential difference in the practical functioning of the two

market-based incentives is that the carbon tax is a direct cost. Companies must actually pay the carbon tax to the government, and so carbon-intensive companies are forced to pass on the tax in the price of the products they sell or take a loss on the sale. Other companies that make carbon-free products, and therefore don't have to pay the tax, can now offer lower prices than the competition.

Under cap and trade, the value of permits is often an **opportunity cost** instead of a direct cost: Suppose a company has been allocated most of its carbon permits for free, so if it wanted to, it could keep on selling the same polluting product for the same price and not go bankrupt.* Fortunately, economic logic says that such a company should still raise prices *even if it got its permits for free*. The reason is that by raising prices, it will sell less of its product and so be able to close down part of its factory. It will then have extra carbon permits it no longer needs and can sell those to someone else. The idea is that by raising the price for its product (and reducing quantity) and by selling surplus permits, it could make even more profit than it would have made if it kept on operating as usual. The concept of opportunity cost is central to the logic of how cap and trade works; it means that cap and trade can produce exactly the same price incentives as a tax, even if the permits are given to the company for free.**

Key difference relative to a carbon tax

One of the most important differences between a carbon tax and a cap-and-trade system is in how the size of the incentive gets set. With a carbon tax, the government gets to choose how big the incentive is. A $30 carbon tax raises the price of carbon-intensive products by a fixed amount ($30 per ton of carbon involved in the product's production), as shown in the British Columbia example in Table 12.2.1.

Suppose that the government decides the $30 tax is not creating enough action on climate (for example, because of advances in climate

*The free allocation of permits to polluting companies is often called grandfathering.

**Incentives for entry (that is, starting up a new firm) and exit (going out of business) may be different, however. Notice that profits will be higher with a grandfathered cap-and-trade system than they would be with a carbon tax, and so exit of polluting firms is less likely.

science, or when the extent of damages starts to be revealed). Adjustment to a tax policy is straightforward: government can raise the tax from $30 to $40. More emissions reductions will start to occur as carbon-free products become cheaper than carbon-intensive ones, and more of the long list of actions on the cost-effectiveness list will start to make sense, since the tax savings are now $40 rather than $30.

In contrast, under a cap-and-trade system the government chooses the number of carbon permits that will be allocated, and it typically commits to this choice for at least several years into the future. Figuring out how many permits to issue first involves trying to estimate how much carbon all the different companies covered under the program would release in the absence of any policy. Some of the carbon is then subtracted from this "business as usual" estimate, in the hopes that a nice-size incentive (neither too small nor too burdensomely large) will appear. The actual incentive that any particular cap-and-trade program produces in an economy is unknown. It depends on the price at which companies choose to trade permits, which in turn depends on factors like technological change and macroeconomic fluctuations. The final incentive to conserve that is produced by cap and trade can therefore be very large, if the permit price ends up being high, or very small if permits end up trading cheaply.

Key difference relative to a carbon tax: examples

Begin with the cap-and-trade system in the European Union, known as the Emissions Trading Scheme (ETS), as an example. The first wave of the ETS allocated permits over the period 2005–2007. Figure 12.3.1 displays the prices of these permits, beginning when they were first traded in 2005 and going through 2007 when the "true up" occurred and the permits were given back to the government in exchange for carbon emissions. What does this mean in terms of incentives and the hypothetical list of actions to mitigate climate change? Toward the end of 2005, permits traded for 22 euro, or about US $27, per ton. This would have worked just like a $27 carbon tax: a company that could take an action to save a ton of carbon for $15, for example, would do it, since it would then be able to sell a carbon permit worth $27 to someone else (making $12 profit in the process). Now consider early 2007: the

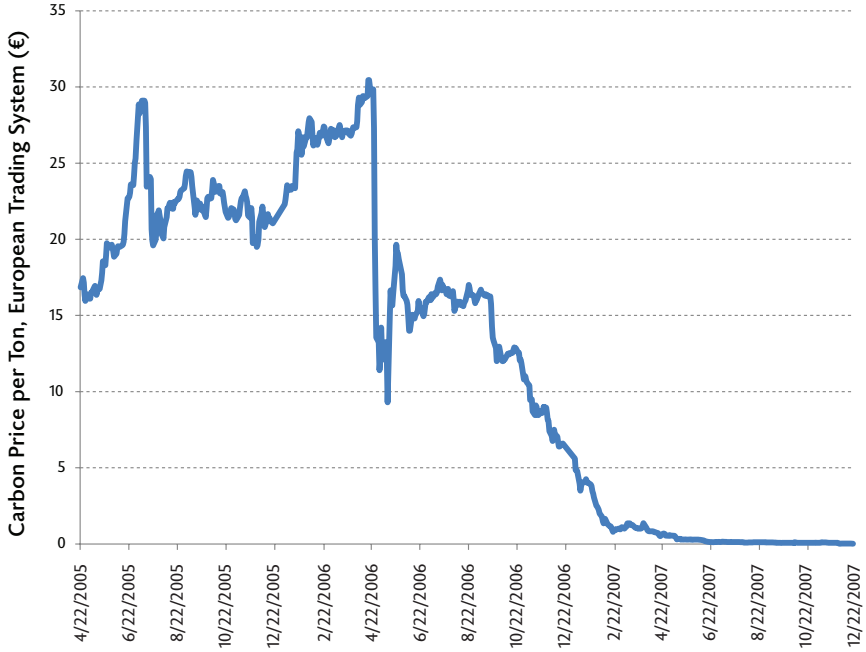

FIGURE 12.3.1 Market-based carbon incentives in the European Union. Price is in euro. Data from Point Carbon.

cap-and-trade price had fallen to about 1.5 euro, or $2. This worked just like a $2 carbon tax: the $15 action was no longer worth it and should be abandoned. In fact, all climate actions costing more than $2 per ton saved would no longer be profitable. By late 2007 the price had fallen to nearly zero, and so the incentive was gone altogether.

Did something change during those years that made climate action less important? Of course not—the climate change problem is global and long-term, and if anything, the urgency to take action was actually increasing rather than decreasing. What this example shows is that permit prices can go up or down for many reasons, even if the true importance of taking action on climate hasn't changed at all. In this case, the sharp reduction in the incentive most likely came from shifts in industrial composition and mistakes in the government's forecast of how much carbon would have been released had no cap-and-trade system been in place.

Subsequent phases of the ETS have issued fewer permits and so have generated larger price incentives on average, but the system continues to experience dramatic price swings. When the EU issued a new round

of carbon permits for 2008, it greatly reduced the number of permits issued, and the price initially spiked to around 30 euro per ton. This gave European businesses and consumers a very strong incentive for reducing carbon emissions, the same as a carbon tax of 30 euro ($44) per ton. By 2013, however, the price had unexpectedly dropped to about 5 euro per ton, likely as a result of some combination of the great recession, rules on how international cap-and-trade permit markets could link with Europe, and renewable energy policy.* Again, we don't think the value of taking action actually fell; the decrease in the incentive came instead from the inherent uncertainty of cap and trade.

European carbon incentives remained quite low for about 4 years, through 2017, and then swung sharply back up, with trades in late 2018 again exceeding 20 euro per ton. It turns out to be very hard to predict economic conditions, technology, and permit trading patterns very far into the future.

Now let's move to California's experience (discussed in more detail in Chapter 9). The system was set up in a fairly standard way, with one, very important, change: a **floor** or reserve price was placed on the price of permits. If something happened in permit trading, and price started to fall dramatically, protections would kick in to hold the permit price (and therefore the incentive to take action on carbon) at a floor level. California set the floor at $10 per ton in 2012, with predetermined annual increases thereafter.

Figure 12.3.2 shows the time path of prices for carbon in California's cap-and-trade market. What can we learn about incentives for Californians to conserve carbon? Early in trading, the carbon price was about $20, and so incentives in the economy were equivalent to a $20 tax. By the beginning of 2014, however, the carbon price had fallen and reached the floor. The protections kicked in, and the price was not allowed to fall below $11.34 (the assigned floor price for 2014). Since then, incentives have risen as the floor rises, periodically rising above the floor when changes in the local economy make demand for permits stronger. The price in 2018 was about $15 per ton (the floor in 2018), and so price incentives in California were about half as strong as they

*For a summary, see Koch et al. 2014.

FIGURE 12.3.2 Market-based carbon incentives in California. Data from California Carbon Dashboard and the California Air Resources Board.

were in British Columbia. This may be less than California lawmakers had hoped for when they set up the cap-and-trade system, but it is still greater than it would have been had the floor not been in place. The use of a rising price floor to combat the uncertainties associated with cap and trade has been a notable success of the program.

Uncertainty in emissions

While cap and trade produces uncertainty in the incentive to conserve (and historically this has sometimes resulted in very small incentives), it is often pointed out that a carbon tax will result in uncertainty in carbon emissions. During a year of weak electricity demand, for example, carbon emissions will go lower than expected, and during a year of strong electricity demand, they will be higher than expected.

Which would we rather have: variation from year to year in the incentive, or variation from year to year in carbon emissions? The economics of cost-effectiveness suggest that variation in incentives from year to year (and place to place, if different economies have separate cap-and-trade programs) can be very expensive. In years when incentives under cap and trade are very low, society will be missing out on lots of

very cheap opportunities to save carbon. In years when cap-and-trade permits are selling for high prices, the economy instead undertakes very expensive actions to conserve. Bouncing back and forth between almost no action and then very expensive action adds up to considerable economic losses because we are replacing missed low-cost opportunities to save (in the low-price years) with expensive opportunities to save (in the high-price years).

In contrast, the ups and downs in carbon emissions that appear with a tax-based incentive do relatively little damage. This is because, as discussed in Chapter 1, it is cumulative, global emissions that will have the greatest impact on climate damages into the future. Variation in emissions in any one year or country (either up or down, depending on which way local and global economic conditions are headed) matter relatively little in the context of the overall climate problem.

12.4 In Depth: Incentives in US Automobile Policy

Transportation, mostly in the form of private cars, is the single largest source of carbon emissions in the United States. This is a sharp reversal from past decades, when electric power emissions were much larger. Figure 12.4.1 shows the history of these two sectors in the United States since the early 1970s, which is the last time that transportation emissions were larger than those from electric power. In this section, we take an in-depth look at the automobile sector to understand the

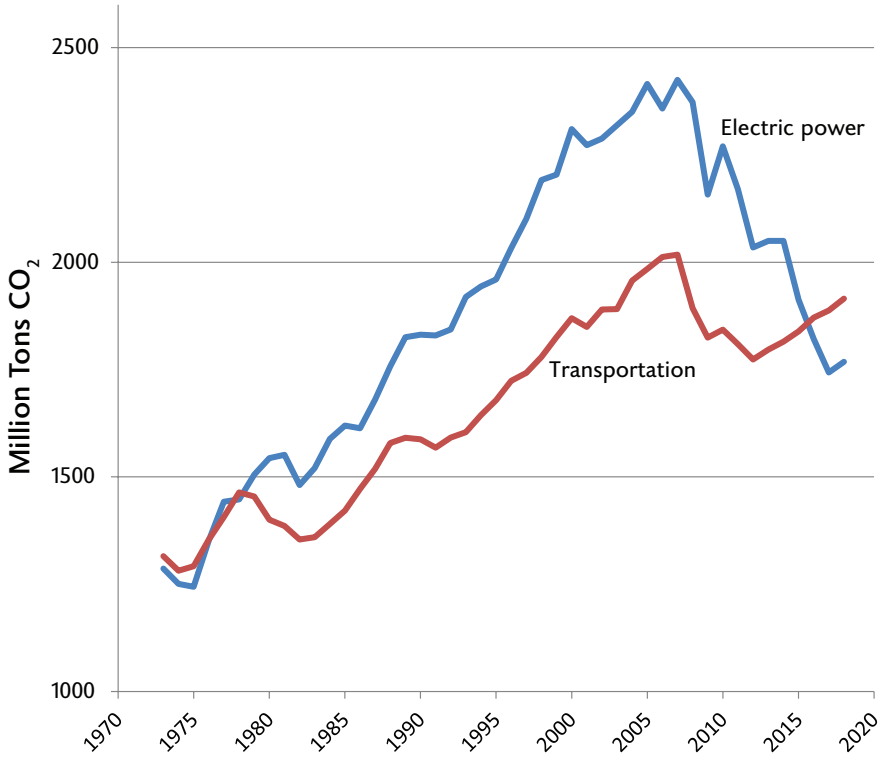

FIGURE 12.4.1 United States emissions of CO_2 from transportation and electric power. Data from the US Energy Information Administration.

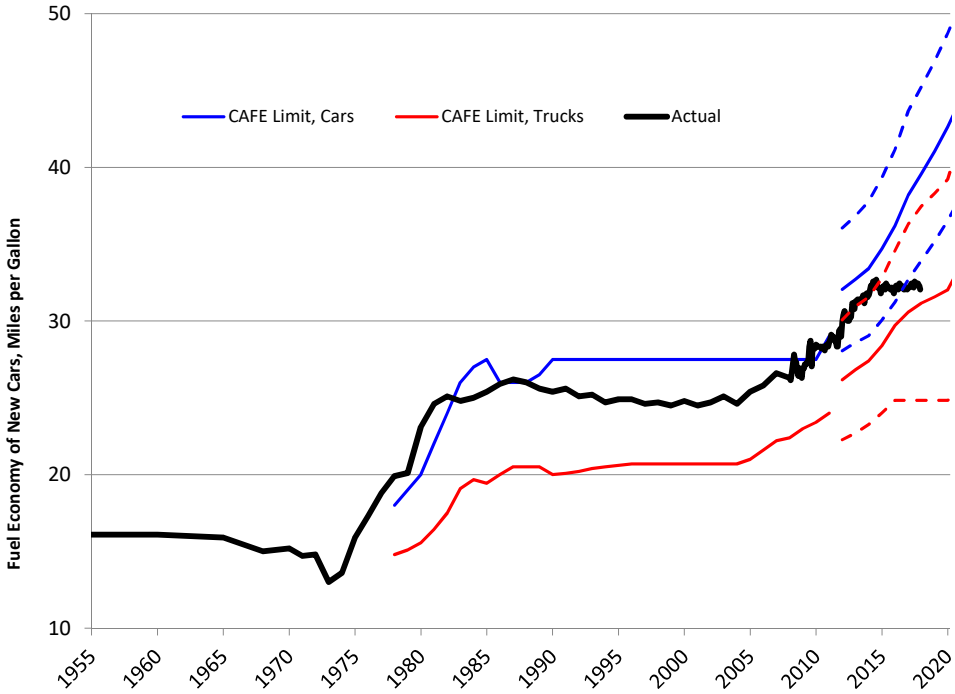

FIGURE 12.4.2 The history of fuel economy in the United States. Data from the National Highway Traffic Safety Administration. CAFE = Corporate Average Fuel Economy.

different incentives for reductions in carbon emissions when using a command-based approach versus a market-based approach.

Gasoline use is also an especially important example for considering the equity impacts of carbon taxation: lower-income households in the United States (and especially those located in rural areas) often need to drive many miles for work or school. They could feel disproportionate financial impacts from a carbon tax: Box 12.4.1 gives an example of one system that could counteract this effect.

History

Figure 12.4.2 shows the time path of fuel economy in the US since 1955, measured in miles per gallon (MPG). The first interesting feature to note is that fuel economy declined steadily for almost 20 years. Technology was improving, so why were cars getting fewer and fewer MPG? Rising incomes meant that households could afford more power and weight, and they went for it. The low point was reached in 1973.

Box 12.4.1 Income Distribution and Gasoline Use

It is often noted that overall gasoline use in the United States does not respond very rapidly to gasoline price, and so perhaps quite a large carbon tax would be needed to create much change. This is almost certainly true if we want to make a big change in only a few years, as everything from the location of people's homes to the number and size of highways and the immense parking structures at many shopping malls seems designed to keep people driving. Change under a carbon tax will move slowly. However, it is important to note that all of the things a carbon tax would eventually affect (housing sprawl, parking garages, and so on) are important—perhaps even necessary—in terms of the long-run change needed to solve the climate problem.

What are the implications of having small short-term responses in transportation infrastructure? Carbon taxes, when they are passed through into gasoline, may be mostly unavoidable in the short term before housing options and infrastructure design start to change. Lower-income households will feel these (unavoidable in the short term) taxes most acutely, since gasoline is a much larger share of their budget, especially for those people living in places with little public transportation service. This has been one of the greatest political challenges of implementing cost-effective climate policy for automobiles. The ideal economic solution would be to, at the same time a carbon tax is imposed, offer low-income households other benefits to make up for the increased tax burden. The carbon dividend (a form of basic income) proposed in the economists' *Wall Street Journal* letter discussed above is one potential way to mitigate the inequitable impacts a carbon tax could have.

Concerns surrounding the inequity of gasoline taxation (one aspect of carbon taxation) have been the subject of much research in economics. In the United States, low-income households drive a lot of miles and so are very exposed to a carbon tax via their gasoline consumption. For example, US households with $25,000 to $50,000 in annual income consume about 800 gallons of gasoline per year. Households with approximately double the income ($50,000 to $75,000 annually) consume about 1,100 gallons per year, much less than double the amount of gasoline. A carbon tax of $40 per ton works out to 35 cents per gallon of gasoline and so would cost the lower-income households 800 @ $0.35 = $280 per year. The higher-income households would pay $385—a higher amount, but a smaller fraction of their income.

(continued on next page)

(Box 12.4.1 continued from previous page)

One important economic finding is that if the total revenue from a gasoline tax were given back evenly (the same dividend check to everyone), lower-income households would, on average, be better off than they had been before the tax. In the example above, if we have the same number of households in each of the two income ranges, then the dividend check would be $332.50.* The lower-income households would pay $280 per year but get a $332.50 dividend check (a gain of $52.50), while the richer households would pay $385 in but get the same dividend of $332.50 back (they would lose $52.50 overall).

The key challenge for a dividend system like the one above is when there are differences between households that have the *same level of income*. Consider two households that both have $35,000 in annual income. One household uses public transport and consumes zero gallons of gasoline. The other drives a lot and uses 1,600 gallons per year. On average, this is exactly the 800 gallons above. But notice that a tax-and-dividend system would be very hard on the 1,600-gallon household (they would pay $560 in per year and get only $332.50 back) and very generous to the household with no cars (they would pay zero and still get $332.50 back). Avoiding this problem by targeting the dividends is difficult, if not impossible, and the subject of ongoing research. Notice that it is also important not to target the dividends *too* well, since part of the overall goal is to encourage a household like the one using 1,600 gallons yearly in the example above to find ways to reduce.

The most important advantage of a tax, relative to a command-based rule, in terms of managing equity concerns is that the tax produces revenue. The revenue can be used to help households that are the most affected by the policy. A command-based system—for example, banning traditional gasoline cars and requiring hybrid or electric drive—would also be very burdensome for low-income households. However, a command-based rule like this wouldn't raise any government revenue, and so dividends or other programs to help reduce the impact on disadvantaged groups would need to come from outside funds.

*To see why, imagine there are 10 households at each of the two income levels (20 households all together). Low-income households would pay 10 @ $280 = $2,800 into the system each year. High-income households would pay in 10 @ $385 = $3,850. This would be $2,800 + $3,850 = $6,650 in revenue per year. Then $6,650 / 20 = $332.50 in dividends available for each household.

Not coincidentally, cars in the muscle car era of the late 1960s and early 1970s were often equipped with powerful V-8 engines, some producing well over 300 horsepower.

Next came two incredible runs upward in the 1970s and early 1980s, when fuel economy almost doubled. The rate of increase in that era was far more rapid than any command-based policy we have seen, and it was achieved with only small advances in technology. Why, and how, was this accomplished? It turns out both answers are straightforward: gasoline got much more expensive, and so people bought smaller and lower-horsepower vehicles.

The era of corporate average fuel economy

Partly in response to high gasoline prices and security concerns in the Middle East, the first significant command-based policy on gasoline use was put into place in 1978—the Corporate Average Fuel Economy (CAFE) standard. It is named a "corporate average" standard since it applies separately for each company, and within companies it applies separately for sedans and light trucks. Note that the "light trucks" designation includes SUVs, minivans, and also many of today's crossover vehicles.

The level of the command-based standard was held quite flat for many years. For example, for every model year between 1990 and 2010, the standard for sedans was 27.5 miles per gallon. That is, all the different sedans that any one company made (calculated as a sales-weighted average) had to get at least 27.5 MPG. Since CAFE standards did not change over these two decades, manufacturers were able to use advances in technology exclusively for improvements in horsepower and weight, holding fuel economy flat. For light trucks (SUVs, minivans, etc.) the standard was weaker, although it did increase slightly from 20.7 MPG between 1996 and 2004 to 23 MPG by 2010.

From Figure 12.4.2 we can see that the true fuel economy of all vehicles on the road (the black line) actually declined somewhat through the 1990s, rather than remaining flat. If the CAFE rule was exactly flat, how is it that fuel economy slipped back downward? The answer lies in the composition of vehicle types. Many car buyers during this period were choosing to replace their sedans (which got an average of 27.5 MPG, following the rule) with SUVs (which got an average of 21 MPG,

also following the rule). The compositional shift allowed manufacturers to stay within the law but still add power and weight back into the vehicle fleet.

In 2012 we saw the most ambitious and far-reaching reform to CAFE since its 1978 inception, with the following three important changes:

1. The target nearly doubled, to 54.5 miles per gallon (averaged across all private vehicles, and including some extra credits for electric vehicles) by 2025.
2. The original two categories (cars and light trucks) were divided into many more categories based on the width and length, or **footprint**, of the vehicles. Vehicles with very large footprints were assigned a much weaker standard to meet than vehicles with small footprints.
3. Trading of the standard among manufacturers was allowed. If a company chooses to exceed the standard, it can sell the credit to another company that can then fall below it.

Incentives with CAFE

What about the incentives, and our list of cost-effective actions, for climate? The first thing to notice is that the decision to apply the rule separately to every company means the strength of the incentive is different for different companies. Ford, General Motors, and Chrysler (the "big three" American automobile companies) were initially constrained by the standard and met the 27.5 MPG requirement almost exactly over the decades. There is evidence that, even though the outcomes were the same at 27.5 MPG, achieving them was much harder for GM and Chrysler (they were more well known for large and powerful cars) than it was for Ford (which sold more small cars to start with and so didn't have as much to do to meet the rule).

To see an even sharper difference in incentives, consider Toyota, the largest foreign company selling cars in the US. Toyota's fleet over this period had an average fuel economy of 30 MPG, reaching almost 35 MPG in the early 2000s. The CAFE rule had no effect on Toyota at all, even though it would still have had an ability to improve the efficiency of its cars if it had been asked. More troubling, some of the fuel-saving

opportunities Toyota had left on the table would have been much cheaper per ton of carbon saved—that is, more cost-effective—than the changes that GM and Chrysler were forced to make. The CAFE rule did reduce carbon emissions (at least from some companies), but it didn't find the most cost-effective ways to do so.

One key improvement to cost-effectiveness, and a change that was made to the rule in 2012, is item (3) in the list above: the ability for car companies to trade compliance. If in 2019 Toyota finds a cheap way to boost fuel economy by 1 MPG, for example, the trading system gives the company a reason to do that even though it is still more than complying with the rule. Toyota can sell its over-compliance to another company, like GM or BMW, that might find it cheaper to buy that 1 MPG than to implement it. The same amount of carbon would be saved, and it would cost less.

Unlike item (3) in the list of changes, which improves cost-effectiveness, the change in item (2) reduces cost-effectiveness. To see why, observe that the footprint basis of the rule now allows compositional effects of the type we saw in the 1990s (switching from cars to SUVs) but throughout the whole fleet instead of just across two categories. Switches to wider and longer vehicles (for example, from compact sedans to midsize sedans) undermine the overall average, since that increase in square footage reduces the fuel economy target that a manufacturer has to meet. This unintended incentive within the regulation has meant that even though the nominal standard has risen quickly in recent years (the colored lines in Figure 12.4.2), the actual fuel economy of new vehicles has remained quite flat between 2014 and 2018. This problem is not unique to the US. Indeed, the same unintended incentives worked to reduce the effectiveness of the fuel economy standard in Japan.

Incentives with a carbon tax

Returning to our study of cost-effectiveness, let's revisit the list of all possible ways to conserve carbon. New technologies to improve fuel economy are definitely on the list, and those are incentivized by the command-based CAFE standards. How about some of the other items on the cost-effectiveness list? Examples include

- Combining trips to work and the store
- Reducing the number of cars in a household from three to two
- Choosing to live closer to work or school
- Walking or bicycling to work instead of driving

All of these (and many more) can be excellent, cost-effective ways to save gasoline. These options will make more sense for some people than others, because individual circumstances determine how much time or convenience is given up when taking these actions.

As an example, think about the reduction from three to two cars for a particular suburban household. Suppose this household observes that the cost of their third car plus the gasoline they put in it is $5,000 per year. The third car sometimes lets the children avoid having to wait as long to be picked up, and it can make getting to work for one of the parents more convenient. Suppose this time and convenience is worth $5,100 to the household. They will keep the car and will get to enjoy $100 of "consumer surplus"—the difference between what something actually costs and the value the person gets from it.* CAFE policy will make that third car a little bit more efficient, reducing the amount that has to be spent on gas. CAFE might also raise the price of the third car a little bit (by putting new technologies into it). Because these two effects tend to offset each other, CAFE does not usually change the decision of the household: people still buy almost as many cars as they always did.

On the other hand, a price incentive on carbon could make a big difference for this household. Even a small carbon tax (which would show up in the price of gasoline) might be enough to raise the overall cost to $5,200 dollars, for example, and so the car would no longer be worth it. This is a very cost-effective action for saving carbon—the household only loses $100 of surplus, while society gains an entire car's worth of carbon reductions.

The advantage of a carbon tax is that it incentivizes every one of the actions on the list above, and in fact every other action that we could write down, to save gasoline. The complete list of actions in the automobile sector is very long (we could probably fill this entire book with

*We can calculate the consumer surplus here as $5,100 (the value to the household) minus $5,000 (the cost).

it!), while the list of beneficial actions implemented as a result of the CAFE standard (mainly, better technology on new cars and reductions in horsepower and weight) is very short. Estimates in the literature vary, but my own research finds that a carbon tax could achieve the same amount of carbon savings as CAFE for one-fifth to one-third the cost. The carbon tax can do this because it utilizes much cheaper actions, much higher up on the cost-effectiveness list.

Double dividends and consumer choices

Separate from our goal of reducing carbon emissions, many advocates of command-based policies like CAFE argue that the policy will also help consumers avoid making mistakes in their car purchase decisions. This is the idea of a "double dividend"—getting two things out of one policy—in this case a cleaner environment and better decisions by consumers.

In this setting, the mistake would be that the typical car buyer isn't thinking very far ahead about gasoline purchases. The hypothetical buyer picks a big and very powerful model and then regrets that choice after learning how much it costs to have the tank filled. A policy like CAFE could mean that the carmaker doesn't even offer a vehicle with such a low MPG for sale anymore, or that it sets the purchase price high enough that most people can't afford it.

Either way, the hypothetical buyer is forced into a smaller, more modestly powered car that was actually a better choice to start with. That extra surplus from the improved decision-making means the environmental goals can be reached more cheaply. Much has been written about this effect in the economics literature, and no consensus has yet emerged. Some authors contend that statistical evidence shows that car buyers (particularly used-car buyers, who account for the majority of the car market) are very careful about fuel use. Small increases in the price of gasoline push used-car buyers very rapidly toward smaller and less powerful models, and so a policy like CAFE might not have the extra benefit of correcting consumer choice.

Other authors find instead that as much as 20% to 30% of future gasoline cost is ignored by new-car buyers. This opens up an opportunity for a policy like CAFE to improve decision-making and therefore improve somewhat on cost-effectiveness. There is so much ground to

make up (if the carbon tax starts at only one-third or one-fifth the cost of CAFE), however, that it could be difficult for this consumer-choice effect to reverse the overall ranking of policies. Questions surrounding the ability of consumers to make good decisions, and the ability of carbon policy to improve on those decisions, are quite important and an active area of research.

12.5 Conclusion

Incentives are the key to understanding cost-effectiveness. As a general rule, a policy that spreads incentives out over as many possible activities and product choices as possible will have the best chance at achieving cost-effectiveness. A carbon tax or other market-based policy can do this by passing the damage done by greenhouse gas emissions through to the prices paid for all products throughout the economy. In contrast, narrow, command-based policies tend to be more costly per ton of carbon saved, because they miss cheaper actions that should have been done first.

Other areas in which command-based rules fall short have to do with incentives for technological change and the costs of enforcement. On technological change, once a command-based rule has achieved the mandated change (switching to a particular technology for lightbulbs, for example), the incentive for further improvement disappears unless a new law is written. A price-based policy, in contrast, would keep rewarding development and use of ever more efficient LEDs even after the mandated technology had been adopted. Enforcement is likewise much simpler with a price-based policy. Most fossil fuels and processes that emit greenhouse gases are already tracked very closely by the government (an important exception is agriculture). Taxing emissions can therefore be done with very low government overhead, and it is much more transparent than command-based rules, because loopholes and politically motivated exceptions are more difficult to hide.

Finally, command-based policy tends to be expensive per unit of carbon reduced (or equivalently, it accomplishes less carbon reduction for a fixed price tag) because many of the actions people can take to conserve carbon are fundamentally private and individual. It would be very difficult, for example, for the government to write a command-based rule that controls which days I stop at the store when driving home from

work, and which days I make a separate trip. Incentive-based pushes, in the form of a carbon tax passed into gasoline price, can make us reconsider small decisions like this, occasionally combining or skipping trips. It is the combination of millions of these small decisions, throughout the economy, that can create real change at minimum cost.

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Figure 12.2.1: Mark Jurrens from Wikimedia Commons, licensed under the Creative Commons Attribution-ShareAlike 4.0 International license. https://commons.wikimedia.org/wiki/File:Lightbulbs.jpg.

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CHAPTER 13

Two Evolving Energy Technology Pathways

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Learning Objectives

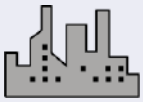
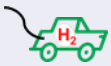
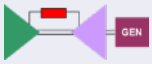
At the end of the chapter, the reader should be able to do the following:

1. Identify the roles of electric power generation and transportation in both climate change and the degradation of urban air quality.
2. Explain the role of combustion in both the generation of electricity and the powering of vehicles today, as well as the role of combustion in climate change and the degradation of urban air quality.
3. Identify the alternatives to combustion for the generation of electricity and the powering of vehicles.
4. Understand fuel cell technology and the application of fuel cells to the generation of electricity and the powering of vehicles.
5. Delineate the attributes and challenges associated with the generation of (1) renewable electric power and (2) renewable hydrogen.
6. Describe the two major pathways that are evolving in the electric grid, the evolution of vehicle engines and fuels, and the merging of the electric grid with transportation in response to mitigating climate change and the degradation of urban air quality.
7. Explain smart grid technology.

Nomenclature

°C	Degrees Celsius
AC	Alternating current
BEV	Battery electric vehicle
CCHP	Combined cooling, heat, and power
CH_4	Methane
CHP	Combined heat and power
DC	Direct current
DER	Distributed energy resources
DG	Distributed generation
FC	Fuel cell
FCEV	Fuel cell electric vehicle
G2V	Grid-to-vehicle
GHGs	Greenhouse gases
GT	Gas turbine
ISO	Independent system operator
MCFC	Molten carbonate fuel cell
MW	Megawatts
PAFC	Phosphoric acid fuel cell
PEMFC	Proton exchange membrane fuel cell
PEV	Plug-in electric vehicle
PFCEV	Plug-in fuel cell electric vehicle
PM	Particulate matter
SMR	Steam methane reformation
SOFC	Solid oxide fuel cell
V2G	Vehicle-to-grid
WDAT	Wholesale distribution access tariff

Symbols

	BEVs		Hydrogen batteries
	Central combustion plants		Hydrogen dispensers
	Electric batteries		Industries
	Electrolyzers		Nuclear plants
	FCEVs		PFCEVs
	Fuel cell/gas turbine hybrid (fuel cell/GT hybrid)		Residences
	Fuel cells (FCs)		Small gas turbines
	Gas turbines (GTs)		Solar photovoltaic panels
	Gasoline stations		University, hospital, office, commercial buildings
	Hydroelectric plants		Wind generators

Overview

Climate change and the degradation of urban air quality are forcing paradigm shifts in the two key sources emitting carbon dioxide (CO_2) and other pollutants into the atmosphere: electric power generation and transportation. Combustion of fossil fuels is the reason, serving as both (1) the conversion technology for both the generation of electricity and the powering of vehicles and (2) the principal source worldwide of CO_2 and "criteria" pollutants (that is, ozone, carbon monoxide, sulfur dioxide, nitrogen dioxide, lead, and particulate; see Box 13.1). While CO_2 is a concern for global climate change, criteria pollutants are primarily a concern because of their local impacts on human health. As emissions of carbon are reduced, attention to the concomitant reduction in the emission of criteria pollutants must be addressed as well.

To reduce the emission of CO_2 and criteria pollutants, the historical reliance on combustion needs to be displaced. This chapter outlines two pathways that are evolving to transform both the electricity and transportation sectors from a classic combustion-dominant construct (that has supported the economic growth and evolution of a myriad of societal conveniences over the last century) to a renewable-dominant construct (that is evolving in the new millennium in response to environmental impacts, geopolitics, and fossil fuel resource constraints). Among the notable characteristics of the two pathways is the merging of the transportation and electricity sectors (for example, plug-in electric vehicles charging with electricity) and the deployment of energy storage technologies to buffer and manage the idiosyncrasies (for example, temporal variation, intermittency, low capacity factor) associated with renewable wind and solar power generation. While the pathways are identical early in the transition, they differ in the future years. In particular, the first pathway projects that electric battery technology and pumped hydro will alone manage the solar and wind resources now and in the future. The second pathway projects that, in addition to battery energy technology and pumped hydro, the following two additional resources will be required in the future:

- Renewable hydrogen "battery" technology.
- 24/7, clean, load-following renewable power generation.

For both pathways, the goal is to establish a 100% renewable electricity sector and a 100% renewable transportation sector with the following characteristics: (1) zero emission of greenhouse gases (to mitigate climate change), (2) zero emission of criteria pollutants (to mitigate degraded urban air quality), and (3) energy sourced locally (to mitigate dependency on other countries for energy).

As a foundation to placing the two pathways into perspective and understanding the underlying technologies, the chapter reviews the historical role of combustion, the rapidly emerging deployment of wind and solar resources as an option to combustion, fuel cell technology for both the generation of electricity and the powering of vehicles, energy storage and clean 24-hours-a-day, 7-days-a-week (24/7) power generation to manage the idiosyncrasies of solar and wind, smart grid technology to manage the complexity of and interactions between the electricity and transportation sectors, and renewable hydrogen as both a transportation fuel and a resource for energy storage.

13.1 Introduction

Combustion is the principal technology that powers the energy economy. Simply stated, combustion is at the heart of our everyday lives, from the provision of electricity to our home and place of work, to the automobiles we drive, to the propulsion of jet aircraft we fly. Combustion is also the principal source of the environmental impact we experience, from climate change to degraded urban air quality.

The following four principal forces are driving the paradigm shifts from our dependency on combustion to alternative technologies for the generation of electricity and powering of vehicles:

1. Degraded urban air quality (1943): The first evidence of persistently degraded urban air quality in the United States was

FIGURE 13.1.1 Los Angeles 1943: Degraded urban air quality. Reproduced with permission from Getty Images.

Box 13.1 Atmospheric Pollutants

In this chapter, two groups of anthropogenic emissions (CO_2 and criteria pollutants) are considered. The formal designation of criteria pollutants (ozone, carbon monoxide, sulfur dioxide, nitrogen dioxide, lead, and particulate) was established in 1970 by the US Clean Air Act based on demonstrated health and environmental impacts established by a series of "criteria" studies. Some of the criteria pollutants ("primary" criteria pollutants) are emitted directly from the exhaust of combustion and other sources, while other criteria pollutants ("secondary" criteria pollutants) are formed in the atmosphere from reactions of primary criteria pollutants. The concentration of criteria pollutants emitted in the exhaust is very low (often less than 10 parts of pollutant per million parts [ppm] of exhaust), but when the emissions accumulate from the large population of sources in an urban basin, they result in a health impact.

In 2009, carbon dioxide was classified by the US Environmental Protection Agency (EPA) as a pollutant that poses a danger to human health and welfare. The typical concentration in the exhaust of a combustion source is approximately 120,000 ppm (that is, 12% of the volume). Unlike criteria pollutants, which affect public health within hours to days of exposure near the source of their emission, CO_2 has a more insidious impact, taking years to generate demonstrable and unambiguous climate change worldwide.

chronicled in the *Los Angeles Times*, describing a tenacious haze that seemed to irritate eyes and cause many to cough (Figure 13.1.1). Today, urban regions throughout the world (for example, in India, China) are affected by degraded air quality.

2. Finite petroleum resources (1980s): Automobile companies recognized that petroleum was finite and demand may outweigh discovery in the next millennium.
3. Climate change (1990s): The world recognized that anthropogenic sources may be affecting the climate, leading to the signing of the UN Framework Convention on Climate Change in 1992 (Chapter 10).

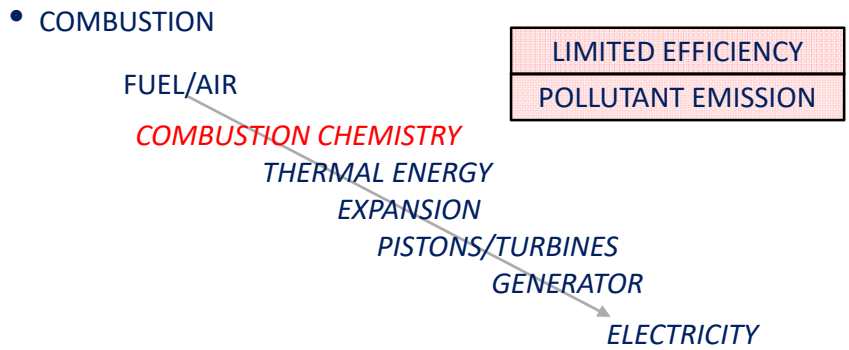


FIGURE 13.1.2 Combustion.

4. Fuel independence (2001): The assault on the World Trade Center enhanced the urgency to reduce US dependence on foreign sources of petroleum.

Combustion

Depending on the type of engine, either air is compressed to a high pressure and fuel is added, or a fuel-air mixture is compressed to a high pressure. In both cases, the fuel-air mixture is then ignited, initiating a **combustion** process (essentially "burning" the fuel-air mixture) that transforms the energy bound in the fuel (for example, gasoline) to high-temperature gas (thermal energy). The high-pressure, high-temperature gas then pushes on a piston (to power the transmission in a traditional gasoline vehicle, or generate electricity in a gasoline hybrid vehicle) or expands through a turbine (to generate electricity for the home and business). From this process, depicted in Figure 13.1.2, you can intuitively deduce that (1) the efficiency (the percentage of energy bound in the fuel that is transformed to useful power) will be limited by the friction associated with all of the mechanical steps, and (2) criteria pollutants will be formed because of combustion chemistry and emitted in the exhaust.

When you consider the role of combustion in everyday life, the examples seem limitless (for example, cooking; heating water; space heating; generating electricity; propelling aircraft and rockets; and powering automobiles, buses, trucks, locomotives, and ships). Simply stated, combustion is interwoven into the fabric of both the quality of life and the economics of the world's markets.

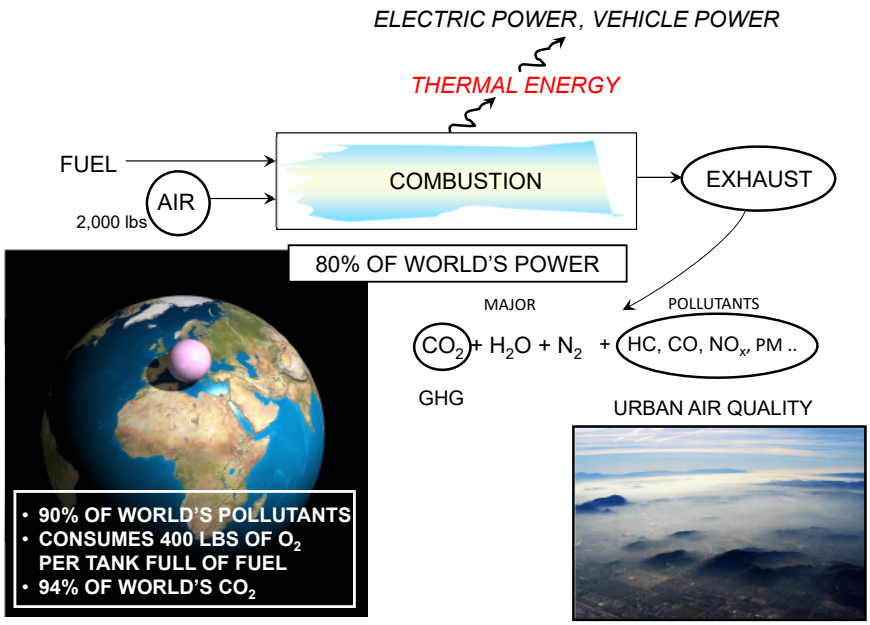


FIGURE 13.1.3 Combustion impacts. Image of earth reproduced with permission from Science Photo Library.

In Figure 13.1.3, the relationship between combustion and the environment is illustrated. Fuel and air are injected into a chamber, ignited to liberate the energy bound in the fuel into thermal energy, and expanded to produce a useful product.

Unfortunately, combustion has an exhaust as a by-product composed of criteria pollutants that degrade urban air quality (affecting the public health) and carbon dioxide (affecting the world's climate). Notably, the amount of criteria pollutant mass in the exhaust is minuscule and was historically ignored until the first consequences to public health in modern times surfaced in 1943 (Los Angeles) and 1952 (London).* It is as if Nature incorporated environmental impacts in the combustion of fossil fuels to counsel the world's population that combustion is not sustainable.

Why is it that such a minuscule emission of a few chemical criteria pollutant molecules affects the urban air basin, and a larger but still

*Ramifications of combustion exhaust were observed centuries before, an example of which is "fumifugium" (Evelyn 1661).

relatively modest emission of CO_2 affects the world's climate? Consider that the atmosphere is evenly distributed in a thin layer around the Earth, barely 10 miles in depth. In Figure 13.1.3, the purple sphere in the image represents the volume of all the air if it were gathered together, relative to the volume of the Earth. The image conveys the surprisingly small air resource upon which life on Earth depends, and the relatively small volume of air into which products of combustion are injected. Within this small volume, CO_2 and other greenhouse gases (GHGs) accrue to affect climate, and secondary criteria pollutants are formed and primary criteria pollutants amass to degrade urban air quality. As noted in Figure 13.1.3, combustion is responsible for over 90% of the world's emission of CO_2 and criteria pollutants.

In addition to contaminating the air resource with CO_2 and criteria pollutants, the combustion process has an impact not widely recognized: namely the consumption of oxygen from the air. For every tankful of gasoline in your car, a ton of air (2,000 pounds) passes through your engine, and 400 pounds of oxygen are consumed. Given the finite resource of oxygen in the atmosphere, this is sobering. While Nature appears to be replenishing the oxygen removed to date, an increasing demand for oxygen could lead to an additional point of environmental stress. Fortuitously, the evolving transition from a classic "combustion-dominant construct" to a "renewable-dominant construct" will, in parallel with reducing the emission of CO_2 and criteria pollutants, serve to mitigate the likelihood of this environmental stress.

The electric grid

A principal role of combustion is the generation of electricity. The electric grid is represented in Figure 13.1.4 in its classic form. Electric power is generated at large, central power plants in the general range of 100 to 1,000 megawatts (MW). While hydro and nuclear contribute to varying degrees, combustion fueled by fossil fuels (natural gas, oil, or coal) has historically been the dominant strategy for the generation of electricity.

The classic form of the electricity grid, however, is not the only way in which electricity can be provided to houses, businesses, and factories. Figure 13.1.5 illustrates the following four potential paradigm shifts from the classic to the future electric grid.

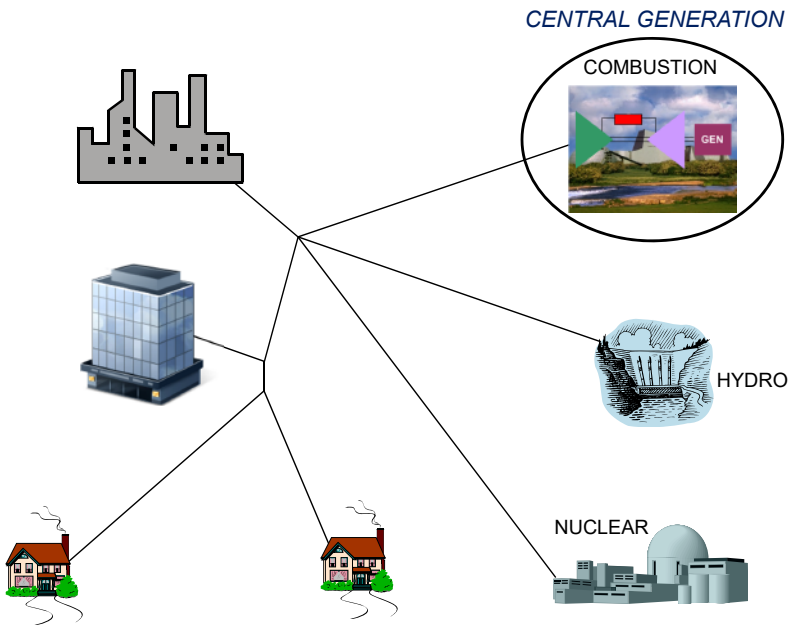


FIGURE 13.1.4 The classic electric grid.

1. Use **distributed generation** (DG), the generation of power at the point of use (Figure 13.1.5 ①). This could take the form of fossil fuel power plants such as gas turbines, solar panels, fuel cells, or ground source heat pumps that extract heat from under the ground. The advantages of this paradigm are threefold:
   - Avoiding transmission losses. By generating electricity at the point of use, the loss in energy due to conveying electricity from central power generators to the urban loads, estimated to be in general 7%, is avoided.
   - Increasing reliability. Generating electricity at the point of use increases the reliability of the electricity supply to the customer. Should the grid experience an outage, for example, DG can power critical circuits (at a minimum) and, if needed, power all circuits.
   - Capturing and using exhaust heat. With generation at the point of use, the heat in the exhaust can be captured and used to serve thermal loads (such as steam, hot water, and chilled water) and thereby displace electricity and natural gas that

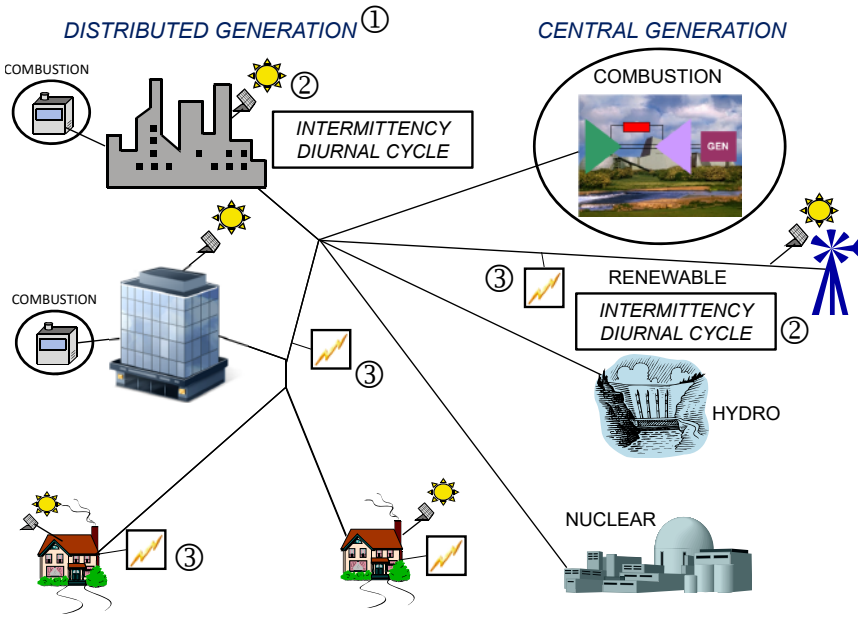


FIGURE 13.1.5 The emerging electric grid.

would otherwise be required for these purposes. This gives rise to high overall efficiencies that can exceed 90%. Terms used to describe this attribute are *combined heat and power* (*CHP*) and *combined cooling, heat, and power* (*CCHP*).

2. Provide direct current power. The clean power generators emerging for the DG market (for example, photovoltaic panels, fuel cells, and microturbine generators) produce direct current (DC) that is converted to alternating current (AC) with a concomitant loss of energy estimated to be 10%. Then, the AC power is converted back to DC (with another estimated loss of 10%) to serve DC loads in a building, examples of which are lighting, personal computers, and servers. By serving these loads directly with DC, DG can avoid the conversion inefficiencies.

3. Deploy renewable power generation. The third paradigm shift is the deployment of renewable solar and wind resources in central generation, as well as the deployment of solar in distributed generation (Figure 13.1.5 ②). The advantage of this paradigm is the displacement of the fossil fuel generation of power, by utilizing the

sun as the fuel resource, and the transition from combustion to a sustainable future that supports a clean, inexhaustible fuel supply (the sun) and protection of the environment. In California, for example, the penetration of renewable solar and wind resources has increased dramatically in the past decade (exceeding 30%) and is on course to meet a target of 60% in 2030 (Figure 13.1.6). California's renewable energy policies are discussed further in Chapter 9.

In contrast to traditional central generating plants that produce electricity continuously around the clock, renewable solar and wind resources vary **diurnally**—that is, the power produced varies throughout the day due to the presence and angle of the sun and the availability and strength of the wind. They also experience **intermittencies**, such as from a cloud momentarily shading a photovoltaic resource and dropping the generation, or a burst or drop in wind momentarily increasing or decreasing generation from a wind source. Diurnal variation refers to the daily cycle, while intermittencies are short-term and less predictable.

Renewable resources also have a low capacity factor, defined as the percentage output divided by the maximum (often called "name plate") output over a month, year, or other period of time. For example, traditional central plants have capacity factors of approximately 50%, whereas renewable resources have capacity factors of approximately 25% (solar) and 32% (wind). The capacity factors of 24/7 base load generators* are below 100% because of load following (that is, plant operators or controllers turning down the generation to match the load), whereas the capacity factors for renewable resources are low because of the diurnal variation.

Renewable resources cannot load follow, generating instead whenever the "fuel" (sun or wind) is available. As a result, renewable wind and solar are "must take" resources, and other technologies must be used to meet the load demand. If the load is less than the renewable generation capacity, either the excess energy must be stored (for example, in electric batteries,

*A base load generator is an electric power plant that provides a constant supply of electricity to meet the minimum load demand.

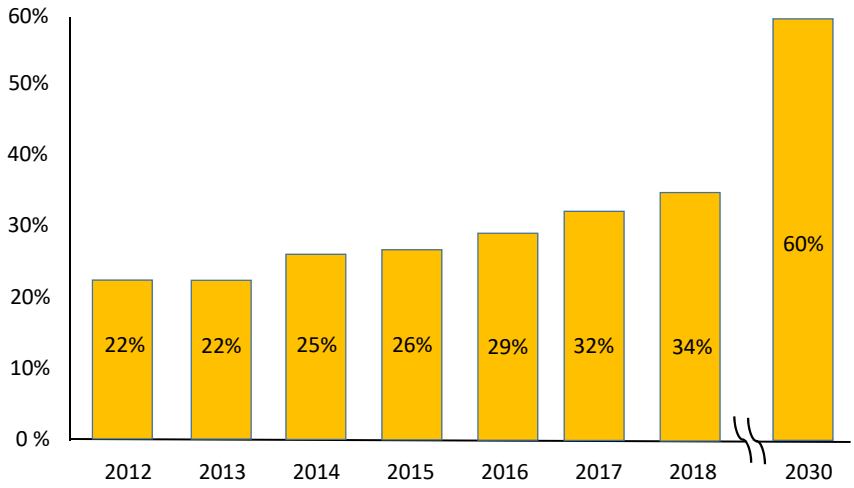


FIGURE 13.1.6 California annual renewable percentage estimates. Data from California Energy Commission 2018.

as pumped hydro, or in the generation of hydrogen), or the renewable generation resources must be **curtailed**. Curtailment is the action of reducing (in the extreme, turning off) the renewable wind or solar generation resource when load on the grid (that is, demand) is insufficient to utilize the electricity that would otherwise be produced.

4. Improve energy storage. A fourth paradigm shift is the deployment of battery storage at both the central and distributed generation levels (Figure 13.1.5 ③) to buffer and manage (1) the diurnal variation and intermittencies associated with wind and solar renewable resources, (2) uncontrolled vehicle charging loads,* and (3) the demand for rapid ramping of spinning reserves**

*Uncontrolled vehicle charging loads result from the charging of plug-in electric vehicles (PEVs) with no control over key variables (for example, the time of day the charging occurs, the duration of the charging, and the rapidity with which charging occurs). As the population of PEVs grows, control over these variables will be required to protect grid resources (for example, transformers) and assure that generation resources are available to meet the charging load.
***Spinning reserves* refers to rotating machinery (for example, gas turbines) that are spinning but generating little or no electricity and ready thereby to immediately (with a short delay) generate electricity if called upon. (This is similar to an aircraft with engines idling at the beginning of takeoff.)

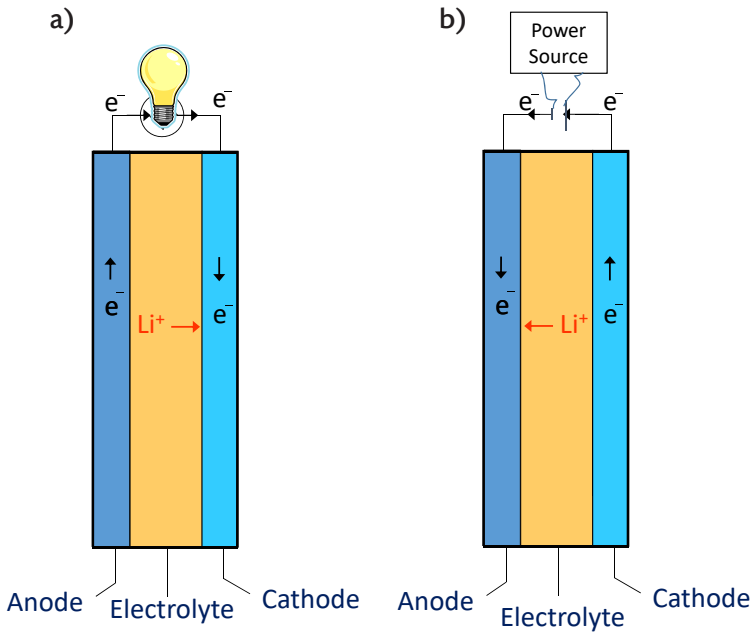


FIGURE 13.1.7 **Lithium-ion battery.**

with the goal to provide a resource that can absorb an increase in generation in the absence of load and also discharge energy when the load exceeds the generation capacity.

The most pervasive electric battery technology used today, from cell phones to multimegawatt applications, is the lithium-ion (Li-ion) battery (Figure 13.1.7). Just like your flashlight battery, the Li-ion battery stores energy (by charging on demand) and dispatches energy (by discharging on demand).

While the electrolyte allows lithium ions to flow in both directions, electrons are rejected by the electrolyte and must instead flow through an external circuit from one electrode to the other. When the battery is fully charged, all of the lithium ions are in the anode. When the battery is discharging (Figure 13.1.7a), the lithium ions travel through the electrolyte to the cathode while the electrons travel through the external circuit and energize a load (for example, a lightbulb). When the battery is charging, energy from a power source (for example, the grid) creates a flow of electrons from the positive cathode back to the negative anode.

Anodes in a Li-ion battery are typically composed of a carbon material that is able to absorb and store the electric charge. The cathode is an oxide of lithium such as lithium nickel manganese cobalt oxide, or lithium manganese oxide.

In the future, energy storage technologies may be required in addition to electric batteries to (1) absorb the enormous amount of otherwise curtailed energy, (2) provide the **ramp rates** (rate at which the generation resource responds to load change) required for both the absorption and reuse of the energy, (3) store the energy for months (for example, from one season to another), and (4) counter the self-discharge associated with electric batteries. While pumped hydro is expected to complement electric batteries, opinions differ as to whether additional, more flexible and higher-capacity energy storage technologies (for example, flow batteries and/or hydrogen "batteries") will be required.

13.2 Fuel Cell Technology

Electricity has historically been generated 24/7 by combustion-based power plants. With the deployment of diurnally varying and intermittent renewable solar and wind generation, the 24/7 plants are being operated more dynamically, namely ramping up and down in response to the varying renewable resources. Because combustion emits carbon dioxide and criteria pollutants as unavoidable by-products, an alternative to combustion that can operate (1) more efficiently than combustion (thereby reducing CO_2 per megawatt hour), (2) with a zero-carbon fuel (thereby emitting no CO_2), and (3) without the emission of criteria pollutants would be preferred.

An emerging alternative to combustion is **fuel cell technology** (Figure 13.2.1), which converts fuel and air to electricity in a single step. Intuitively, you can imagine a higher efficiency in the absence of mechanical friction. You can also imagine virtually zero formation and emission of criteria air pollutants, due to relatively low-temperature and relatively benign electrochemistry. In addition, fuel cells are quiet—a welcomed attribute for deployment as a distributed generator in the midst of where the public resides (homes) and works (industry, office buildings, and hospitals, for example).

The manner by which fuel cells operate is illustrated in Figure 13.2.2. Similar to the electric battery presented in Figure 13.1.7, the fuel cell is composed of an anode and cathode separated by an electrolyte. But rather than storing energy, a fuel cell generates electricity continuously as long as fuel (hydrogen) and oxygen (from the air) are provided.

Hydrogen enters and is dissociated at the anode into protons (H^+) and electrons (e^-). While the electrolyte is receptive to transporting the protons to the cathode, electrons are rejected and required to find an alternative path. Engineers take advantage of this by providing a path for the electrons to travel through a load, represented in Figure 13.2.2 by

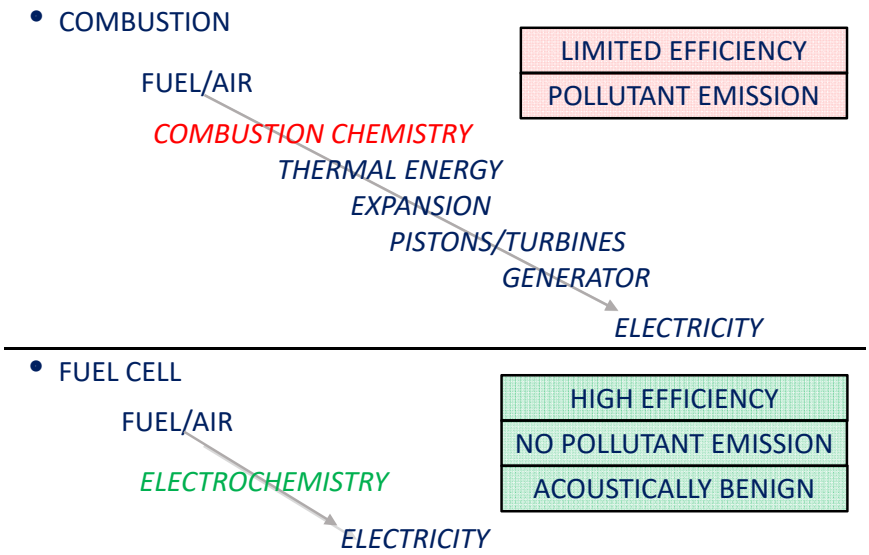


Figure 13.2.1 Power generation options.

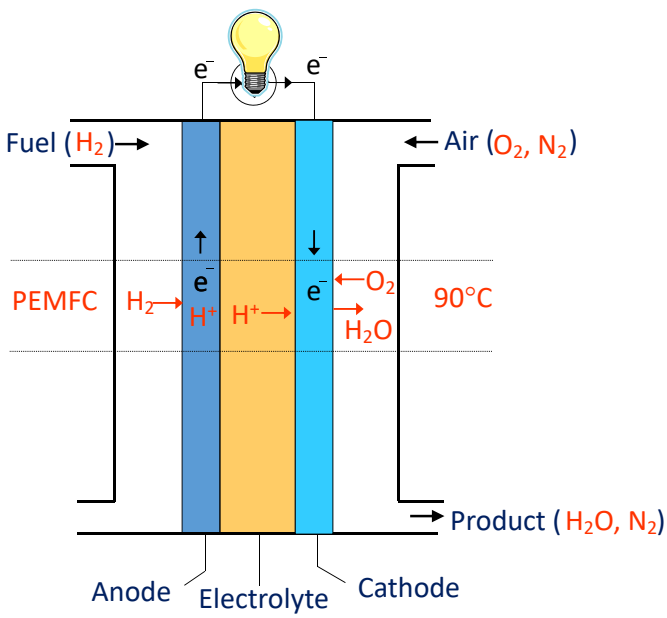


FIGURE 13.2.2 Proton exchange membrane fuel cell stack.

a lightbulb. The electrons transfer energy to, and thereby support, the load. While "spent," the electrons are sufficiently energetic to react with the oxygen entering the cathode channel and the protons exiting the electrolyte, and they close the electrochemical reaction by generating water. The water then mixes with the nitrogen from the air to comprise the fuel cell exhaust.

Types of fuel cells

The fuel cell stack depicted in Figure 13.2.2 is associated with a particular type of fuel cell, the proton exchange membrane fuel cell (PEMFC). In addition to the PEMFC, the three other major fuel cell types are shown in Figure 13.2.3—the phosphoric acid fuel cell (PAFC), the molten carbonate fuel cell (MCFC), and the solid oxide fuel cell (SOFC). The types vary by the chemistry utilized, the electrolyte used (which provides the name of each fuel cell type), the operating temperature, the time required to turn the fuel cell on and off, and the rate and extent to which the power output can be changed. All operate on hydrogen but can also run off fuels containing hydrogen (for example, natural gas, biogas, and propane) that are re-formed (usually at high temperature with the addition of steam) to release the hydrogen for fueling the stack.*

Because PEMFCs turn on and off like an automobile engine, operate at a relatively low temperature, and rapidly change power output in response to load, they are ideal for powering both ground-based vehicles (from forklifts, to automobiles, to heavy-duty trucks) and space vehicles (for example, space modules, space stations) and for providing backup power in the event of a grid outage (for example, for servers and telephone cell towers). Ballard is an example of a manufacturer of PEMFC systems with applications that include buses, trucks, and urban light-rail trams.

The other fuel cell types require several hours to turn on and off.

*Reformation (or re-formation) is a process to extract hydrogen from the hydrogen embedded in fossil and bio fuels. The most common fossil fuel reformed is natural gas, which is rich in methane (CH_4), using a steam methane reformation (SMR) process. When methane is exposed to heat and steam, the hydrogen can be separated and purified for industrial applications and the refining of gasoline, as two examples.

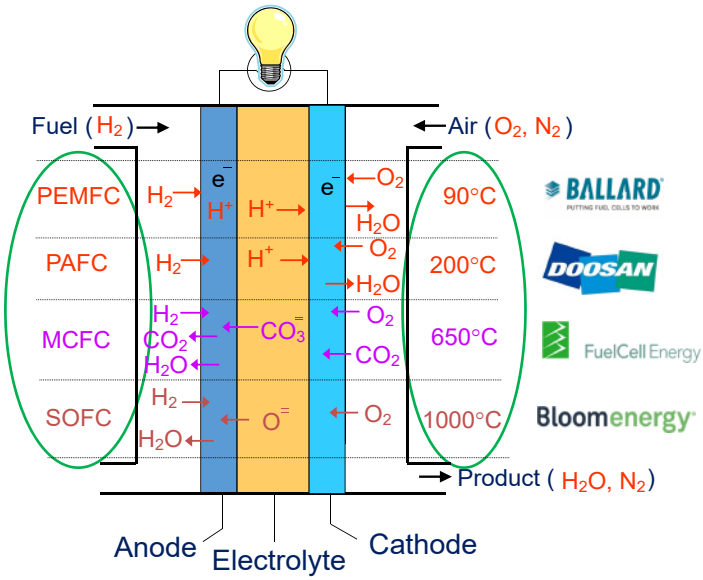


FIGURE 13.2.3 **Fuel cell types.**

As a result, they are dedicated to generating electricity for facilities that have a relatively constant 24/7 load. These loads, while relatively constant, can vary. For example, the load can be different during the day than at night, or during a weekday than on the weekend. The extent to which each fuel cell type can load follow varies. PAFCs are flexible in this regard, whereas MCFCs and SOFCs are less flexible.

PAFCs were the first fuel cell product to be commercialized (in 1992), and today Doosan (their sole manufacturer) offers systems from 400 kilowatts (kW) to 40 megawatts (MW) based on a 400 kW module. (A few kilowatts would be adequate for a home, whereas a megawatt would be appropriate for a hotel.) While the vast majority of the systems deployed worldwide operate on natural gas that is converted to hydrogen through a reformer external to (that is, separated from) the fuel cell stack, Doosan has deployed a 40 MW system that operates directly on hydrogen supplied by a waste stream at a petrochemical plant in South Korea. PAFCs operate at an elevated temperature (200°C), which allows combined heat and power (CHP) and combined cooling, heat, and power (CCHP) applications with efficiencies exceeding 90%.

The basic module of the MCFC commercial unit, 1.4 MW, is replicated to achieve the power ordered by the customer. For example,

ten 1.4 MW modules provide 14 MW of power. Typical systems are 2.8 MW, with the largest system, 59 MW, in service in South Korea. MCFCs were first commercialized in 1993 by FuelCell Energy, the sole manufacturer, as the first high-temperature system (650°C). The higher temperature provides both attractive options for CHP and CCHP and the ability to internally reform the fuel (for example, natural gas). The technology has also led to

- The operation of fuel cells on biogas (sourced from water resource recovery facilities), thereby generating carbon-neutral renewable electricity.
- The generation of carbon-neutral hydrogen as well as electricity and heat, referred to as tri-generation.

Bloom Energy has pioneered the introduction of high-temperature (1,000°C) SOFC technology beginning with commercialization in 2009. While the size of the basic module has varied, 250 kW is representative. The technology is purpose-built to be solely an electric generator (that is, not equipped for CHP/CCHP), using the heat instead to generate more electricity with overall fuel-to-electricity efficiencies exceeding 60% and exhaust temperatures as low as 65°C. Similar to MCFCs, SOFCs use internal reformation. A second SOFC manufacturer entering the market is Mitsubishi Hitachi Power Systems with a 250 kW and 1 MW fuel cell (FC) module integrated with a gas turbine (GT) to create a fuel cell/GT hybrid.

Deployment of fuel cells

As shown in Figure 13.2.4, fuel cells are deployed as distributed generators, with sizes ranging from hundreds of kilowatts to tens of megawatts, across a myriad of market segments on the customer side of the electric meter.* These include

- Industry① (Figure 13.2.4).

**Side of the meter* refers to the customer side or utility side of the electric utility meter. The customer side of the meter encompasses the circuits owned and managed by the customer. The utility side of the meter encompasses the circuits and electrical resources owned and managed by the utility.

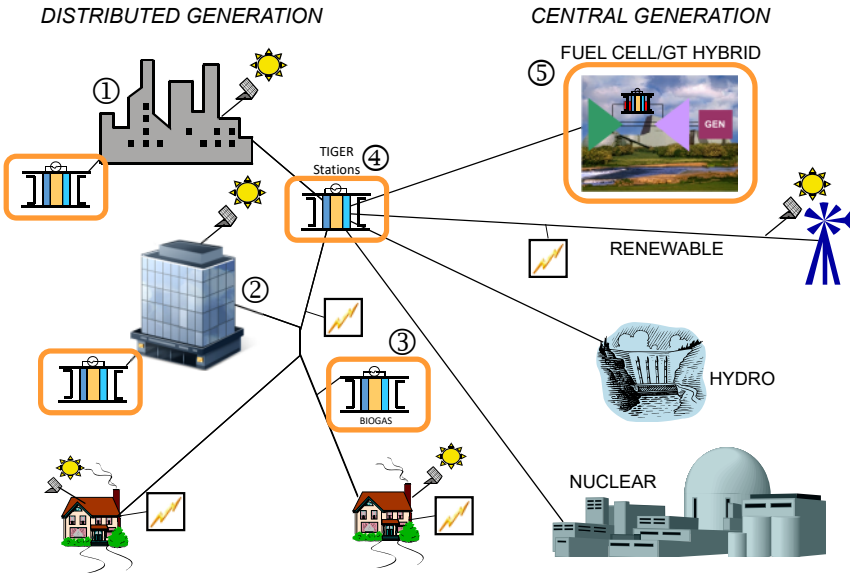


FIGURE 13.2.4 **Fuel cell deployment.**

- Office buildings, commercial developments, universities, and hospitals②.
- Water resource recovery facilities③.

Fuel cell technology has been installed throughout the world, with initial market concentrations in Korea, Japan, Europe, and California. In California, over 250 MW of product is installed throughout the state (Figure 13.2.5), with higher concentrations in the two major population centers of northern California and southern California.

On the utility side of the meter, large fuel cell systems are being deployed as **TIGER** (transmission integrated grid energy resource) stations to support local grid constraints (Figure 13.2.4 ④). Rather than serving a single customer, these TIGER stations are integrated into the electricity grid. Examples include 10 MW TIGER stations powering "cloud" server farms (for example, eBay, Apple, and Microsoft); a 15 MW TIGER station in Bridgeport, Connecticut; a 30 MW TIGER station in Delaware; and a 59 MW TIGER station in South Korea. Also depicted are fuel cell/GT hybrid systems being developed for 1,000-MW-scale central generation (Figure 13.2.4 ⑤).

Notable in Figure 13.2.4 is the absence of combustion sources of

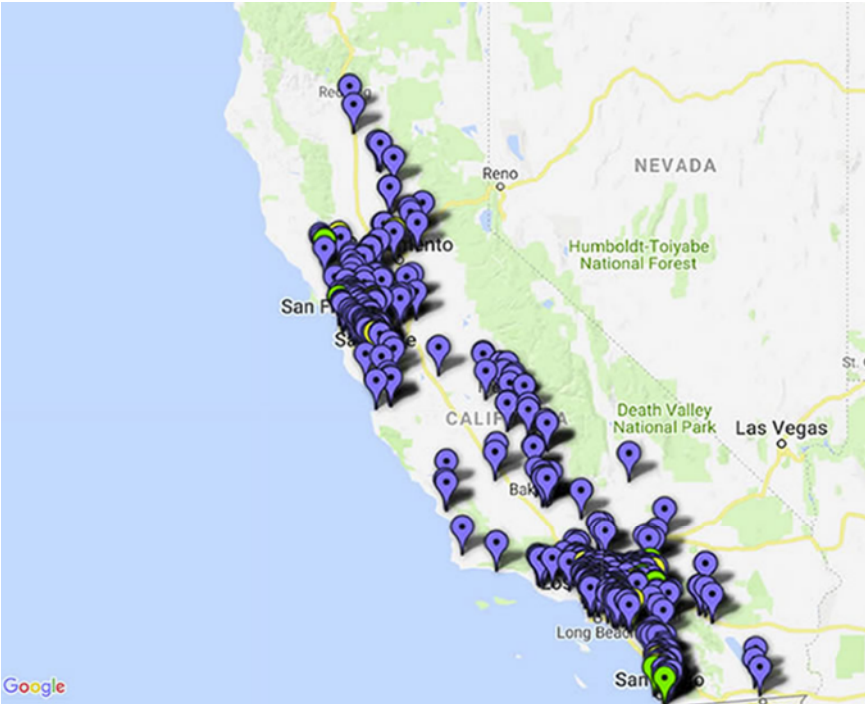


FIGURE 13.2.5 Plot of fuel cell sites in California in 2019. Reproduced from California Stationary Fuel Cell Collaborative.

electricity, representing the culmination of the paradigm shift from a combustion-dominant electric grid, with the associated limited efficiencies and emission of criteria pollutants, to an electrochemical-dominant electric grid, with high efficiencies and virtually zero emission of local air pollutants such as nitrogen oxides. While this is notable, it is important to recognize that this paradigm, while having zero emissions of local air pollutants, may not have zero emissions of carbon. If the fuel cells are operating on natural gas, biogas, or syngas, carbon dioxide generated in the reformation process will be liberated in the exhaust. If the fuel cells instead are operating on renewable hydrogen (from otherwise curtailed solar and wind, for example), Figure 13.2.4 represents a 100% renewable grid.

13.3 100% Renewable Grid

This section sets out two pathways toward a 100% renewable electricity grid, using the four new paradigms discussed in Section 13.1 and the fuel cell technologies discussed in Section 13.2. These pathways, illustrated in Figure 13.3.1, are being implemented today in many regions of the world, particularly Europe and California. The two pathways differ in the management of (1) load balancing, reliability, and dynamics associated with diurnal and seasonal variation, intermittency, and the limited capacity factors that accompany a high penetration of solar and wind power generation; and (2) the uncertainty in forecasting intermittent solar and wind resources. Both scenarios hold in common that energy storage is required, but they differ in (1) the amount and types of energy storage and (2) the need for a clean, firm, 24/7 power generator in addition to solar and wind power generation.

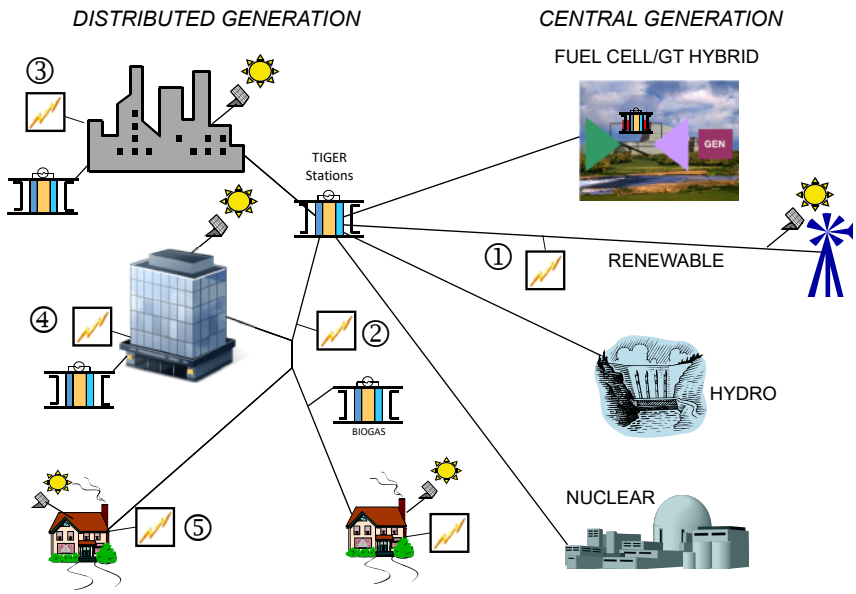
Pathway 1

Pathway 1, depicted in Figure 13.3.1a, assumes that electric battery technology and pumped hydro storage alone will be sufficient to manage the diurnally varying and intermittent solar and wind resources. To this end, Li-ion batteries are being deployed at the transmission① and distribution② levels of the utility grid, at industry③, at hotels/hospitals/universities④, and at homes⑤. The basic strategy is for the batteries and pumped hydro to absorb the excess electricity generated by solar and wind resources when loads on the grid are below the renewable generating capacity, and then to recover the energy as electricity from the electric batteries and hydro reservoirs when the utility loads exceed the renewable generating capacity (particularly at times solar and wind resources are not generating during their diurnal cycles).

Pathway 2

Pathway 2, depicted in Figure 13.3.1b, argues that electric battery and pumped hydro storage alone, while providing a cornerstone to storing

(a) Pathway 1



(b) Pathway 2

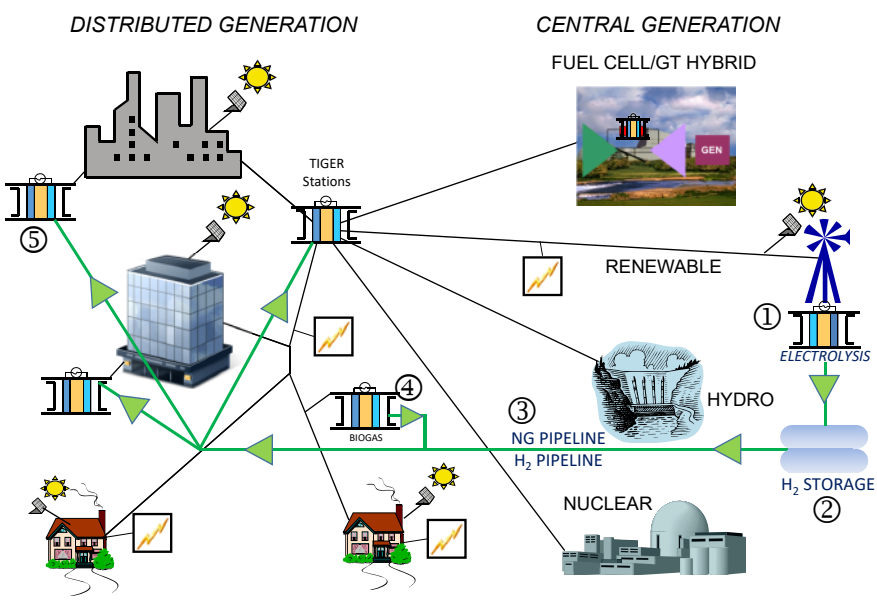


FIGURE 13.3.1 100% renewable grid.

energy available from otherwise curtailed wind and solar resources, are insufficient to provide a reliable electricity supply. To systematically and rigorously evaluate the requirements, energy systems analyses tools have been developed to explore the technologies required to enable and manage the solar and wind resources associated with a 100% renewable grid. Under the auspices of the California Energy Commission, for example, a systems analysis tool, the Holistic Grid Resource Integration and Deployment (HiGRID) code, was developed to guide planning for a modern electric grid. From evaluation of a myriad of scenarios to determine the resources needed to manage the intermittency, diurnal variation, and constrained capacity factor associated with solar and wind, two key resources emerged as being required: (1) a "hydrogen battery" resource and (2) a 24/7, clean, load-following renewable power-generating resource.

"Hydrogen battery" resource Due to the massive amounts of energy that are projected to be (1) available from otherwise curtailed solar and wind resources, (2) required to support the grid when loads exceed the available wind and solar, and (3) required to overcome the limitations of electric batteries (degradation, cost, self-discharging, and inability to accommodate seasonal shifts in energy demand), systems analyses such as HiGRID are consistently demonstrating that hydrogen in general, and renewable hydrogen in particular, is required as a major cornerstone in achieving a 100% renewable grid. To this end, a number of sources of renewable hydrogen are emerging. Here are some examples:

- Electrolytic renewable hydrogen: The generation of renewable hydrogen through electrolysis (Figure 13.3.1b ①) is expected to be the largest source that can absorb the levels of projected curtailed energy, store the energy by injection into the natural gas or dedicated hydrogen pipeline (Figure 13.3.1b ②), and convey the energy to the points of use (Figure 13.3.1b ③).
- Tri-generation: A smaller-scale source is the generation of carbon-neutral hydrogen from a stationary fuel cell operating on biogas produced, for example, at waste water recovery facilities that process human sewage and food waste, landfills that store biodegrading

human waste, and dairies that deal with large volumes of cow manure (Figure 13.3.1b ④). These facilities typically produce biogas rich in methane, which, if emitted, is significantly more climate change intensive than CO_2. Tri-generation captures and uses the biogas to produce carbon-neutral electricity and heat. By operating the fuel cell with more biogas than required for the electricity and heat alone, excess carbon-neutral biohydrogen is made available at the stack and can be extracted and injected into the natural gas or dedicated renewable hydrogen pipeline. At waste water recovery facilities and dairies, the heat can be used to support the digesters and thereby displace fossil fuel boilers, further reducing CO_2 emissions. Tri-generation is the epitome of sustainability, namely recovering and converting the energy from human and animal waste to renewable electricity, renewable heat, and renewable hydrogen.

24/7, clean, load-following renewable power-generating resource
Stationary fuel cell systems, of the designs discussed in Section 13.2, are emerging as a technology to generate the required clean, 24/7, load-following, renewable power with the added attribute of virtually zero emission of pollutants. Already meeting initial market demand for base load power generation, more than 30% of the fuel cells operating today in California are generating renewable power by operating on locally derived and directed biogas. To meet the challenge of the next-generation 100% renewable grid, stationary fuel cell systems are being deployed today with the requisite load-following attributes and also the ability to operate on hydrogen as well as natural gas and biogas. Simply stated, stationary fuel cell systems are

- A resource, along with energy storage, to enable and manage a 100% renewable grid.
- A match for the utilization of the renewable hydrogen generated from otherwise curtailed wind and solar resources (Figure 13.3.1b ⑤).

13.4 Merging of Transportation

The next generation of vehicles is emerging in response to environmental pressures and a goal of fuel independence. The environmental pressures, which include the mitigation of climate change and air quality degradation, require a dramatic reduction in the emission of GHGs and air pollutants from the transportation sector as well as the electric sector. Fuel independence requires removing reliance on the international sourcing of carbon-rich fossil fuels and the associated geopolitics. In response, vehicles of all sizes are transitioning from combustion engines and mechanical drivetrains to alternative vehicles with battery and fuel cell engines and electric drivetrains. The transition began with light-duty vehicles, expanded into medium-duty vehicles, and is now emerging with heavy-duty vehicles including buses. This transition involves a merging of the transportation system with the electricity generation system.

Alternative vehicles encompass **fuel cell electric vehicles** (**FCEVs**) and **plug-in electric vehicles** (**PEVs**). Examples of PEVs are **battery electric vehicles** (**BEVs**) and **plug-in fuel cell electric vehicles** (**PFCEVs**). All of these vehicles have a few key characteristics in common. First, alternative vehicles are designed to operate on fuels that portend (1) a potential of zero emission of both GHG and criteria pollutants and (2) an opportunity to be generated locally and thereby achieve the goal of fuel independence. Second, alternative vehicles have no tailpipe emissions of carbon or criteria pollutants. The GHG and criteria pollutant emissions, if any, come solely from the fuel supply chain, such as the generation of electricity or production of hydrogen. Electricity and hydrogen are the two fuels emerging to power alternative vehicles.

Electricity as a fuel

For PEVs, the electric grid becomes the source of the fuel. As shown in Figure 13.4.1, PEVs garner electricity from the home, from the place of work, and in the conduct of business at commercial centers such

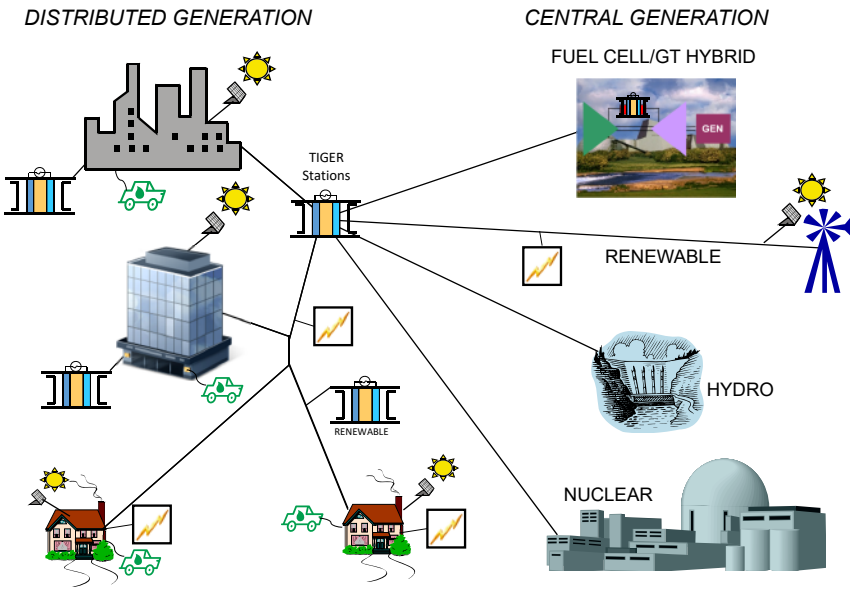


FIGURE 13.4.1 **Merging of transportation and the electric grid.**

as big-box stores, shopping centers, and hotels. Referred to as G2V (grid-to-vehicle), extracting energy from the grid adds a new load to the grid. Conversely, PEVs have the potential to provide beneficial attributes to the grid. With what is called V2G (vehicle-to-grid), energy can be extracted from qualified vehicles to serve loads when generating assets are strained.

The existing grid is able to accommodate modest charging events, but as the number of charging events increases (for example, at homes), local transformers may overload and fail. As a result, either upgrades to transformers or controlled charging (that is, smart charging), or both, will be required.

In Figure 13.4.1, while the emissions of pollutants from the tailpipes and electric grid are virtually zero and the emission of carbon from the vehicles is zero, the carbon emissions from the electric grid will not be zero with stationary fuel cells (as mentioned above) operating on fossil fuels (for example, natural gas) and biogas. What is required is a zero-carbon fuel.

Hydrogen as a zero-carbon fuel

For FCEVs, hydrogen is the fuel. For PFCEVs, hydrogen is the "long-range" fuel (300 to 400 miles) while electricity is the "short-range" fuel (50 to 150 miles). While the vehicles themselves emit zero carbon, the supply chain of electricity (as noted above) and hydrogen can be major sources of atmospheric carbon if not carefully planned. For example, hydrogen has been traditionally generated in large plants by the steam reformation of natural gas at elevated temperatures. The principal component of natural gas is methane (CH_4), with concentrations varying around the world from 70% to over 90%. Other components can be other hydrocarbons (for example, propane and ethane) and inert chemicals such as carbon dioxide and nitrogen.

Today, over 50 million metric tons of hydrogen from steam methane reformation (SMR; see Section 13.2) are produced annually worldwide, and 11 million metric tons are produced in the United States to support manufacturing (for example, of chemicals, foods, and electronics) and the refining of petroleum to generate gasoline. Notably, the amount of hydrogen needed to fuel 20 million FCEVs in California (today's population of all vehicles in California) is just 20% more than the hydrogen generated today for the production of gasoline in California. If all the vehicles were PFCEVs, less than 80% would be required. However, SMR hydrogen has an associated emission of CO_2. What is required is the generation of renewable hydrogen without the emission of carbon.

A representative zero-carbon cycle is shown in Figure 13.4.2 for the future generation, distribution, and utilization of renewable hydrogen for the transportation sector as well as the electricity sector. As described in Figure 13.3.1b, an initial step in the production of renewable hydrogen is the generation of carbon-neutral biohydrogen using tri-generation (Figure 13.4.2 ①) for fueling FCEVs and PFCEVs as well as stationary fuel cells. As noted previously, the vast majority of renewable hydrogen is expected to be sourced from the generation of electrolytic zero-carbon hydrogen from otherwise curtailed solar and wind. Not only can electrolytic zero-carbon hydrogen be stored over long periods of time and used in stationary fuel cells as diurnal or seasonal demand requires (Figure 13.3.1b), it can also be used to fuel FCEVs and PFCEVs (Figure 13.4.2 ②).

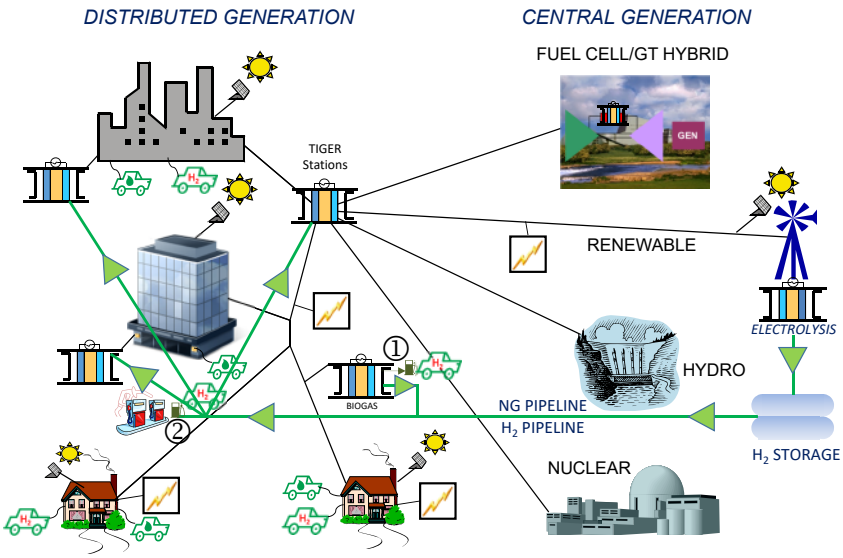


FIGURE 13.4.2 **100% renewable grid and transportation.**

To use the California example again, systems analyses show that the amount of renewable zero-carbon hydrogen generated by otherwise curtailed renewable resources will be more than ample to fuel FCEVs. While water is also required, fueling all the state's 20 million vehicles with electrolytic zero-carbon hydrogen would need less than 1% of the daily water flow in the California Aqueduct. If all vehicles were PFCEVs, less than 0.2% would be required.

For dispensing hydrogen to FCEVs, fueling stations are today being deployed at existing gasoline stations (Figure 13.4.2 ②). The locations are already zoned for fueling, and the public is familiar with the location as a fueling site. Hydrogen dispensing can be added to an existing island (displacing a gasoline dispenser) or on a newly established fueling island. Over time, gasoline dispensers could be replaced one by one as hydrogen-fueled vehicles displace gasoline-fueled vehicles.

California, again, provides an illustration of the scale of fueling infrastructure that will be required. Approximately 9,800 gasoline stations serve the California population, with multiple stations often sharing the same intersection. However, hydrogen dispensing will not be required at all of the existing gasoline stations. The reasons include the high

(a) Northern California

(b) Southern California

FIGURE 13.4.3 Hydrogen fueling stations in California in 2019. Green, in operation; yellow, in development; gray, not operational. Reproduced from California Fuel Cell Partnership.

efficiency of hydrogen vehicles, meaning they can drive farther before refueling than gasoline-powered cars can, and the replacement of competition from the fuel pricing at intersections (often leading to four gasoline stations at an intersection) to the smart phone. For example, it is estimated that a minimum of 1,600 hydrogen stations are needed to fuel a full build-out of FCEVs in 2050. While this number of stations gives drivers a maximum 6-minute access to a hydrogen dispenser, the actual number will likely be larger in order to not overcrowd any one station. If PFCEVs alone were deployed (that is, no FCEVs), the minimum number of stations required statewide would be 93. The larger the percentage of PFCEVs in 2050, the fewer the number of stations over and above 1,600.

In 2019, the number of hydrogen stations in California is approximately 50 (Figure 13.4.3). They are concentrated at population centers targeted for the introduction of FCEVs by the automobile manufacturers, along with key connector stations (for example, between northern and southern California) and destination stations popular with tourists (for example, Santa Barbara, Lake Tahoe, and Napa Valley).

13.5 Smart Grid Technology

With the introduction of distributed generation (DG), renewable generation, and PEVs, evidence of adverse impacts on grid operation is surfacing. These impacts include curtailed solar and wind, and increasing challenges in managing intermittent solar and wind—for example, by buffering intermittencies and by increasingly high afternoon ramp rates to augment the loss of solar late in the afternoon when loads increase. Arguably, to accommodate and manage DG, renewable generation, and PEV penetration, major changes in the operation of the grid must be developed and implemented. The deployment of DG and associated distributed energy resources (DER) such as energy storage requires visibility to, and control over, this new paradigm. Increasing the penetration of intermittent renewable resources requires an accurate forecasting of intermittent solar and wind resources, as well as a methodology to handle the uncertainty that these resources introduce into the modeling, planning, and operation of the system. Managing a high penetration of PEVs requires more visibility into the distribution system so that their impact on the load profile can be managed and they can be used as a grid resource for providing energy and ancillary services. Such "visibility" (that is, the amount and resolution of information that is accessible to system managers) includes real-time operating information on individual transformers.

Smart grid technology is emerging as a major strategy to handle these challenges. A smart grid is a grid with the intelligence to (1) maintain (and increase) the efficiency and reliability of the grid, (2) provide the grid operator with visibility and remote control of the system components through sensing throughout the transmission and distribution network, and (3) provide two-way communication and controls to enable a path for grid automation and electricity markets participation.

California provides an example of where the smart grid is emerging, with a focus on four major levels (Figure 13.5.1):

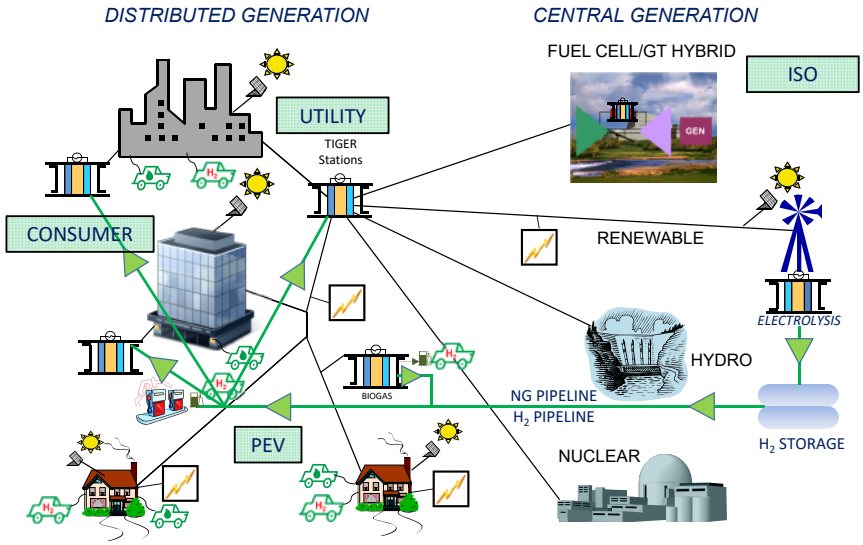


FIGURE 13.5.1 Smart grid.

- **Consumer level:** Facility energy management and control by residential owner, office building manager, industrial plant manager, or campus microgrid operator.
- **PEV level:** Automobile manufacturer and/or utility management schemes, control of PEV charging (smart charging), and potential V2G energy storage recovery.
- **Utility level:** Utility management and control of distribution system services and resources.
- **Independent system operator (ISO) level:** ISO management and control of the full portfolio of grid services and resources, including electricity markets, to ensure that loads are balanced and that supply is reliable and sufficient to meet the grid dynamics, namely load changes and rate of the load changes.

Smart grid technology in the country has developed and improved significantly during the past decade through investment in research and demonstration projects such as the California Public Utilities Commission's smart grid investment plan and the US Department of Energy's Irvine Smart Grid Demonstration program. These efforts resulted in advances and deployment of smart metering, smart appliances, automated

substations and other distribution system upgrades, advanced sensing and controls, high-speed communications, smart inverters, and smart switches. The broad deployment of smart grid technology faces challenges, including these examples:

- **Interoperability:** A smart grid requires the various components of the system to communicate with one another or at least a central controller/operator. To achieve this, communication protocols, standards, and a robust communication infrastructure must be developed upon which vendors, utilities, and regulatory agencies can agree and comply.
- **Reliability and cost:** The reliability of the system must be ensured without having excessive redundancy, in order to minimize the overall cost of the system.
- **Data management:** The collection of high-resolution data is required to obtain an accurate picture of the system status and also verify the system load flow and transient models.
- **Cybersecurity:** As the system moves toward automation and remote control, the system must be secured through cybersecurity measures and encrypted communications.
- **Too much change, too quickly:** The smart grid paradigm will dramatically change the roles of utilities, independent system operators, aggregators, and service providers in a relatively short amount of time. Therefore, it is prudent to develop road maps and guidelines for the industry to follow and prepare for their revised roles. For example, with more distributed energy resources, the role of the utility changes from delivering energy to providing ancillary services and backup and/or serving as an aggregator of distributed energy resources.
- **Development of a wholesale electricity market:** First, the generating resource needs to establish an agreement with the utility to access the transmission system. Today this is done through wholesale distribution access tariffs (WDATs.) Second, the grid operators need to allow the distributed energy resources (DER) to participate in the market. This will present challenges since the DER can be very flexible (compared with conventional generation and even renewable

resources) and are located deep in the distribution system where the ISOs do not have visibility.

To achieve the compelling potential attributes of smart grids and microgrids (for example, high efficiency, lower GHG and criteria pollutant emissions, lower operating costs, the accommodation of grid ancillary and emergency services, and the ability to enable and expand the evolving electricity), research is required to advance smart communications, controls, energy storage, high-resolution and robust sensors, power electronics, load-following and high-ramping 24/7 clean power generation, smart PEV charging/discharging, and energy management systems. In parallel, research is required to establish and implement policies that support the development and deployment of the empowered concomitant electricity markets.

13.6 Microgrid Technology

A microgrid is a collection of generation resources, loads, and other DER that presents itself to the grid as a single controllable entity in order to (1) provide ancillary services to the grid in support of grid operations and (2) separate from the grid in the event of a grid outage and operate in an islanded mode. As shown in Figure 13.6.1, the normal operation of the microgrid is "grid-connected." In this mode, the grid provides power when microgrid generation resources are unable to alone support the load. In this mode, the microgrid is also able to provide resources to the grid, these are called **ancillary services**. These ancillary services include local load and generation management wherein the microgrid can shed or add loads and can reduce or increase generation in response to signals from the utility or ISO when the grid itself is experiencing a local deficit in generation resources (for example, no wind to drive wind generators, or no sun to drive solar generators) or a local excess in

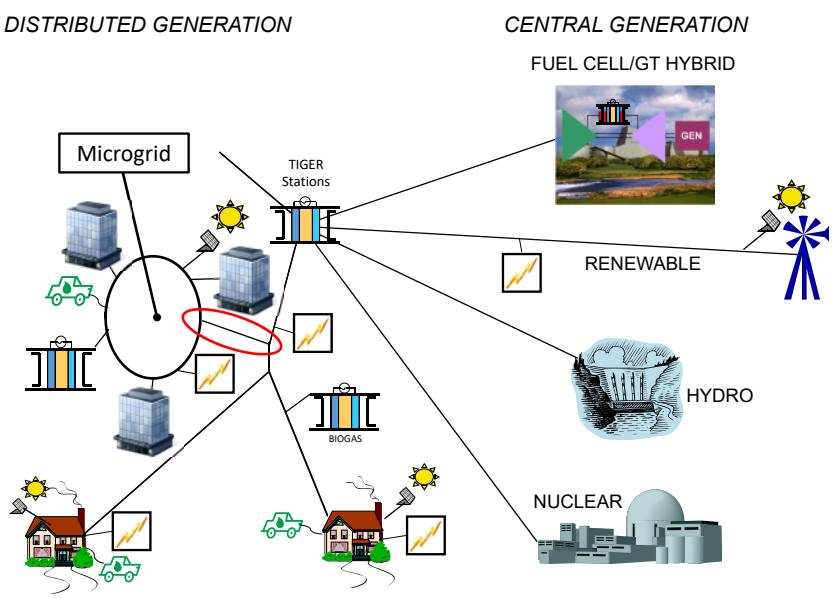


FIGURE 13.6.1 Microgrid technology.

generation (for example, generation from renewable resources that exceeds existing loads). Overall, microgrids reduce the impacts associated with intermittent and flexible resources on the grid.

Microgrids also increase the reliability and resiliency of the community served by the microgrid and the community adjacent to, but outside, the microgrid. In the case of a grid outage, the microgrid can seamlessly disconnect and remain in operation and maintain the microgrid community with electricity. While some loads may have to be shed to match the load to the microgrid generation resources, loads critical to the operation and safety of the microgrid community can be retained intact. An islanded microgrid can provide services such as shelter and food to the adjacent community. In principle, an islanded microgrid can provide electricity to grocery stores, fire stations, gasoline stations, and hospitals in the adjacent community and can assist the utility in restarting the grid.

The potential of microgrids is driving the evolution of microgrid controllers to communicate with loads, generation resources, and other DER (for example, energy storage systems) and thereby (1) optimize the grid-connected microgrid performance, (2) provide ancillary services, (3) support engagement in the electricity markets, (4) manage seamless islanding and reconnection, and (5) provide emergency services to communities adjacent to the microgrid.* In addition, the microgrid controller must communicate in the future with the utility, ISO, and other microgrids to provide (or buy) the services outlined.

A nanogrid (Figure 13.6.2) is a controllable grid within a microgrid, typically a smart building (equipped with a building management system, for example) that is capable of providing ancillary services to the microgrid and separating from the microgrid (retaining building critical loads in service) in case of a microgrid outage, and of managing DER, lighting, and plug-in loads within the nanogrid.

**Emergency services* refers to services provided during a natural disaster or other unforeseen occurrences. These services include energizing critical loads such as hospitals, shelters, and other critical facilities, as well as providing mobility to the community through providing electricity to PEVs and hydrogen to fuel cell vehicles.

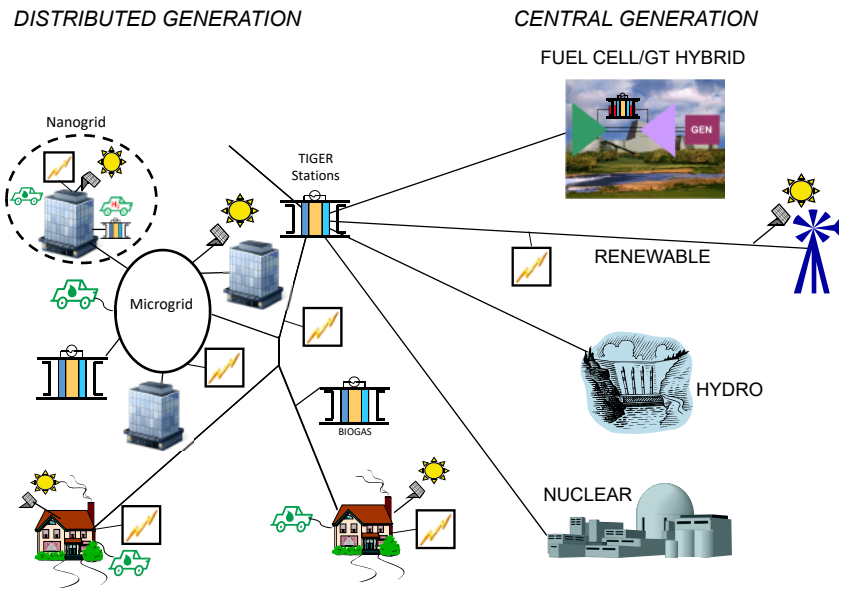


FIGURE 13.6.2 Nanogrid technology.

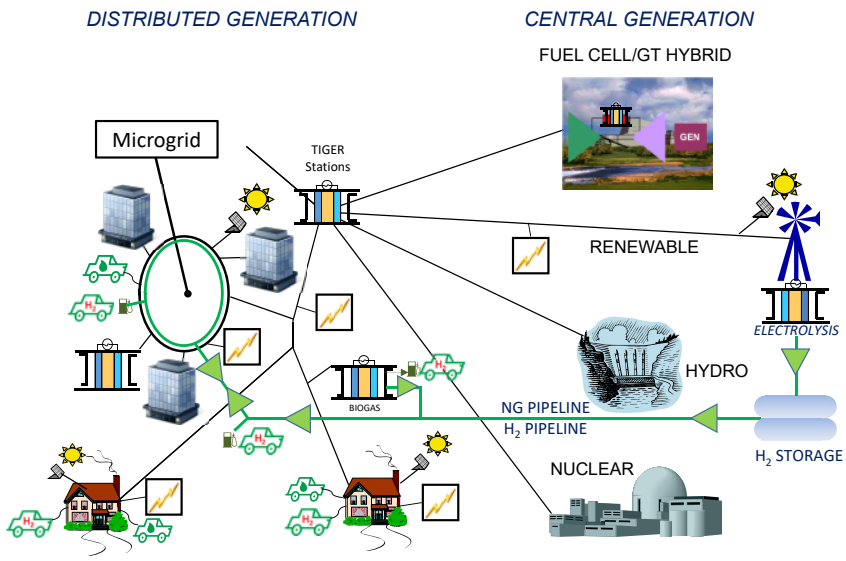


FIGURE 13.6.3 Hydrogen microgrid.

As the population of microgrids increases and the technology evolves, other possibilities emerge, including the following:

- Microgrids could become part of the hydrogen economy, not only utilizing hydrogen for generation and fueling FCEVs, but also generating hydrogen for use within the microgrid and potential export from the microgrid (Figure 13.6.3).
- Microgrids could operate at a frequency different from the grid, connecting to the grid through a power electronics connection, thereby eliminating the need to synchronize with the grid.

Nanogrids also have the potential to transform the manner by which electricity is distributed in a building. In addition to alternating current (AC), electricity can be distributed as direct current (DC), serving directly DC loads (such as computers, servers, and LED lighting). Since evolving distributed generators produce DC (for example, fuel cells, photovoltaic panels), the inversion of DC to AC and the rectification of AC to DC and the consequent losses of up to 20% can be avoided, as discussed in Section 13.1.

13.7 Summary

To address both climate change and the degradation in urban air quality, paradigm shifts in the electric and transportation sectors began at the turn of the century. However, they will need to evolve over decades before settling into the new paradigm. The principal attributes of the new paradigm are (1) the generation of electricity from diurnally varying and intermittent renewable wind and solar; (2) energy storage, to capture and later use energy from otherwise curtailed renewable resources; (3) the integration and electrification of transportation as a challenging load (on the one hand) and a potential source for the grid to tap for stored energy (on the other hand); and (4) smart grid control and management.

Two pathways are emerging, differing only in (1) the need for fuel cell electric vehicles, (2) the amount of energy storage required, and (3) the need for 24/7, clean, load-following renewable power generation in order to manage the diurnally varying and intermittent renewables.

Electric vehicles

Pathway 1 The opinion of many is that BEVs are sufficient and, with advances in battery technology, the energy density will dramatically increase, the charging time will dramatically decrease, and the weight will dramatically decrease to provide the range, fueling time, and size provided historically by petroleum-fueled internal combustion vehicles.

Pathway 2 Others believe that, while BEVs have a role, FCEVs and PFCEVs are needed to provide the range and refueling time to which the public is accustomed with conventional gasoline and diesel internal combustion vehicles. FC technology is also suitable for medium-duty vehicles (such as delivery trucks) and for heavy-duty vehicles (that is, buses and large trucks) where BEV technology is limited or insufficient.

FC technology is applicable as well for off-road construction vehicles, locomotives, and ships.

Energy storage

Pathway 1 The opinion of many is that electric storage batteries and pumped hydro are sufficient and, with advances in electric battery technology, the energy density will evolve to absorb the high levels of curtailed energy projected as the grid builds out.

Pathway 2 Others believe that a renewable hydrogen "battery" is required to

- Provide the massive storage capability to complement electric batteries in absorbing the high levels of curtailed energy projected as the grid builds out.
- Buffer the self-discharging character of electric batteries.
- Provide the capability of diurnal and seasonal shifts in energy stored and energy required.
- Provide zero-carbon renewable hydrogen transportation fuel for powering fuel cell vehicles on the transportation sector.

24/7, clean, load-following power generation

Pathway 1 The opinion of many is that technological advances in electric batteries will provide, along with V2G, the energy storage and ramping to manage and buffer the variability of solar and wind and thereby render 24/7, clean, load-following power generation unnecessary.

Pathway 2 Others believe power generation will be required that is clean (that is, emitting neither GHGs nor criteria pollutants), 24/7 (that is, around the clock, every day of the week), and load following (that is, able to ramp up and down to meet both load demand and diurnal variation and intermittency of wind and solar) to complement and buffer the variability of solar and wind and achieve the goal of a reliable and resilient 100% renewable grid and a 100% renewable transportation system.

The goal of this chapter is to present the key considerations

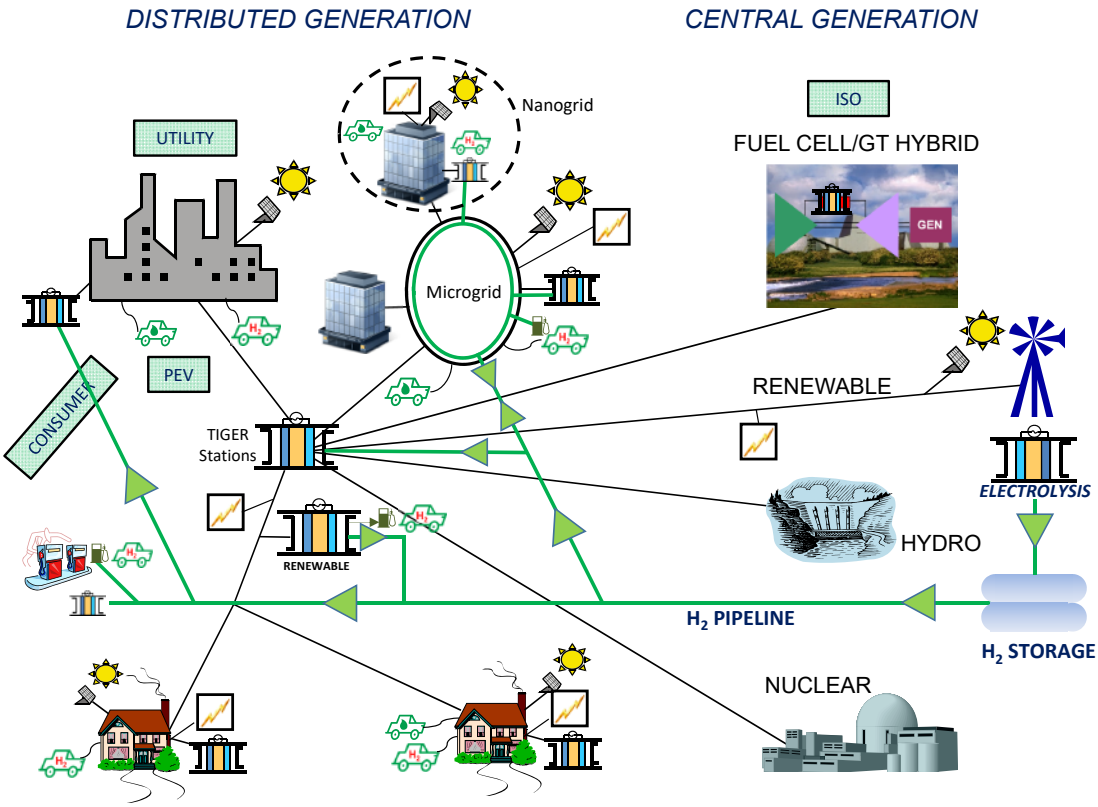


FIGURE 13.6.4 **Pathway 2: the future grid interwoven with transportation, microgrid technology, and smart grid technology.**

necessary to achieve 100% renewable electricity and transportation sectors (to address climate change) commensurate with zero emission of criteria pollutants (to address degraded urban air quality) while achieving fuel independence. To this end, two pathways have been described. Whether pathway 1 (Figure 13.3.1a) or pathway 2 (Figures 13.3.1b and 13.6.4) or another form is realized in the decades to come will depend upon factors such as (1) the evolution and practice of technology, market dynamics, and social dynamics (that is, public support and acceptance); (2) the impacts of climate change and degraded air quality; and (3) policies of the world's governments.

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All figures provided by the author unless otherwise indicated.

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CHAPTER 14

Environmentally Sustainable Transportation

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Learning Objectives

At the end of the chapter, the reader should be able to do the following:

1. Describe the impacts of transportation on air quality and greenhouse gas emissions that lead to climate change; understanding these impacts is critical to devising sustainable solutions.
2. Understand the general relationships between traffic and emissions; congested traffic has higher emissions, so congestion mitigation techniques and traffic smoothing can reduce emissions.
3. Realize that the amount of vehicle use has increased dramatically over the last several decades and has a significant role in transportation emissions.
4. Understand the four general solutions to mitigate transportation emissions: vehicle technology, low-carbon fuels, VMT management, and intelligent transportation systems, including the use of connected and automated vehicles.
5. Understand how future "intelligent" transportation systems using low-carbon fuels (including electricity) can reduce emissions.
6. Understand the potential positive and negative environmental effects of vehicle automation.
7. Understand the challenges to sustainable transportation, and appreciate the political, technological, and economic perspectives in achieving transportation solutions.

Overview

The efficient movement of both people and goods is at the heart of a productive and equitable society. However, today's transportation systems emit a significant amount of pollutants that degrade our urban air quality and cause climate change. This chapter provides background material on transportation-related environmental impacts and then discusses potential alternatives and methods of mitigation. A variety of mitigation methods are available, including improving vehicle technology, using low-carbon fuels, managing travel demand, and applying intelligent

transportation system management techniques. The mitigation opportunities are expanding because transportation is undergoing several major "revolutions," with new emerging forms of shared mobility, the use of electricity to power our vehicles, and the increasing use of connected and automated vehicle technology. This chapter addresses mitigation opportunities and challenges as well as strategies to steer these transportation revolutions toward a more sustainable future.

14.1 Introduction and Background

Over the last century, the transport of both people and goods has grown dramatically, affecting our economy, society, and environment. The ability to move people and commodities between different locations has allowed our society to prosper, expanded our economic opportunities, and improved our overall quality of life. Our total vehicle miles traveled (VMT) per capita increased dramatically, even as the use of transportation modes narrowed. Our use of most other modes shrank, while our dependence on cars increased.

Unfortunately, with the benefits of greater automotive use has come many negative consequences, including (1) safety and health effects from pollution, crashes, and less walking; (2) reduced productivity and financial loss from congested traffic; and (3) environmental impacts, including local air quality and climate change. In this chapter we first provide background information on mobility and congestion, impacts of transportation on emissions, and the relationship between vehicle emissions and traffic. We then describe a suite of sustainable transportation solutions related to vehicle technology, low-carbon fuels, travel demand management, and intelligent transportation systems (ITS), including connected and automated vehicle technology. The US, the focus of this chapter, was the leader in creating car-centric lifestyles and cities but now is the home of many mobility innovations.

Mobility and congestion

Personal mobility—the ability to access work, school, health services, and other activities—is key to the successful functioning of a modern society. Greater mobility has greatly enhanced our productivity and quality of life. And the greater ease of shipping goods has greatly enhanced our economy.

Motor vehicles—cars, trucks, and buses, as well as motorcycles and scooters—are at the heart of personal mobility and goods movement.

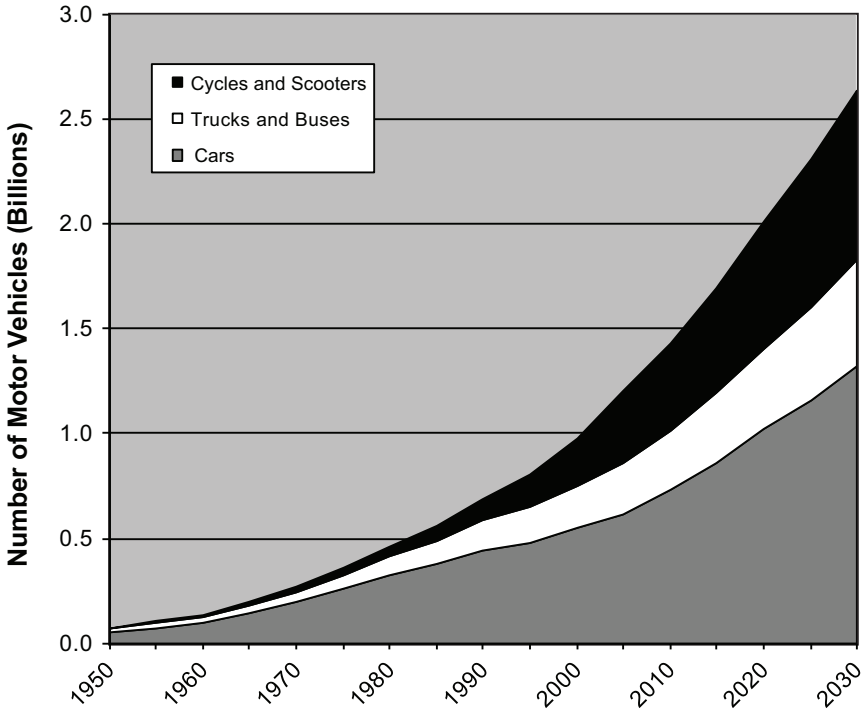

FIGURE 14.1.1 Rapid increase in vehicles globally, historical and projected. Adapted from Sperling and Gordon 2010.

In the US and many other countries, the number of motor vehicles has rapidly increased, as shown in Figure 14.1.1. The US has the highest per capita motor vehicle ownership of any major nation, as shown in Figure 14.1.2. Indeed, US dependence on the motor vehicle has led to a vulnerable "transportation monoculture," as outlined in the timeline shown in Table 14.1.1. Over time, the use of public transportation has steadily dwindled in the US to about 2% of trips. Most other nations are following this same path, becoming increasingly dependent on motor vehicles, though not to the same extent as the US.

During the twentieth century, rapid growth in motor vehicle use was accompanied by massive investments in roadway infrastructure, boosted in the US from the late 1950s into the early 1970s by the building of the Interstate Highway System. After the 1970s, new roadway construction was slowed by urban opposition and the high cost of building in urban areas. With more vehicle travel and slowed investment in road capacity, traffic congestion worsened.

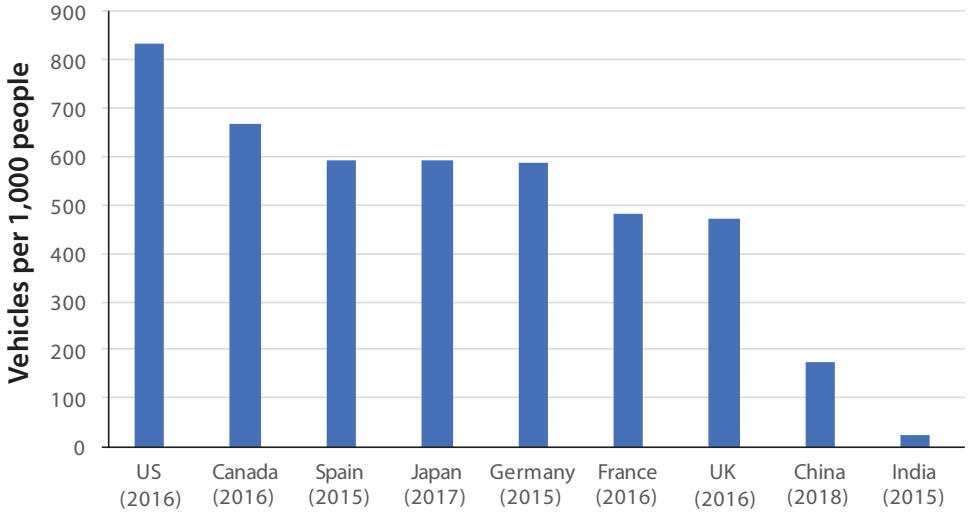

FIGURE 14.1.2 Motor vehicle ownership, various countries. Source: compiled by authors.

TABLE 14.1.1 Evolution of transportation monoculture in the US

1859	First US oil well discovered
1908	Model T (with ICE) debuts
1926	US transit ridership reaches highest peacetime levels
1930	Car ownership reaches 200 for every 1,000 Americans
1947	Suburban building boom begins following World War II
1956	US Interstate Highway System launched
1973	Arab oil embargo constricts supply
1979	Iran-Iraq war doubles oil prices
2000	First hybrid electric cars sold in US
2003	Car ownership reaches 1.15 vehicles per American driver
2005	Motor vehicle population worldwide exceeds 1 billion
2008	Crude hits $140/barrel
2016	Crude drops below $30/barrel
2018	1 million EVs sold in US

SOURCE: Adapted from Sperling, D., and Gordon, D. 2010. *Two Billion Cars, Driving Towards Sustainability*. Oxford University Press, New York, NY.

Increased roadway congestion has grown everywhere, from small cities to large megacities (see, for example, the Urban Mobility Scorecard at http://mobility.tamu.edu/ums). Roadway congestion is occurring during longer portions of the day and is delaying travelers and goods more than ever. The costs of congestion are large. These costs include the following (in the US):

- More than 3 billion gallons of fuel wasted annually.
- More than 2.6 million extra metric tons of CO_2 per year being emitted into the atmosphere.
- Nearly 7 billion extra hours in travel time, valued at roughly $160 billion—equivalent to 42 hours and $960 per rush-hour commuter.

Various solutions to roadway congestion exist. We could build more lanes to increase roadway capacity, though this is quite costly and induces more people to drive. Another possibility is to improve traffic system "operations" through traffic management techniques such as responding quickly to traffic incidents (more details on this in Section 14.2). In terms of managing "demand," we can implement pricing mechanisms to limit the use of current roadway capacity. We could also promote shared mobility programs, such as car sharing and multi-passenger app-based ride sharing, increase the capacity of public transit, construct more walking and bicycling paths, provide greater incentives for use of alternatives to single-occupant private cars, and enact alternative work locations and schedules (for example, telecommuting). We could also implement urban design and land use planning that lead to less VMT, including (1) mixing residential and nonresidential land uses within a neighborhood, (2) increasing housing and industrial density, (3) allowing for innovative planning and zoning, and (4) implementing some type of growth management. These land use measures tend to reduce the distance that people travel, as destinations become closer together, and reduce the share of trips made by the private car.

Some policies that would alleviate roadway congestion would increase emissions if they created more capacity that encouraged people to drive more. And some policies would enhance mobility of physically and economically disadvantaged travelers. If policies are implemented well, though, they will continue to improve mobility and accessibility,

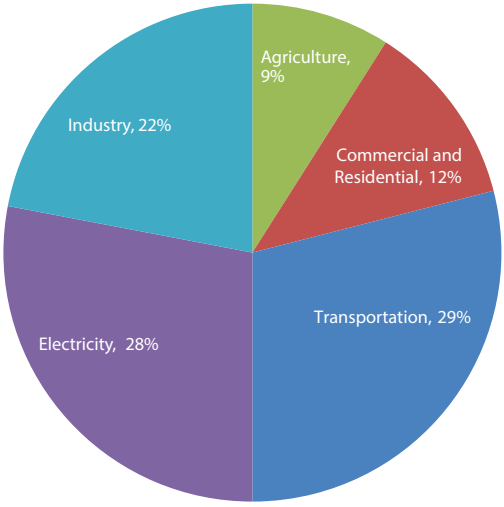

FIGURE 14.1.3 Contributors of GHG emissions in the USA in 2017. Adapted from US Environmental Protection Agency 2019.

while reducing congestion, greenhouse gas emissions, and local air pollutants.

Impacts of transportation on emissions

As described in the previous section, today's transportation systems depend on motor vehicles. As shown in Figure 14.1.3, by 2017 transportation as a whole had become the largest emitter of greenhouse gases in the United States. In fact, in 2017 the US Environmental Protection Agency (US EPA) reported transportation emissions to be 1,866 million metric tons of CO_2 equivalent (MMT CO_2e), approximately 29% of total US emissions. If one also considers the refining of fuels and the energy used to build roads, the emissions attributable to transportation are even higher. Where electricity generation has low greenhouse gas (GHG) emissions, transportation's share of the total is much higher. For example, in California in 2017, transportation-related emissions accounted for 41% of California's GHG emissions, or about 48% with refining of transportation fuels.

Transportation is also the largest source of directly emitted air pollutants that cause local air pollution, including carbon monoxide (CO), oxides of nitrogen (NO_x), and particulate matter (PM). Motor vehicles emit other gases as well, including hydrocarbons (HC) that lead to the

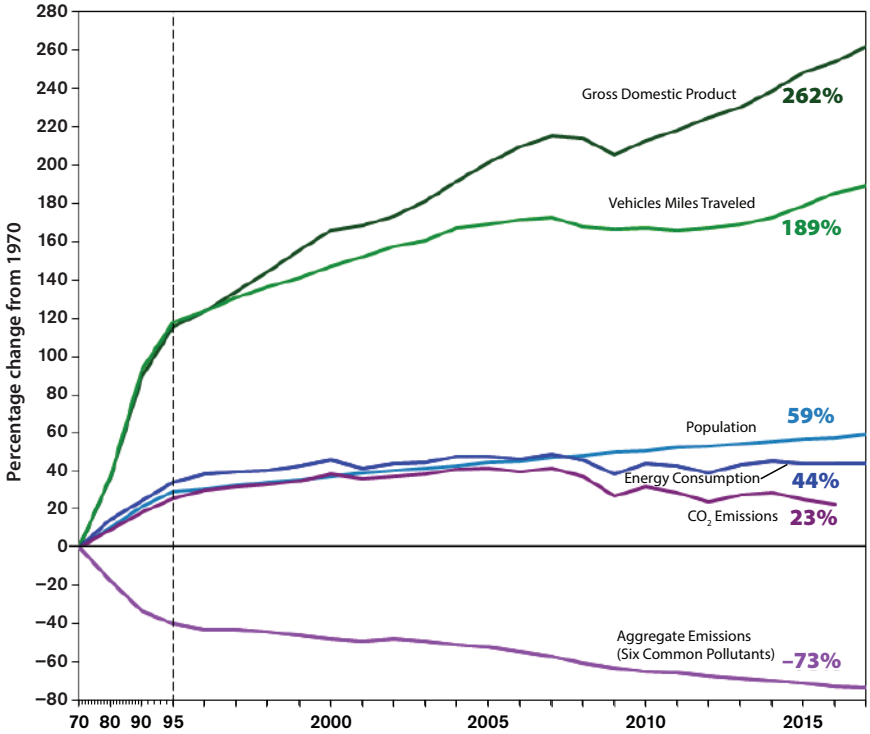

FIGURE 14.1.4 Air pollution emissions yearly trends. Adapted from US Environmental Protection Agency 2019.

formation of ozone (O_3) and secondary PM. And air-conditioning units in vehicles increase fuel use and emit hydrofluorocarbon (HFC) refrigerant emissions that are short-lived climate super pollutants (Chapter 15). Vehicle-related pollution causes about 15,000 premature deaths annually in the US and between 184,000 and 242,000 globally.

Fortunately, air quality has dramatically improved in US cities since the 1970s. Figure 14.1.4 shows that air pollutants from cars and light trucks were reduced by 73% from 1970 to 2016, even though VMT almost doubled.

This huge reduction in air pollutants was due to technological advances in vehicle emission control technology and the reformulation of gasoline and diesel fuels. These technology and refining improvements are the result of increasingly stringent performance standards adopted by the US EPA and the California Air Resources Board (CARB). Hydrocarbon and carbon monoxide exhaust emissions from new light-duty

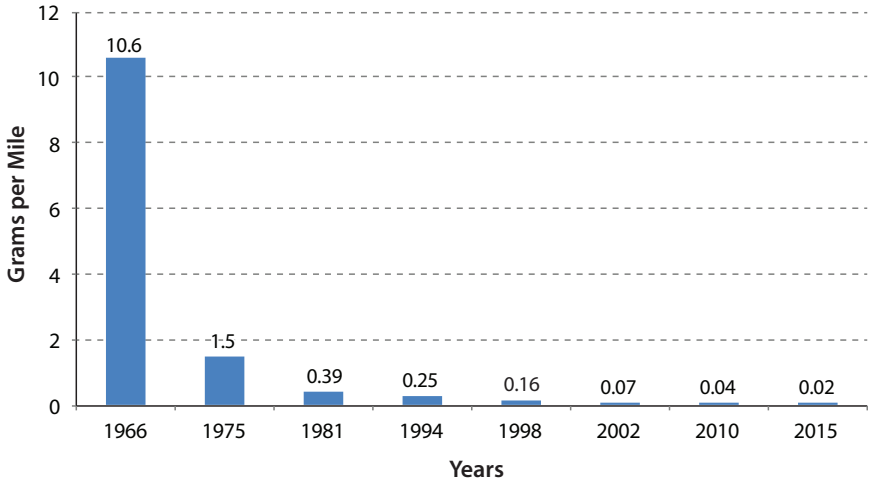

FIGURE 14.1.5 California tailpipe HC performance standards for new light-duty vehicles. Source: Authors.

vehicles have decreased by over 99% in the US, as shown in Figure 14.1.5. Massive improvements are also being achieved with trucks, ships, locomotives, and other transportation modes, but they are lagging improvements in cars. Chapter 9 discusses California's air quality efforts in more detail.

Vehicle activity and emissions

In order to understand the breadth of potential transportation-related emissions reductions, it is useful to understand the relationship between vehicle activity and the corresponding emissions. There are several factors that play a role in how much a vehicle emits from the tailpipe. A typical driving trip will consist of idling, accelerating, cruising, and decelerating. The proportion of a trip spent in these different stages will depend on the driver's behavior (for example, aggressive versus mild driving habits), the roadway type (for example, freeway versus arterial roadway), and the level of traffic congestion.

We can create histograms of emissions for large regional areas. Data collected from passenger vehicles in Southern California are presented in Figure 14.1.6. As indicated, most trips produce about 330 grams of CO_2 emissions per mile, corresponding to approximately 26

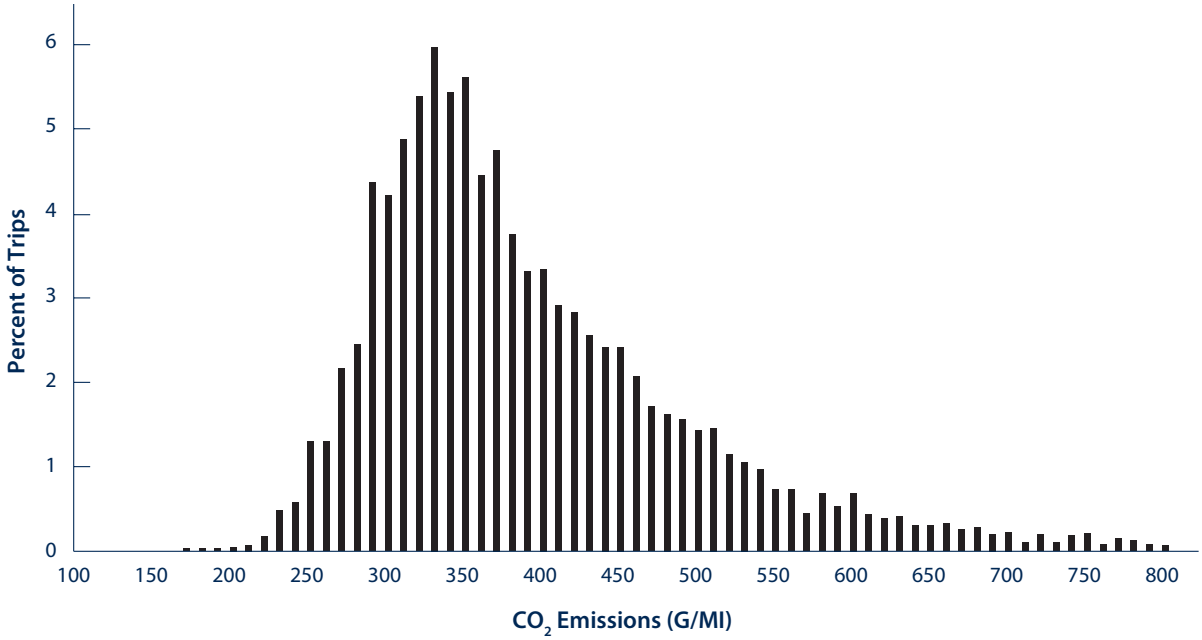

FIGURE 14.1.6 CO_2 emissions, in grams per mile, for a representative database of passenger vehicle trips in Southern California. Reproduced with permission from Barth and Boriboonsomsin 2009.

miles per gallon of fuel economy. Other trips, however, produce far less or far more CO_2 emissions per mile, depending on the specific driving pattern. This variation comes from the driver's behavior, the roadway type, and the level of traffic congestion. Other vehicle types will have quite different emissions depending on their weight, power, and other vehicle factors.

Electric vehicles have zero tailpipe emissions, but their energy efficiency (and upstream power plant emissions) is affected by these same factors.

If one plots emissions against speeds, one observes a U-shaped pattern as shown in Figure 14.1.7. The resulting emissions-speed curve can be generalized for different types of vehicles, different driving behaviors, and different types of trips, as shown in Figure 14.1.8. This generalized curve can then be used as a tool for evaluating different carbon reduction schemes for transportation management. The upper line in Figure 14.1.8 shows a representative emissions-speed curve for typical traffic. We can use this curve to examine how different traffic

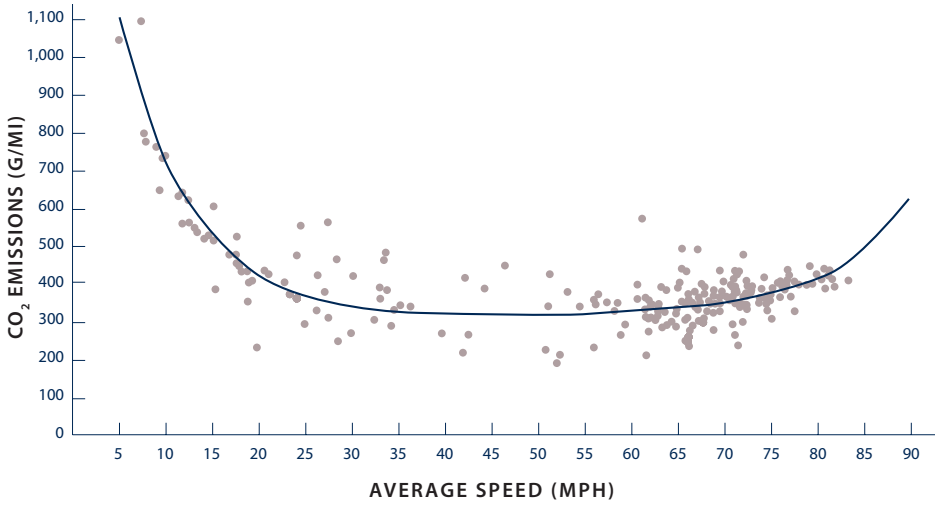

FIGURE 14.1.7 Emission-speed plot of individual trips or trip segments. Reproduced with permission from Barth and Boriboonsomsin 2009.

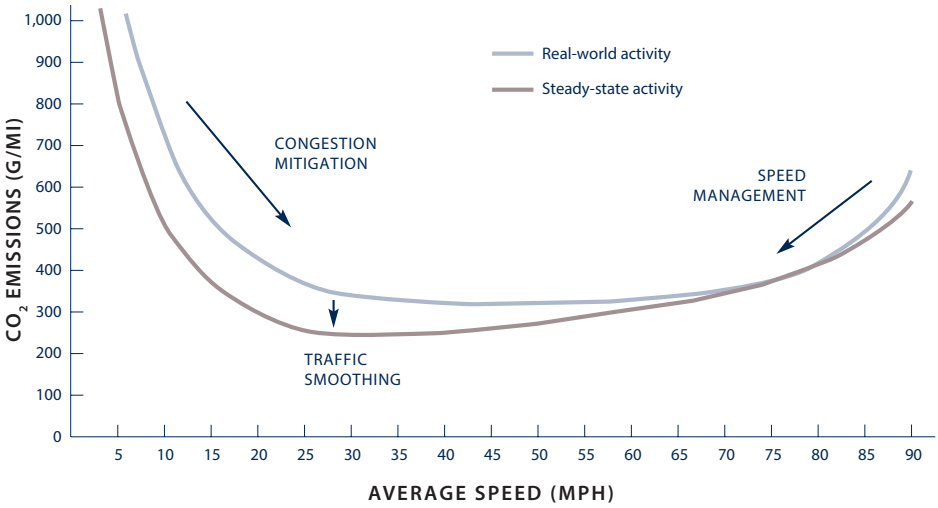

FIGURE 14.1.8 Possible use of traffic operation strategies in reducing on-road CO_2 emissions. Reproduced with permission from Barth and Boriboonsomsin 2009.

management techniques can affect vehicle emissions such as CO_2. The lower line represents the approximate lower bound of CO_2 emissions for typical internal combustion vehicles traveling at a constant steady-state speed. Several important results can be derived from this figure:

- If congestion reduces the average vehicle speed below 45 mph (for this particular freeway scenario), emissions increase. At these lower speeds, vehicles operate less efficiently and spend more time on the road, resulting in higher emissions. In this scenario, congestion mitigation programs will directly reduce emissions.*
- If moderate congestion reduces average speeds from a free-flow speed over 70 mph to a slower speed of 45 to 55 mph, this moderate congestion can reduce emissions (because emissions are higher and energy efficiency is lower at very high speeds). With no congestion, average traffic speeds can increase to over 65 mph, increasing emissions.
- Smoothing stop-and-go traffic will reduce emissions.
- Electric vehicles powered by renewable energy will have near-zero life cycle emissions; if electric vehicles are powered by fossil fuels, emissions from power plants will be lower at lower speeds, for the same reason as for combustion engine vehicles but even more so because regenerative braking captures energy in stop-and-go traffic.

*This analysis assumes that the travel demand won't change when congestion is reduced. However, experience has shown that if congestion is reduced on our roadways, there is often "latent" demand that will increase traffic on those particular roadways. This "induced demand" or "rebound effect" is described in further detail later in this chapter.

14.2 Sustainable Transportation Solutions

Pollutant and GHG emissions can be reduced in many ways. See Figure 14.2.1 for a simplified framework. GHG emissions may be treated as *primary energy carbon intensity* multiplied by *vehicle and transportation efficiency* multiplied by *total travel demand*.

Primary energy carbon intensity can be reduced by using lower-carbon fuels or low-carbon electrification, which is described later in this section. The energy needed to drive a specific distance can be reduced by improving both (1) vehicle efficiency and (2) transportation system efficiency, again assuming no induced demand (note that induced demand can be mitigated using the methods outlined in Section 14.1). This analytical construct—separating the determinants of emissions into carbon intensity, efficiency, and demand—can be used as a policy framework. A large carbon tax would address all three strategies, though it must be very large to be effective. In practice, an environmentally sustainable transportation solution will depend on a mix of policies and strategies.

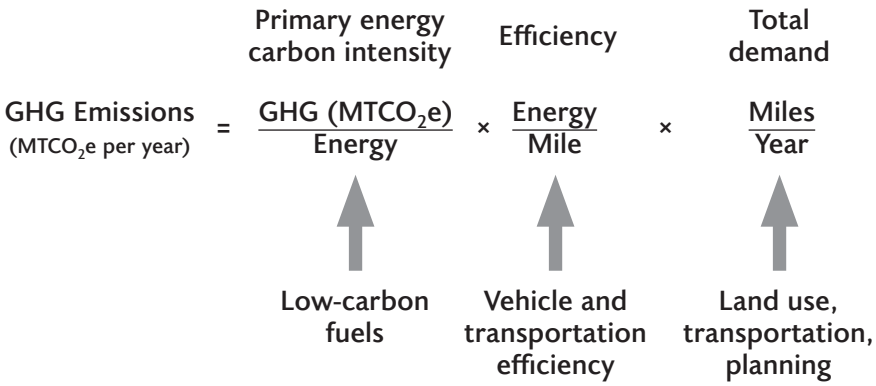

FIGURE 14.2.1 General approach for calculating GHG emissions from transportation.

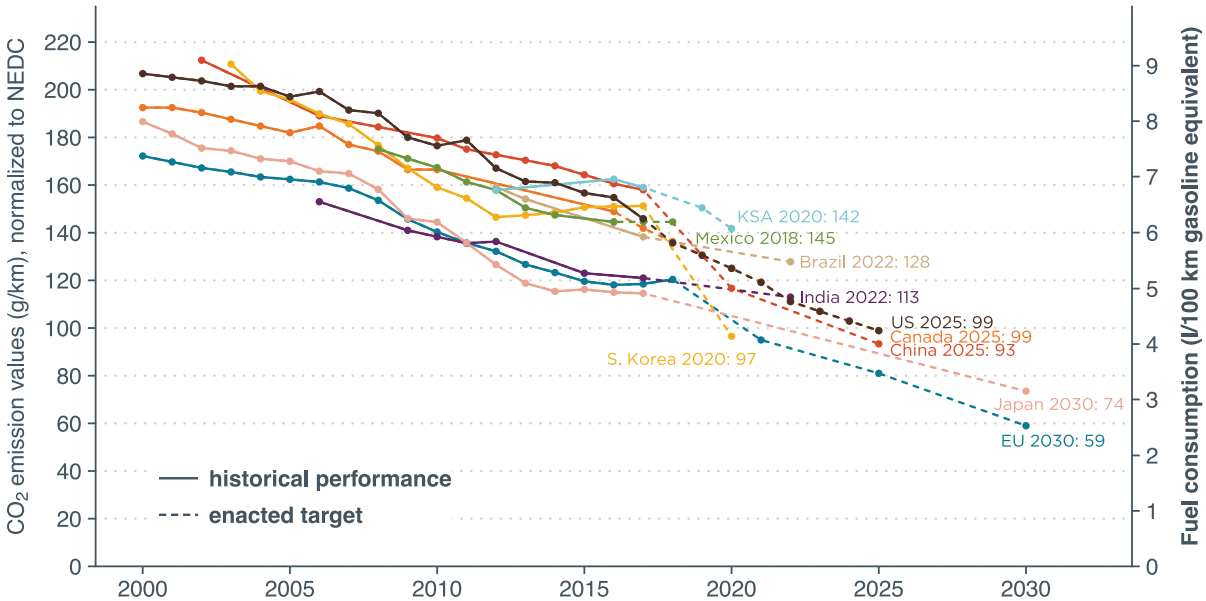

FIGURE 14.2.2 Average passenger car GHG emissions normalized by distance traveled for different regions. Reproduced with permission from the International Council on Clean Transportation 2019.

Vehicle technology

There has been considerable effort over the years to make vehicles more energy efficient, thereby reducing pollutant and GHG emissions. Many of these vehicle-based technologies are described in Chapter 13. In recent years, vehicles have benefited from lighter materials and more-efficient combustion engines and powertrains. In just the past few years, the greater use of electric powertrains, including gasoline-electric, plug-in hybrid, battery electric, and fuel cell electric technologies, has provided the promise of even much greater efficiency improvements. Overall vehicle efficiency improvements are illustrated in Figure 14.2.2 for different areas of the world. The improvements are due to a combination of aggressive policies and large technology investments by automobile manufacturers.

The increasing use of electric powertrains provides the promise for continued improvements in energy efficiency. The continuing drop in battery costs assures that this trend will continue into the foreseeable future. Figure 14.2.3 illustrates the number of electric vehicles (EVs) that are being introduced in different parts of the world.

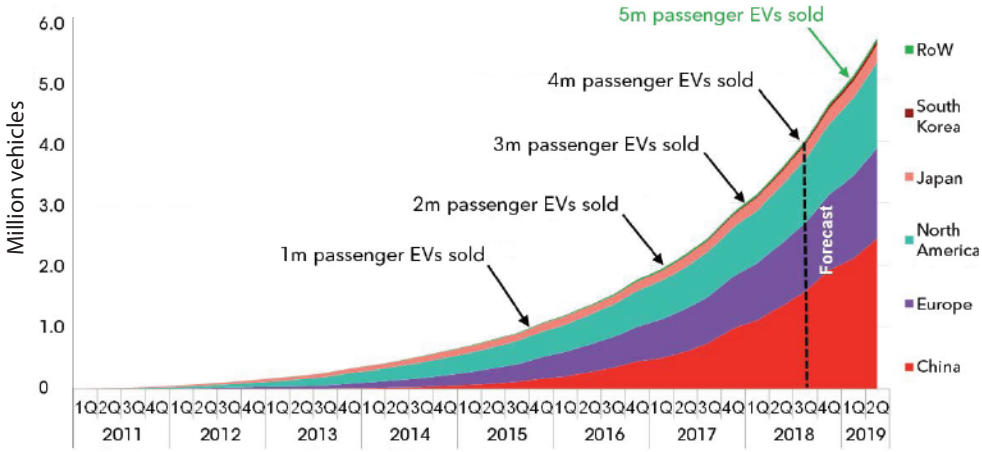

FIGURE 14.2.3 The number of electric vehicles (EVs) being introduced for different regions. Reproduced with permission from BloombergNEF 2018.

Low-carbon fuels

Another key strategy for reducing GHG emissions is to utilize low-carbon fuels. Today's dominant fuel for transportation is gasoline, followed by diesel fuel and then jet fuel (Figure 14.2.4). All of these fuels are petroleum based and contribute significantly to CO_2 emissions. A number of other fuels are being introduced that are less carbon intensive, including bio-based fuels, electricity, and hydrogen. Their market share is currently quite small when compared with petroleum-based fuels. As described in Chapter 13, both electricity and hydrogen (as well as biofuels) can be utilized as effective energy carriers for transportation. Liquid biofuels have the advantage of being easily portable and having high energy density, like petroleum fuels. When made from crop and food wastes, liquid and gaseous biofuels have very low life cycle greenhouse gas emissions, sometimes even less than zero because waste disposal and methane leakage are avoided. With steady improvements in processing and farming, even biofuels made from crops, such as corn and sugarcane, tend to be significantly superior to petroleum fuels. As processes for converting grasses, trees, and other cellulosic material into liquids are improved (Chapter 18), resulting in even lower life cycle greenhouse gas emissions, biofuels will likely prove the superior alternative fuel for aviation and perhaps long-haul trucking, where portability and high energy density are valued most highly.

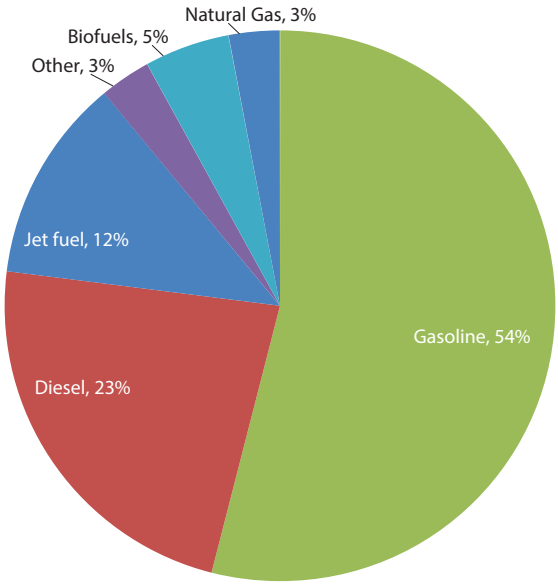

FIGURE 14.2.4 Fuel utilization for the US transportation market, 2018. Data from Energy Information Administration 2019.

Life cycle analysis is necessary for comparing emissions of different fuels. A life cycle analysis includes all emissions from extraction through combustion, including, for example, the energy from farm machinery and carbon released from soils when growing biofuels, emissions from the operation of refineries, and the transport of fuels in tankers, pipelines, and trucks.

Table 14.2.1 provides rough estimates of life cycle emissions of different vehicle-fuel combinations, compared with gasoline-powered internal combustion engine vehicles. Note that these life cycle emission comparisons (per kilometer) could vary considerably since they rely on a large number of assumptions. For example, GHG emissions for an electric vehicle depend on the carbon intensity of the electricity used to charge the vehicle. This varies widely across space and time, from close to zero carbon in regions powered predominately by nuclear and low-carbon renewable sources, to carbon emissions exceeding those from internal combustion engines in places where electricity is generated from coal.

In general, petroleum-based fuels are convenient fuels for vehicles, since they have high energy density (per unit of volume), are easily

TABLE 14.2.1 Greenhouse gas emissions per kilometer, relative to gasoline-powered internal combustion engines, full energy cycle

Fuel/Feedstock	*Percent Change*
Fuel cells, using hydrogen from solar	−90 to −85
Cellulosic ethanol	−90 to −40
Battery electric vehicles, electricity from low-carbon sources	−60 to −25
Hybrid electric vehicles	−40 to −30
Battery electric vehicles, current US power mix	−40 to −20
Diesel	−25 to −15
CNG from NG	−20 to 0
Gasoline	—
Battery electric vehicles, new coal plant	0 to +10

NOTE: Actual impacts could vary considerably; these estimates reflect a large number of assumptions and should be treated as illustrative.

portable and refuel vehicles quickly (because they are liquid), and have energy infrastructure already in place. However, petroleum-based fuels have high GHG emissions and emit large quantities of conventional pollutants. As a society, we have grown dependent on petroleum and have become quite cost-efficient at extracting and refining fossil fuels, resulting in low prices.

In some cases, though, alternative fuels are demonstrably cheaper than petroleum, even in the US, where petroleum products tend to have lower prices than elsewhere. For example, as of 2019, a kilowatt hour costs about $0.12 in the US on average—equivalent to about 3–4 cents per mile, an energy cost about one-third that of gasoline-powered cars. In areas with low-carbon electricity, these electric vehicles also offer significant GHG emission savings.

VMT reduction methods

As described earlier, total VMT in the US continues to grow at a steady pace (for example, see Figure 14.1.4). VMT was flat from 2008 to 2012, primarily because of the economic recession, but has been increasing since then.

In terms of potentially reducing VMT, we can refer back to a variety of mobility measures outlined in Section 14.1. In general, these include the following:

- Use pricing mechanisms to encourage users to reduce the number and distance of their trips and increase the number of passengers per vehicle. Several regions across the US are already increasing the number of toll and commuter lanes on their roadway networks, while cities such as Singapore, London, and Stockholm have implemented congestion pricing schemes that charge drivers to enter the city center.
- Provide incentives for using alternative modes such as transit and biking, as well as shifting work locations and schedules, for instance by telecommuting.
- Reduce urban sprawl, increase land use densities, and improve the mix of jobs and housing.

Transportation efficiency

Another important strategy for reducing emissions from transportation is to improve the efficiency of transportation system operations. As described above, today's transportation systems are often congested, which wastes time, money, and fuel. This wasted fuel translates to increased pollutant and GHG emissions. Over the last several decades, a number of **intelligent transportation system** (**ITS**) techniques have emerged that are squarely aimed at reducing these environmental impacts. Referring back to Figure 14.1.8, ITS techniques and applications target three general areas: (1) congestion mitigation (for example, advanced signal control, predictive ramp metering, incident management), whereby congestion is reduced and speeds increased; (2) better management of speeds (on the right side of Figure 14.1.8) for different roadway types, using techniques such as variable speed limits and intelligent speed adaptation; and (3) smoothing of traffic by using techniques such as cooperative adaptive cruise control and speed harmonization. These "eco-friendly" intelligent transportation system technologies are typically categorized into three areas: vehicle systems, traffic management systems, and travel information systems.

Vehicle systems represent vehicle features and functions that allow a vehicle to "see," respond to, and communicate with its surroundings. Sensors such as on-board radar and computer vision technologies enable a vehicle to monitor the distance to the vehicle in front and to

TABLE 14.2.2 Intelligent transportation system applications utilizing connected and automated vehicle technology

V2I Safety
- Red light violation warning
- Curve speed warning
- Stop sign gap assist
- Spot weather impact warning
- Reduced speed/work zone warning
- Pedestrian in signalized crosswalk warning (transit)

V2V Safety
- Emergency electronic brake lights
- Forward collision warning
- Intersection movement assist
- Left turn assist
- Blind spot/lane change warning
- Do not pass warning
- Vehicle turning right in front of bus warning (transit)

Agency Data
- Probe-based pavement maintenance
- Probe-enabled traffic monitoring
- Vehicle classification-based traffic studies
- CV-enabled turning movement & intersection analysis
- CV-enabled origin-destination studies
- Work zone traveler information

Environment
- Eco-approach and departure at signalized intersections
- Eco-traffic signal timing
- Eco-traffic signal priority
- Connected eco-driving
- Wireless inductive/resonance charging
- Eco-lanes management
- Eco-speed harmonization
- Eco-cooperative adaptive cruise control
- Eco-traveler information
- Eco-ramp metering
- Low emissions zone managment
- AFV charging/fueling information
- Eco-smart parking
- Dynamic eco-routing (light vehicle, transit, freight)
- Eco-ICM decision support system

Road Weather
- Motorist advisories and warnings (MAW)
- Enhanced MDSS
- Vehicle data translator
- Weather response traffic information (WxTINFO)

Mobility
- Advanced traveler information system
- Intelligent traffic signal system (I-SIG)
- Signal priority (transit, freight)
- Mobile accessible pedestrian signal system (PED-SIG)
- Emergency vehicle preemption (PREEMPT)
- Dynamic speed harmonization (SPD-HARM)
- Queue warning (Q-WARN)
- Cooperative adaptive cruise control (CACC)
- Incident scene pre-arrival staging guidance for emergency responders (RESP-STG)
- Incident scene work zone alerts for drivers and workers (INC-ZONE)
- Emergency communications and evacuation (EVAC)
- Connection protection (T-CONNECT)
- Dynamic transit operations (T-DISP)
- Dynamic ridesharing (D-RIDE)
- Freight-specific dynamic travel planning and performance
- Drayage optimization

Smart Roadside
- Wireless inspection
- Smart truck parking

SOURCE: Adapted from Iteris. 2016. Connected Vehicle Reference Implementation Architecture. http://www.iteris.com/cvria/html/applications/applications.html.

detect when a vehicle is leaving a lane, and they support adaptive cruise control systems that allow a driver to select a desired speed and set a following distance. In addition, communication devices (for example, dedicated short-range communications, cellular) will likely be deployed to enable vehicle-to-vehicle, vehicle-to-infrastructure, and infrastructure-to-vehicle applications that are primarily focused on improving safety. It is important to point out that improved anticollision systems may have a significant indirect energy and emissions savings: fewer crashes result in less congestion, allowing for higher average traffic speeds with less stop and go (Figure 14.1.8). In addition to safety applications, a variety of mobility and environmental applications have also emerged, as illustrated in Table 14.2.2. These applications take advantage of connected vehicle technology such as cooperative adaptive cruise control where vehicles communicate with each other to cooperatively manage following distance, braking, accelerating, and more. These technologies are allowing vehicles to become increasingly automated, with the goal of full vehicle automation coming in the next decade.

Traffic management systems have become more sophisticated with the advent of better sensor technology, more reliable communication channels, and advanced information processing. Transportation managers are better equipped to estimate traffic conditions, detect and remove traffic incidents, and craft better travel demand management strategies (that is, manage the number of vehicles on a congested roadway). The overarching goal of traffic management is to take full advantage of the existing roadway capacity, thus keeping traffic flowing smoothly at moderate speeds. In doing so, it will have a large impact in reducing energy consumption and GHG emissions from each vehicle. In addition, traffic management system strategies go even further by reducing the number of vehicles and VMT in the transportation network without compromising overall travel needs, thereby reducing the total contributions of energy consumption and emissions from the transportation sector.

Travel information systems provide information to drivers, such as route guidance systems, geolocation systems, and electronic payment systems. All of these systems add convenience to the traveler while reducing energy consumption and emissions. For example, a route

guidance system will cut back on unnecessary travel that may occur when a driver gets lost or chooses a long, out-of-the-way path. En route driver information can reduce energy and emissions associated with driving around in search of a specific location or parking. Electronic payment systems also eliminate the need for a driver to decelerate the vehicle, idle while a manual transaction takes place, and then accelerate the vehicle back to a desired speed. If this payment can occur without slowing down, energy consumption and emissions are greatly reduced.

In general, environmentally friendly ITS applications (that is, specific ITS applications that reduce energy and emissions) have slowly been emerging over the last decade, as have safety and mobility programs mentioned in Table 14.2.2. Pioneering research programs in the US, the European Union, and other regions have made significant progress in developing and testing these ITS applications and technologies with a focus on environmental benefits. From these research programs, it is clear that specific environmental benefits can be maximized when different ITS applications are "tuned" so that emissions and energy consumption are reduced. The actual energy and emissions savings vary, but they are typically on the order of 5% to 20%. It is important to point out that there is not a single ITS technology solution that has demonstrated a large reduction in energy consumption and emissions. But since most of these applications are additive, greater benefits may be achieved when a combination of environmentally friendly ITS programs is put into place.

14.3 Vehicle Automation

In recent years, interest in vehicle automation has soared. Some reports have predicted that vehicles could be fully automated (that is, not requiring a driver) by as early as 2025, though this is highly unlikely other than in tightly bounded areas with easy driving conditions. As an extension of ITS, vehicle automation could have both positive and negative effects on society (Figure 14.3.1). Vehicle automation could lead to reduced emissions, due to congestion reduction (for example, crash avoidance, platooning), traffic smoothing (for example, cooperative adaptive cruise control), and better speed management (for example, speed harmonization). Indeed, eco-driving behaviors could be directly programmed into the automated vehicle operation.

On the other hand, vehicle automation could potentially increase emissions by increasing vehicle travel. People might use their automated vehicles for additional purposes or choose a more distant place to live, since the time cost of travel would be reduced. Automated vehicles could be used by a wider range of users, including youth and elderly. "Drop-off" errands might increase, resulting in new empty vehicle relocation trips, such as returning home without any passengers.

Some early conclusions regarding automated vehicles include the following:

- Partial and full automation can reduce energy use and emissions, but only if incentives exist to encourage pooled use of vehicles.
- Automated vehicles that communicate and coordinate with other vehicles and the infrastructure will likely have greater improvements in safety, mobility, and the environment compared with autonomous vehicles without those capabilities.
- Automated vehicles have the strong potential to induce travel demand, unless incentives exist for pooled use of the vehicles.

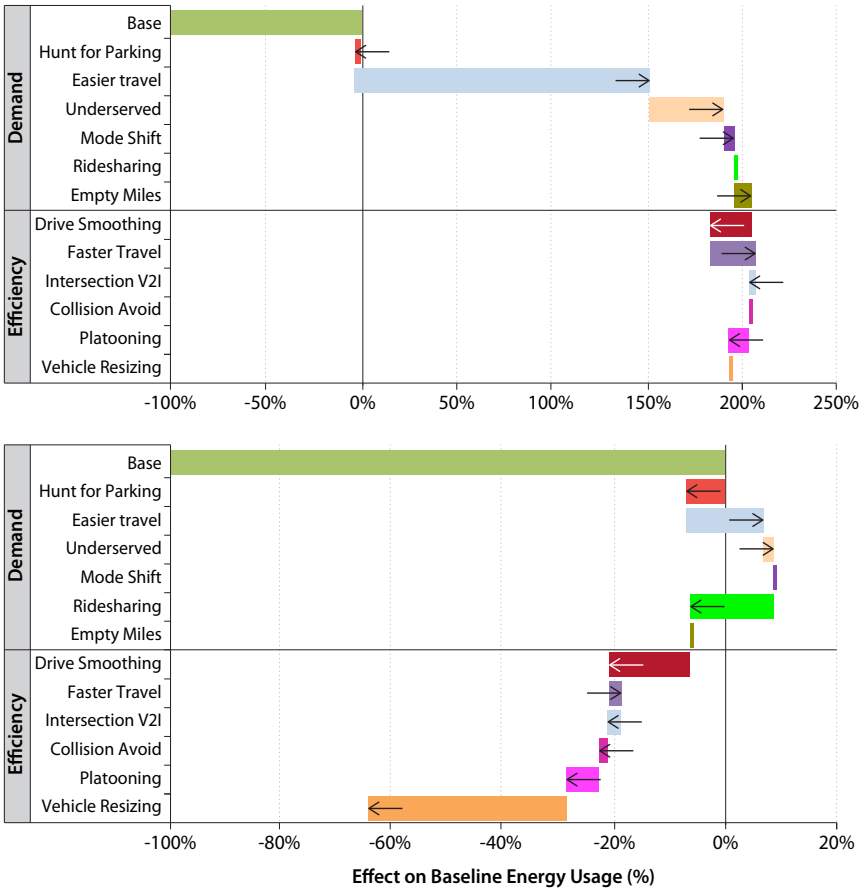

FIGURE 14.3.1 Potential energy/emissions impacts of automated technology. The upper-bound case is shown in the top panel, and the lower-bound case in the lower panel. Reproduced with permission from Stephens et al. 2016. Figures 10 and 11.

- It may be advantageous to first introduce automation in fleet applications or shared mobility, since their operations (that is, total travel) can be closely managed and pooling can be more easily encouraged.

14.4 Improved Air-Conditioning Efficiency and Refrigerants

Motor vehicle air-conditioning systems consume between 3% and 20% of all motor fuel, depending on the climate, vehicle, drive cycle, and congestion. Worldwide, more people are purchasing vehicles with air conditioning (AC). As fuel efficiency standards across the globe make the global fleet increasingly fuel efficient, AC will account for a growing percentage of vehicle fuel use. Warmer temperatures due to climate change will further increase the use of air conditioning. GHG emissions due to AC are almost three times greater in higher-temperature climates, making system efficiency improvements even more important in warmer regions.

Changes in refrigerants and improvements in AC efficiency can cut per-vehicle GHG emissions associated with AC use by up to 70%

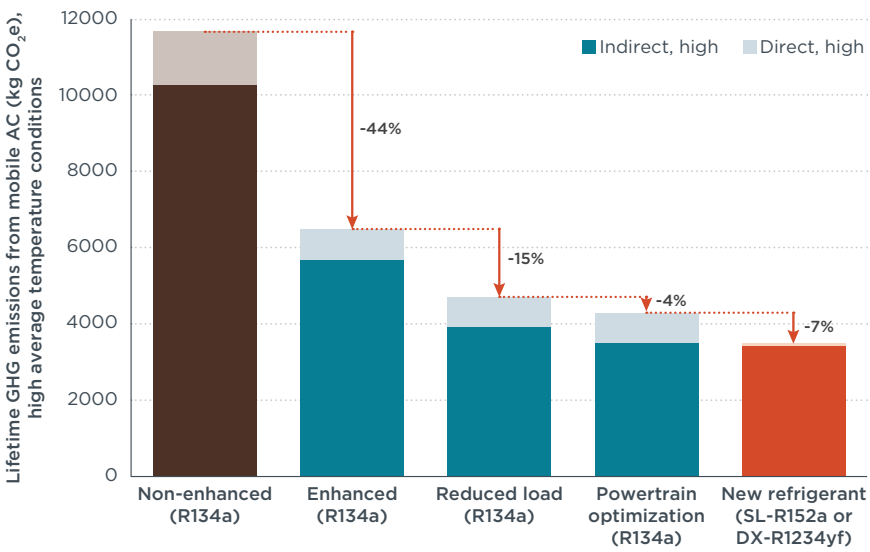

FIGURE 14.4.1 Greenhouse gas reduction potential from an internal combustion engine passenger vehicle air conditioner operating at higher average-temperature conditions, such as those found in Florida. Reproduced with permission from Blumberg et al. 2019.

compared with older systems (Figure 14.4.1). As of 2019, most vehicles still used HFC-134a (R-134a) refrigerant, which has a 100-year global warming potential (GWP_{100}) of 1,300. Enhanced R-134a systems reduce GHG emissions by approximately 40% and are now prevalent in the market. Fortunately, cost-effective alternatives that use low-GWP refrigerants and technology to improve AC system efficiency are available that can reduce vehicle-AC-related GHG emissions by another 50%.

14.5 Key Takeaways

- Transportation plays a crucial role in energy use, GHG emissions, and local air quality.
- There are generally four different ways to mitigate transportation emissions: through vehicle technology, low-carbon fuels, VMT management, and intelligent transportation systems, including the use of connected and automated vehicles.
- Vehicle electrification is well underway and is providing opportunities for large emission reductions.
- Huge improvements in vehicle technology have reduced pollutant emissions and, to a lesser extent, CO_2 emission.
- The amount of vehicle use has increased dramatically over the last several decades and has a significant role in transportation emissions.
- VMT can be reduced by increasing the use of pooled travel (for example, buses, transit, shared mobility that is pooled).
- Other VMT reduction methods may include adopting incentives and disincentives to reflect full social costs of travel and, eventually, transitioning from individual vehicle ownership to use of mobility services that are pooled.
- Sustainable transportation requires advances in all aspects of transportation, including technological, political, economic, and behavioral aspects.
- Vehicle automation is likely to be deployed in the near future and should be managed so as to achieve environmental sustainability.

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CHAPTER 15

Technologies for Super Pollutants Mitigation

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Learning Objectives

1. **Explain the importance of rapid action to mitigate super pollutants, also known as short-lived climate pollutants (SLCPS).**
   You will learn how mitigation of black carbon, methane, tropospheric ozone, and hydrofluorocarbons (HFCs) can have a powerful and relatively rapid impact to bend the warming curve because of the large contributions of these climate pollutants to current global warming (>40%) and their short atmospheric lifetimes. You will be able to explain some of the main benefits of immediate action to reduce emissions of these short-lived climate pollutants.

2. **Describe and evaluate measures to bend the curves of black carbon, methane, and ozone.**
   Next, you will learn about specific measures to mitigate emissions of black carbon and methane. Mitigation of methane will also reduce levels of tropospheric ozone, a potent greenhouse gas. You will be able to describe how reduction of these substances can contribute to human health, food security, and climate justice.

3. **Describe and evaluate measures to bend the HFC curve, including the Montreal Protocol and other policy instruments.**
   You will learn how the Montreal Protocol, a 1987 international agreement that was designed to protect the stratospheric ozone layer, has also resulted in significantly reduced warming from greenhouse gases such as chlorofluorocarbons (CFCs). You will be able to explain how the 2016 Kigali Amendment to the Montreal Protocol goes further and has the potential to avoid up to 0.5°C of warming by 2100 by mandating the global phasedown of HFCs, a class of powerful greenhouse gases. Finally, you will learn how parallel efforts to improve energy efficiency of air conditioning and other cooling equipment can double the climate benefits of the HFC phasedown.

Overview

This chapter focuses on Solution #9 from the *Bending the Curve* report, part of the technology-based solutions cluster:

> Immediately make maximum use of available technologies and regulations to reduce methane emissions by 50% and black carbon emissions by 90%. Phase out hydrofluorocarbons by 2030 by amending the Montreal Protocol.

The last few chapters have discussed technologies and policies to bend the warming curve by reducing emissions of carbon dioxide (CO_2). However, as discussed in Chapter 4, the benefits of CO_2 mitigation will not be felt for at least a decade or two, and CO_2 mitigation alone will not be enough to keep us below the 2°C threshold of dangerous warming, nor the more prudent 1.5°C threshold.

Moreover, decreasing CO_2 emissions by transitioning away from fossil fuels might have the paradoxical effect of *increasing* global warming in the short term. Fossil fuels contain sulfur and other impurities. Their combustion results in the formation of sulfate aerosols in the atmosphere. Efforts to reduce sulfates have been under way for several decades because of their damaging effects on human health and natural ecosystems, but these aerosols also reflect sunlight, causing a cooling effect that partly offsets the warming from carbon dioxide. As the use of fossil fuels decreases, the loss of sulfate aerosol cooling will be felt almost immediately, while the warming effects of the emitted CO_2 will take decades or even centuries to diminish.

In this chapter, we will explore a complementary solution: reducing a key group of warming agents knows as **super pollutants** or **short-lived climate pollutants** (**SLCPs**) to bend the warming curve quickly (over a few decades) while we pursue CO_2 mitigation to bend the curve in the long term (over several decades to centuries). Combined, these efforts, if enacted by 2020, give us a significant chance (about 90% probability) of keeping warming well below 2°C (aiming for 1.5°C) in this century and beyond.

Figure 15.1 summarizes the properties of the four short-lived climate pollutants we'll be considering: **black carbon particles** (a major

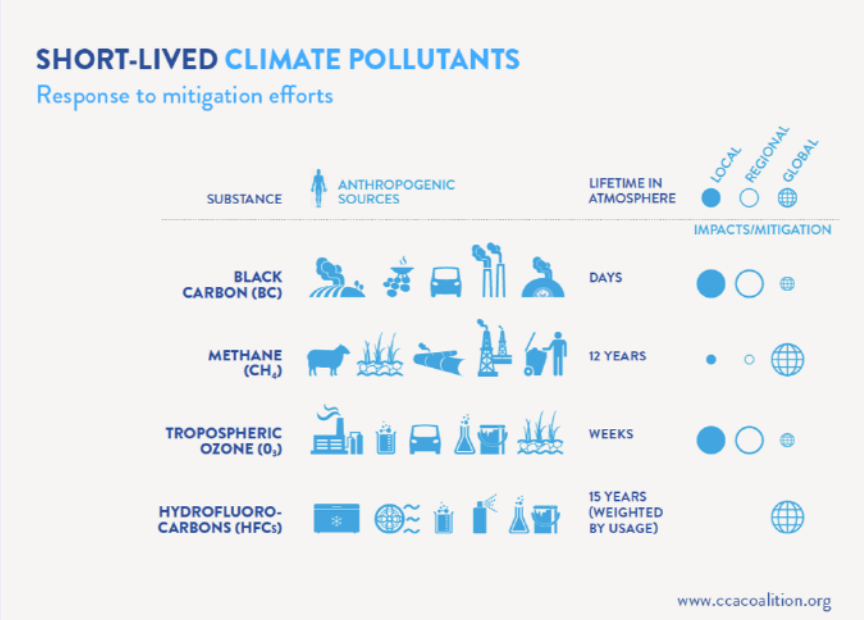

FIGURE 15.1 This figure shows the lifetime of black carbon, methane, tropospheric ozone, and hydrofluorocarbons as well as their geographical impacts and mitigation potentials. Reproduced with permission from Climate and Clean Air Coalition.

component of soot), the greenhouse gases **methane** and tropospheric **ozone** (not to be confused with the beneficial ozone in the stratosphere), and **hydrofluorocarbons** (**HFCs**). These four warming agents are called short-lived climate pollutants (SLCPs) because their typical lifetimes in the atmosphere range from about a week to 15 years, compared with hundreds or thousands of years for CO_2 (see Box 1.3.1 in Chapter 1 for a discussion of atmospheric lifetimes and warming potentials of greenhouse gases). Reducing emissions of these substances quickly brings down their concentrations in the atmosphere. For example, if all black carbon particle emissions were eliminated today, black carbon would disappear from the atmosphere within a few weeks.

We will mostly use the scientific term SLCPs in the rest of this chapter, but these four climate pollutants are often called super pollutants because of their strong warming effects. It has been recognized since 1975 that these warming agents are much more potent, pound for pound, than CO_2. The warming effect of gases is measured in terms of

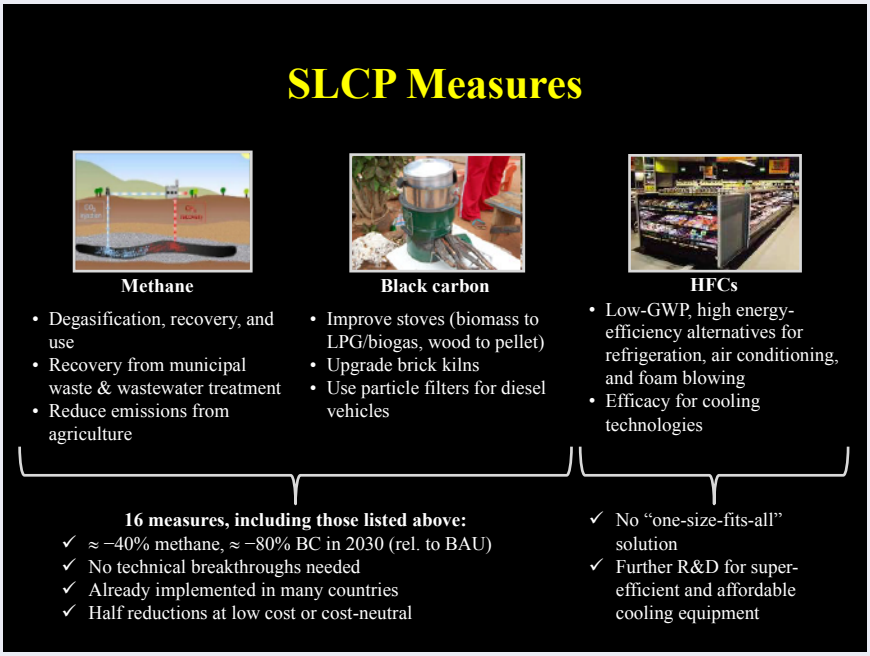

FIGURE 15.2 Short-lived climate pollutant measures. BC = black carbon; BAU = business as usual; R&D = research and development. Adapted from the Climate and Clean Air Coalition; data from UNEP and WMO. 2011.

their global warming potential (GWP), which is defined in Box 1.3.1 in Chapter 1. Methane is about 30 times more powerful than CO_2, black carbon is 500 to 2,000 times more powerful, and HFCs produce from 1,000 to over 4,000 times more warming on a 100-year time scale.

As detailed later in this chapter, mitigation of these SLCPs, if completed by 2030, can bend the warming curve by up to 0.6°C by 2050 (about 0.4°C from methane mitigation, 0.1°C from black carbon, and 0.1°C from HFCs), cutting the rate of projected warming by about half compared with "business as usual" and reducing the projected sea level rise between 2020 and 2050 by 20%. We can summarize the required emissions reductions as "80/40/100": an 80% reduction for black carbon; a 40% reduction for methane; and a complete phaseout of high-GWP HFCs. By 2100, these measures combined could avoid up to 1.2°C warming. For comparison, aggressive CO_2 mitigation would avoid about 0.1°C to 0.3°C by 2050 and up to 1.9°C by 2100.

In this chapter, we will describe some of the available measures to

produce the required 80/40/100 reductions in emissions of black carbon, methane, and HFCs, some of the most effective of which are highlighted in Figure 15.2. While many more SLCP mitigation measures are possible—a 2011 study by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) examined over 2,000 of them—the key measures discussed in this chapter account for 90% of the avoided warming. These measures are based on existing technologies and do not require new technical breakthroughs.

It's important to note that the sources of SLCPs as well as the measures for emissions reductions are highly dependent on the region under consideration. For Africa and Asia, the critical measures include reducing black carbon emissions from biomass cookstoves and diesel vehicles as well as reducing methane emissions from coal, oil, and gas production and municipal waste. For North America and Europe, the key mitigation measures include reducing methane emissions from oil and gas production, long-distance natural gas transmission pipelines, and municipal waste as well as reducing black carbon emissions from residential biomass heating, shipping activities, and open agricultural biomass burning.

You may have noticed that we have not discussed mitigation measures for tropospheric ozone emissions. This is because ozone is not directly emitted by human activities; we will see later in this chapter that measures to reduce methane emissions and fossil fuel combustion will significantly decrease ozone as well.

The final sections of this chapter cover the phasedown of HFCs under the Kigali Amendment to the Montreal Protocol, an international treaty signed in 1987 to phase out substances that deplete the ozone layer. Generally considered the world's most successful environmental treaty, the Montreal Protocol solved the first great threat to the global atmosphere by phasing out chlorofluorocarbons (CFCs) and related fluorinated gases and by putting the ozone layer on the path to recovery in the 2030s. At the same time, because CFCs and other fluorinated gases are also powerful climate pollutants, the success of the Montreal Protocol has avoided warming that would have grown to equal or surpass the warming caused by CO_2 today. The success of the Montreal Protocol is continuing with the Kigali Amendment, which was approved in 2016 and entered into force at the beginning of 2019.

15.1 Why Should We Mitigate Short-Lived Climate Pollutants?

Climate benefits of SLCP mitigation

We can see the importance of mitigating SLCPs by looking at Figure 15.1.1. We have already seen this figure in Chapter 4. It shows the temperature record (purple line) from 1950 to about 2010 and possible future temperature pathways up to 2100. As we have previously discussed, the planet has already warmed by 1°C. Most researchers conclude that warming of less than 1.5°C (relative to preindustrial times) will have impacts that, while significant, will mostly be manageable. This zone of presumed relatively "safe" temperatures is colored green. Red represents the zone of "dangerous" warming above 2°C.

The curved lines in the figure represent different possible temperature pathways, based on the choices we make now and in the near future. The highest, gray "business as usual" curve shows the evolution of temperatures if human emissions continue to grow unabated. (Some policymakers now call this the "disaster curve" rather than the more benign-sounding "business as usual curve.") This pathway leads to temperature increases that will likely exceed 4°C by 2100. As described in previous chapters, the impacts of warming in this range are not merely dangerous; they could be catastrophic for human society and natural ecosystems. This is the warming curve we must bend to ensure a sustainable future for our children and their descendants. The other curved lines show possible mitigation scenarios, as described below.

It's important to keep in mind that, although these pathways are shown as definite lines, there is actually a range of possible temperature trajectories for each of these pathways. Refer back to Box 1.4.3 in Chapter 1 for more details on this concept. The lines represent the *most likely* temperature outcome for each pathway, as determined by computer models.

The dotted black "CO_2 only" line shows the expected effects if we

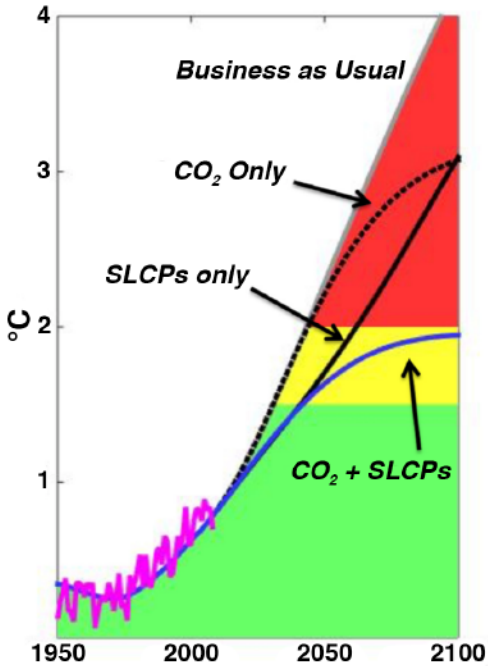

FIGURE 15.1.1 Projections of future warming along business-as-usual and mitigation pathways. From Ramanathan et al. 2017.

make significant efforts to reduce carbon dioxide, but not SLCPs. We can see that this scenario bends the warming curve well below the business-as-usual line, but the benefits happen very slowly and don't really become apparent until after about 2050. In contrast, the solid black "SLCPs only" mitigation line drops below the business-as-usual curve almost immediately because of the short atmospheric lifetimes of SLCPs. This pathway delays the time to cross the 2°C threshold by 20 to 30 years.

A mitigation strategy that focuses on reducing both CO_2 and SLCPs simultaneously—the solid blue line in the figure—is the only pathway that keeps warming below the 2°C threshold throughout this century. Reducing SLCPs bends the curve immediately and buys us time for the long-term effect of CO_2 reduction to take effect. Pursuing *both* CO_2 and SLCP mitigation simultaneously is our best—indeed, our only—hope for avoiding dangerous warming of the planet.

Commentary on temperature thresholds: From a scientific perspective there are no sharply defined physical thresholds beyond which negative impacts will start to happen. In fact, damaging effects of the current

warming of 1°C are already being experienced in most parts of the world and will get progressively worse as temperatures keep increasing, as documented in the 2018 *Special Report* from the Intergovernmental Panel on Climate Change (IPCC) on the impacts of 1.5°C warming. Our best understanding of the climate system indicates that sustained warming of 2°C would be unprecedented over at least the past 2 million years and would lead to very severe impacts on human health and threaten food and water security. In practice, such temperature thresholds are used as benchmarks to evaluate the effectiveness of mitigation measures. The yellow area between 1.5°C and 2.0°C represents the transition zone between "safe" temperatures and dangerous climate change. Keep in mind that we generally are referring to warming that is averaged globally, even though in reality warming is not evenly distributed, with some regions, such as the Arctic, warming at least twice as much as the global average.

Health and food security benefits of SLCP mitigation

Mitigation of SLCPs has important co-benefits in addition to helping to bend the warming curve. Black carbon and tropospheric ozone have significant negative impacts on human health, and ozone is a major cause of damage to agricultural crops. The mitigation measures detailed in this chapter can save about 2.4 million lives lost each year and about 50 million tons of crops lost each year to air pollution. The health benefits from reduction of black carbon and ozone are valued at about $5 *trillion* per year. The health benefits and food benefits alone would justify mitigation of these pollutants even without consideration of the cooling benefits from cutting them.

Climate justice benefits of SLCP mitigation

It's also important to bear in mind that, as we discussed in Chapter 2, the negative impacts of these pollutants are borne disproportionately by the global poor. The poorest 3 billion human beings, representing 40% of the global population, have limited access to energy from fossil fuels and contribute only about 5% of global CO_2 emissions. Poverty forces the poorest 3 billion to rely on eighteenth-century technologies such as

inefficient wood-burning stoves for cooking. The poorest 3 billion on the planet are far more exposed to threats such as drought, flooding, heat waves, and sea level rise. Meanwhile, the wealthiest 1 billion represent about 13% of the world's population but emit about 50% of global CO_2 pollution. Their greater resources provide more opportunities to adapt to the impact of global warming, such as using air conditioning to reduce deaths from heat waves. Mitigation of SLCPs would help to reduce these disproportionate impacts. Moreover, some of the solutions, such as more efficient stoves, would result in improved quality of life for many among the global poor.

The disproportionate responsibilities of the global wealthy and vulnerabilities of the global poor add a moral and ethical component to climate change. As discussed in Chapters 6, 7, and 8 on societal transformation, solutions to these issues should involve not only scientists and engineers, but also religious communities, philosophers, ethicists, climate justice advocates, and others from civil society. Mitigating short-lived climate pollutants brings these issues into particularly sharp focus. Addressing them will require an alliance among science, religion, health care, and public policy.

Political benefits of SLCP mitigation

Fortunately, reducing SLCPs poses fewer political barriers than cutting carbon dioxide. First, governments are more likely to agree to emissions reduction strategies that can deliver local benefits. Second, already available technologies and policies (such as air pollution regulations for black carbon and methane and the Montreal Protocol for HFCs) readily allow for deep cuts in these pollutants. Third, unlike reductions in carbon dioxide emissions, whose main benefits arrive only after decades of mitigation efforts, SLCPs mitigation would satisfy the immediate interests of countries because of rapid and visible improvements in health and food security. Visible early success in fighting climate change through limiting SLCPs would also enhance the credibility of climate change policies and thus accelerate progress on the more challenging task of limiting carbon dioxide. A plan to reduce short-lived climate pollutants would align the self-interests of many polluting nations. It is not surprising that the

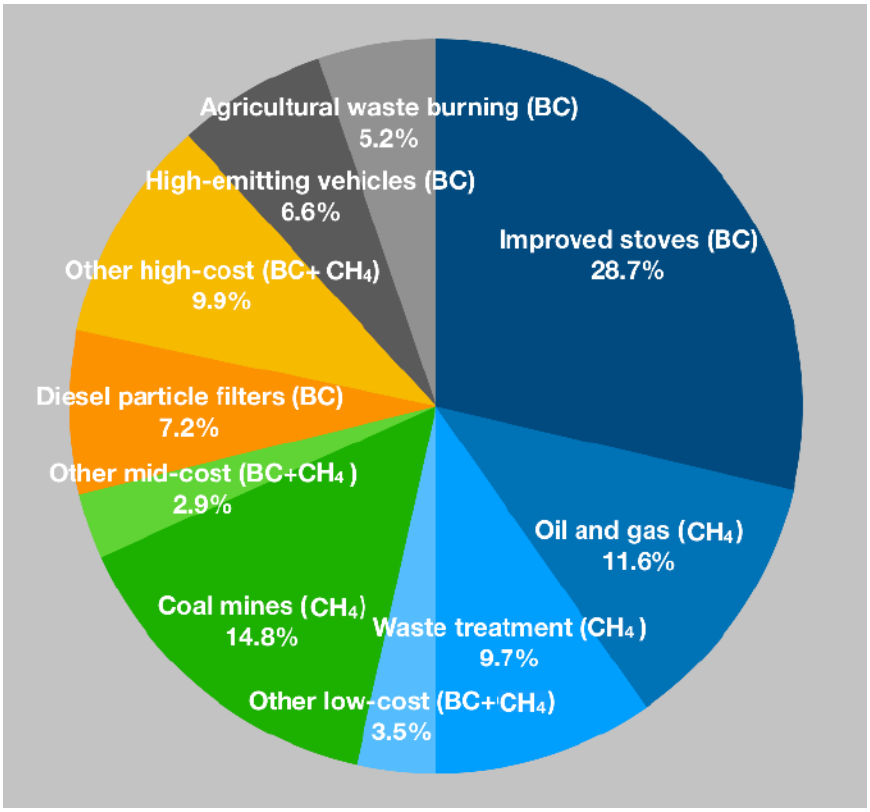

FIGURE 15.1.2 **Black carbon and methane mitigation measures. Numbers indicate the share of warming reduction from each measure as a percentage of the total warming reduction for all 16 measures in the 2011 UNEP report. Labels indicate whether the measure targets black carbon (BC) or methane (CH_4). Colors indicate the cost grouping: blue indicates minimal cost or cost savings; green indicates moderate costs; orange or yellow indicates high costs; gray indicates costs that are difficult to quantify.** Data from UNEP and WMO 2011.

Climate and Clean Air Coalition, formed in 2012 by the United Nations to focus on SLCP mitigation, already has 61 member nations working together to mitigate SLCPs (Box 15.1.1).

Economic costs and benefits of SLCP mitigation

To date, there are only limited studies on the costs and benefits of measures to reduce SLCPs. However, studies that account for co-benefits such as human health improvements and the gains from reduced crop loss, as well as the avoidance of damage that would otherwise result

from warming, show a clear net societal benefit from SLCP mitigation measures. Furthermore, off-the-shelf technologies exist for mitigating most of these emissions.

For black carbon and methane, a comprehensive cost analysis was provided by the 2011 UNEP study that was highlighted in the Overview. That study, which identified the 16 key measures for black carbon and methane mitigation discussed in Figure 15.2, also classified these measures into four groups: measures with minimal costs or that yielded cost savings; measures with moderate costs; measures with high costs; and measures whose costs are difficult to quantify because they depend in part on improved governance mechanisms in developing countries. Figure 15.1.2 summarizes these results for the top 16 measures recommended in the UNEP report. Notice that over half of these measures can be accomplished with minimal costs or cost savings; however, most of these measures have up-front costs for their initial implementation, with the savings realized over many years and not always by those paying the up-front cost. It's also important to note that these cost estimates do not include savings due to improvements in human health or avoided crop damage. Even measures that are identified as high-cost could be adopted based on health or food security co-benefits. The European Union, for example, has implemented standards for diesel particle filters based primarily on health benefits from improved air quality.

For HFCs, the cost-benefit calculus is just as compelling as that for black carbon and methane. The companies that make refrigerants such as HFCs have learned how to profit from the switch to safer substitutes, without increasing the cost to consumers in any significant way. Indeed, when these companies lose the intellectual property protection for their chemicals, they welcome the transition so they can sell their newer substitutes. Moreover, under the Kigali Amendment to the Montreal Protocol, developed countries contribute to a dedicated funding mechanism that pays the incremental cost for developing countries to switch to safer substitutes. We'll be discussing the costs and benefits of HFC mitigation in more detail in Sections 15.5 and 15.6.

It is important to consider what weight should be given to such cost-benefit analyses when facing an existential threat from runaway climate change. Former California governor Jerry Brown has compared

the climate threat to the threat the US faced in World War II, when it is unlikely a cost-benefit approach was used to determine how the US should produce the needed war material. (Wagner and Weitzman's book *Climate Shock* explains why, in their view, a cost-benefit analysis shouldn't be used to determine how to address the existential threat of climate.) Even if a cost-benefit analysis isn't the most appropriate metric to evaluate climate solutions, however, the studies we've discussed show that the cost-benefit arguments for SLCP mitigation are quite compelling.

Box 15.1.1 Climate and Clean Air Coalition

The Climate and Clean Air Coalition (CCAC) is a global organization of governmental, nongovernmental, and intergovernmental entities that have committed to improving the air quality through actions that reduce short-lived climate pollutants (SLCPs), consistent with the recommendation in Solution #9 of reducing global methane emissions by up to 40% and black carbon emissions by up to 80%. The CCAC was launched in 2012 by the United Nations Environment Programme (UNEP) and six countries—Bangladesh, Canada, Ghana, Mexico, Sweden, and the United States. There are 61 state partners (nations) and 67 nonstate partners (such as international finance institutions, regional development banks, and city networks) at the time of this writing. In 2015, CCAC countries contributed about 40% of global black carbon emissions, and CCAC countries could supply about 50% of total mitigation by 2030.

The CCAC's activities target the main sectors responsible for SLCP emissions: cooking and heating, industry, transport, agriculture, fossil fuels, waste management, refrigeration, and cooling. The CCAC is currently focused on 11 initiatives. Seven are sector-specific initiatives that include diesel, oil and gas, waste, bricks, HFCs, household energy, and agriculture. The remaining four, which include supporting national action and planning, assessments, finance, and health, cut across sector lines to reduce emissions for all SLCPs.

http://ccacoalition.org/en/content/who-we-are.

Moving toward SLCP mitigation

Given the clear net benefits, why have nations not aggressively promoted SLCP mitigation so far? There are several reasons:

- Perhaps the most important reason is that the combined climate, health, and food security benefits of SLCP mitigation have only been recognized since about 2010. While the scientific study of SLCPs is at least 40 years old, scientists studying the health effects of SLCPs as air pollutants were working separately from the scientists studying SLCPs' climate impacts. The vital role that SLCP mitigation can play in bending the warming curve has only begun to catch the attention of climate scientists in the last 10 years.
- Cost-benefit studies that show the combined societal benefits of SLCP mitigation—from reduced warming together with health and food security benefits—have only become available in recent years.
- Until around 2010, the attention of climate scientists, activists, and policymakers was focused primarily on CO_2 emissions. There was concern that a sudden shift in focus to SLCPs would create the impression that action on CO_2 mitigation could be delayed or avoided, presenting a "moral hazard."
- In all areas of environmental science, there is a time lag between scientific findings and policy response.

However, significant progress in SLCP mitigation is now underway. The Climate and Clean Air Coalition (http://ccacoalition.org/en, described in Box 15.1.1) coordinates policies and practices at the international level. In the US, the State of California has enacted legislation to drastically cut emissions of SLCPs. In addition, the United States Climate Alliance, which includes governors whose states represent 40% of the US population, is aggressively pursuing SLCP mitigation and has developed a detailed road map for reducing emissions.

15.2 Mitigating Black Carbon

Black carbon, a major component of soot, consists of small particles of carbon that are mainly produced by incomplete combustion of fossil fuels or biomass, such as wood or other organic materials. These particles are classified as **aerosols** because they are light enough to remain in the atmosphere for anywhere from several hours to a few weeks.

Black carbon impacts

While many aerosols reflect solar radiation (sunlight) and have a cooling effect, black carbon absorbs sunlight and radiates infrared heat, significantly contributing to the anthropogenic greenhouse effect. Black carbon is estimated to be the second or third most important warming agent behind CO_2, with an impact comparable to that of methane.

Black carbon has additional negative impacts beyond its direct warming effect. In particular, when black carbon particles "rain out" of the atmosphere, some land on surfaces covered with snow or ice. There, the dark particles absorb sunlight, reducing the reflectivity of these surfaces and accelerating melting of snow, ice, and underlying permafrost. This in turn amplifies warming, particularly in the Arctic. It's estimated that implementing the black carbon and methane mitigation measures discussed in this chaper could reduce Arctic warming between 2005 and 2040 by nearly two-thirds, compared with a business-as-usual scenario.

Moreover, black carbon has serious negative impacts on air quality and human health. Black carbon particles are classified as **$PM_{2.5}$,** which refers to particles that are less than 2.5 micrometers in size (*PM* stands for "particulate matter"). A micrometer is one-thousandth of a millimeter. (For comparison, most bacteria are between half a micrometer and 5 micrometers long, so we're considering particles that are quite small indeed.)

Because they are so small, $PM_{2.5}$ particles like black carbon can be

inhaled deep into the lungs, where they are difficult to dislodge, and even into the bloodstream. This results in significant negative impacts on human health, including premature deaths from lung cancer and heart disease. A recent study by UNEP estimated that measures to reduce black carbon could avoid 2.4 million premature deaths annually by 2030 (within a range of 0.7 to 4.6 million annual deaths).

Black carbon sources

In combustion (burning), carbon-rich molecules such as those in plant matter or fossil fuels combine with oxygen to produce carbon dioxide and water vapor. In actual combustion, not all of the carbon is converted to carbon dioxide. Some of it remains in complex interlinked molecules that form black carbon aerosols. Major sources of black carbon pollution include a variety of types of combustion, as detailed in Figure 15.2.1. The largest category is residential and commercial combustion. About 75% of this is from cooking with solid fuels (coal, firewood, and dung) by the world's poorest 3 billion. The next largest source is transport, with more than 90% of the emissions due to diesel vehicles. Next is industrial processes (8%) where solid fuels are used for combustion in boilers, kilns, and furnaces. Agriculture contributes 7% of black carbon emissions, mainly through burning of agriculture residues and waste.

Fortunately, a range of policy measures and off-the-shelf technologies are already available to address many of the major sources of black carbon, as we'll see in the next section.

Black carbon mitigation

Table 15.2.1 summarizes the nine most important black carbon mitigation measures, as identified by UNEP in 2011. In this section, we will highlight a few of these key measures.

As shown in Figure 15.2.1, the largest single source of black carbon is residential and commercial combustion, and this is primarily for heating and cooking of food. In particular, cooking with traditional, inefficient stoves fueled by wood, dung, or agricultural waste (Figure 15.2.2) is a major source of black carbon emissions worldwide, second only to burning of biomass. Household members, mostly women, must in many cases walk several kilometers each day to obtain firewood and

TABLE 15.2.1 Black carbon mitigation measures affecting BC and other co-emitted compounds

Sector	*Measure*
Transport	Diesel particle filters for road and off-road vehicles
	Elimination of high-emitting vehicles in road and off-road transport
Residential	Replacement of coal by coal briquettes in cooking and heating stoves
	Pellet stoves and boilers, using fuel made from recycled wood waste or sawdust, to replace current wood-burning technologies in the residential sector in industrialized countries
	Introduction of clean-burning biomass stoves for cooking and heating in developing countries
	Substitution of clean-burning cookstoves using modern fuels for traditional biomass cookstoves in developing countries
Industry	Replacement of traditional brick kilns with vertical shaft kilns and Hoffman kilns
	Replacement of traditional coke ovens with modern recovery ovens
Agriculture	Ban on open field burning of agricultural waste

SOURCE: Adapted from United Nations Environment Programme and World Meteorological Organization. 2011. *Integrated Assessment of Black Carbon and Tropospheric Ozone*. UNEP, Nairobi, Kenya.

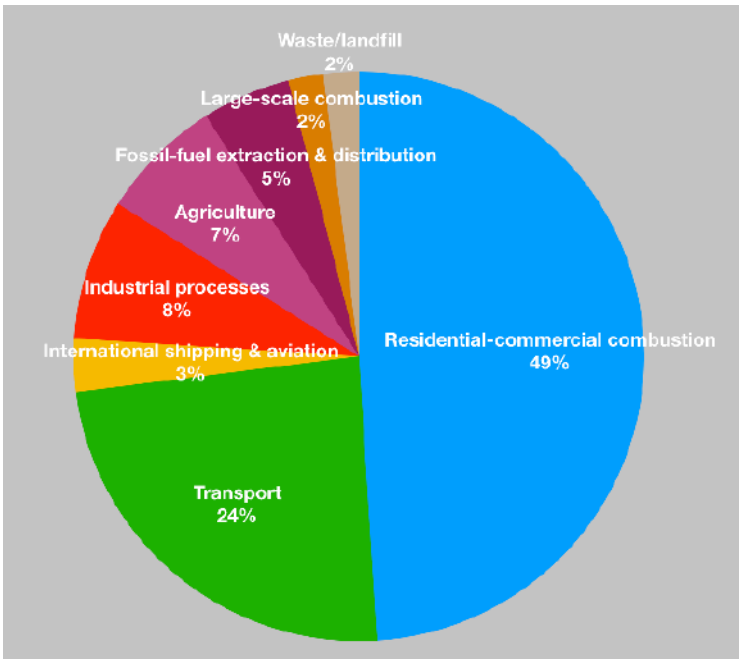

FIGURE 15.2.1 Black carbon percentage contribution from various sources, 2005. Data from UNEP and WMO 2011.

FIGURE 15.2.2 Woman cooking in Mukteshwar, Indian Himalayas, India.
Photograph by V. Ramanathan.

are exposed to high levels of indoor particulates while cooking. Indoor air pollution is estimated to cause about 3 million premature deaths each year.

Pollution from cooking stoves is a particularly acute problem for the 3 billion global poor, many of whom lack the infrastructure and financial resources for gas or other fossil fuel stoves. An estimated 38% of households worldwide lack access to efficient, low-emission cook-stoves, particularly in developing regions of Asia and sub-Saharan Africa.

Replacing biomass fuels such as wood or dung with fuels such as liquified petroleum gas or kerosene can significantly reduce black carbon emissions, but this is only possible in areas with developed fossil fuel and transportation infrastructures. In less-developed areas, inefficient traditional cooking methods can be replaced by cleaner forced-draft biomass stoves, which use a small fan to increase oxygen flow, promoting more efficient and complete combustion and cutting black carbon emissions by 80%. Because the stoves require less fuel, they can also cut

CO_2 emissions by 50%. This is a win-win solution that not only reduces global emissions but provides a significant improvement in quality of life.

Improving stoves is the single most effective SLCP mitigation measure and actually saves money over the long run in reduced fuel costs. Considering the benefits, why haven't these stoves been more widely adopted? Paradoxically, one obstacle is the initial cost to buy a stove, which may be moderate by the standards of developed nations but can amount to a month's earnings or more for a low-income household. However, each stove is estimated to reduce warming emissions by the equivalent of 5.3 tons of CO_2 per year.

Compensating householders for these reduced emissions based on a reasonable carbon price is one way to pay back the cost of the stove and even provide a small income stream. This kind of bottom-up mechanism that directly rewards individuals for their actions to protect climate may prove to be a key strategy for reducing SLCPs and is the approach taken by Project Surya (www.projectsurya.org). Other pilot programs to promote and fund wider use of clean cookstoves are also underway, under the auspices of organizations such as the Climate and Clean Air Coalition (Box 15.1.1) and the Clean Cooking Alliance (cleancookingalliance.org).

In the transportation sector, a variety of measures are also available to mitigate black carbon emissions. Diesel engines in particular emit much higher levels of black carbon than gasoline engines. However, diesel particle filters are available that can eliminate up to 95% of black carbon particulate emissions from each vehicle. Cities, states, and regions around the world, including Santiago (Chile) and New York City, have implemented regulations requiring the use of diesel particle filters. The State of California requires particulate filters for commercial vehicles such as heavy-duty trucks, and the European Union has required filters on all new diesel engines since 2009.

In addition to capturing diesel particles with filters, reductions in black carbon and other emissions from vehicles can be achieved through many of the same transportation measures discussed in Chapter 14. More fuel-efficient vehicle use, electrification of transportation systems (including use of hydrogen cells in larger trucks), smart transportation

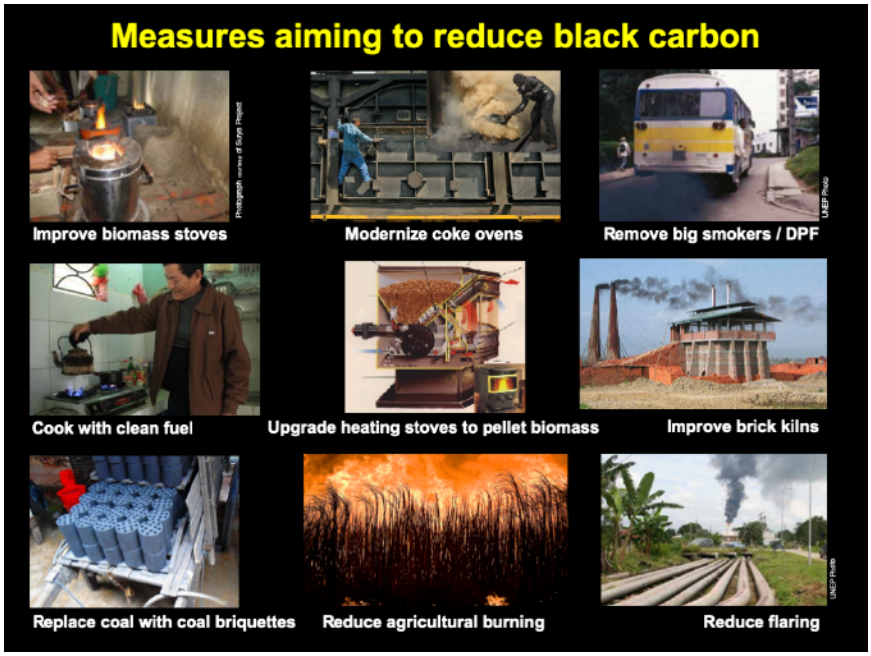

FIGURE 15.2.3 Nine measures that aim to reduce black carbon emissions. Reproduced with permission from Climate and Clean Air Coalition; data from UNEP and WMO 2011.

systems, and reduction of vehicle miles traveled all reduce total emissions of black carbon as well as CO_2.

Elimination of the most heavily polluting vehicles, mostly older vehicles with poor emission controls, is another effective measure to reduce black carbon emissions from transportation. However, this can be difficult to implement in countries with weak governance and inadequate enforcement systems.

Policies to reduce or ban agricultural waste burning can also contribute to black carbon mitigation. Such policies have already been enacted in the European Union and California. By requiring diesel particle filters and phasing out agricultural waste burning, the State of California succeeded in reducing black carbon concentrations by 50% between 1990 and 2010.

Figure 15.2.3 displays some of the measures that are currently available to mitigate black carbon emissions.

15.3 Mitigating Methane

Methane (chemical formula CH_4) is a particularly important warming agent because it affects global temperatures in four different ways. First, it is a powerful greenhouse gas in its own right, with a warming effect that is 30 times more powerful than carbon dioxide over 100 years and more than 85 times more powerful over 20 years. Second, although methane has a relatively short lifetime in the atmosphere (about 12 years), it decomposes to carbon dioxide, a significant fraction of which will remain for hundreds to thousands of years. Third, methane can react with other chemicals to produce ozone, which is also a significant greenhouse gas. Finally, methane in the upper atmosphere can react with hydrogen to produce water vapor, yet another greenhouse gas.

Because of this "quadruple threat," methane mitigation can have a significant impact in bending the warming curve. Due to its short atmospheric lifetime, the benefits of methane reduction will begin to appear relatively quickly, within a decade or two.

Studies indicate that full implementation of the methane mitigation strategies discussed in this section could bend the global warming curve by 0.4°C by 2050. Moreover, implementing *both* the methane and black carbon mitigation measures discussed in the previous section could save over 2 million lives, 50 million tons of crops, and $5 trillion annually by 2050.

Sources of methane

Data from ice cores show that methane concentrations in the atmosphere were relatively steady for the past few thousand years but began to increase dramatically around the beginning of the Industrial Revolution, rising from just over 700 parts per billion (ppb) in the preindustrial era to more than 1,800 ppb today. Studies have confirmed that this rise is primarily due to human activities. The primary anthropogenic sources of methane are shown in Figure 15.3.1.

One major source of emissions is the exploitation of fossil fuels. The same geologic processes that produce coal and oil also generate methane, which is often found in association with coal beds and oil fields. Natural gas is primarily composed of methane (around 90%). Anthropogenic methane emissions associated with fossil fuel extraction and use include the following:

- Methane leaks from natural gas production, processing, and pipeline distribution systems (sometimes called "fugitive emissions")
- Methane escape during completion of oil wells and oil production
- Methane leaks from active and inactive coal mines

A second source of methane is bacterial decay of organic matter in the absence of oxygen. This occurs in underwater or underground environments such as wetlands, swamps, or landfills and is referred to as **anaerobic decomposition**. Bacteria in the digestive tracts of livestock can also produce methane through a process known as **enteric fermentation**. Anthropogenic sources of methane from anaerobic decomposition and fermentation include the following:

- **Livestock**—before digesting their food, ruminants such as cattle, goats, and sheep ferment the plant material they eat in a specialized stomach (called a rumen). This enteric fermentation process produces significant quantities of methane.
- **Manure**—decomposition of waste from livestock and poultry releases methane.
- **Wet rice agriculture**—flooded rice fields create anaerobic conditions similar to those in a natural wetland.
- **Waste**—decomposition of organic food waste in landfills and human waste in wastewater systems produces methane.

Methane mitigation strategies

As in the case of black carbon, there is a range of technologies already available to reduce anthropogenic methane emissions. Many of these technologies involve capturing methane and burning it for heat or electric power generation. Although burning methane converts it to carbon

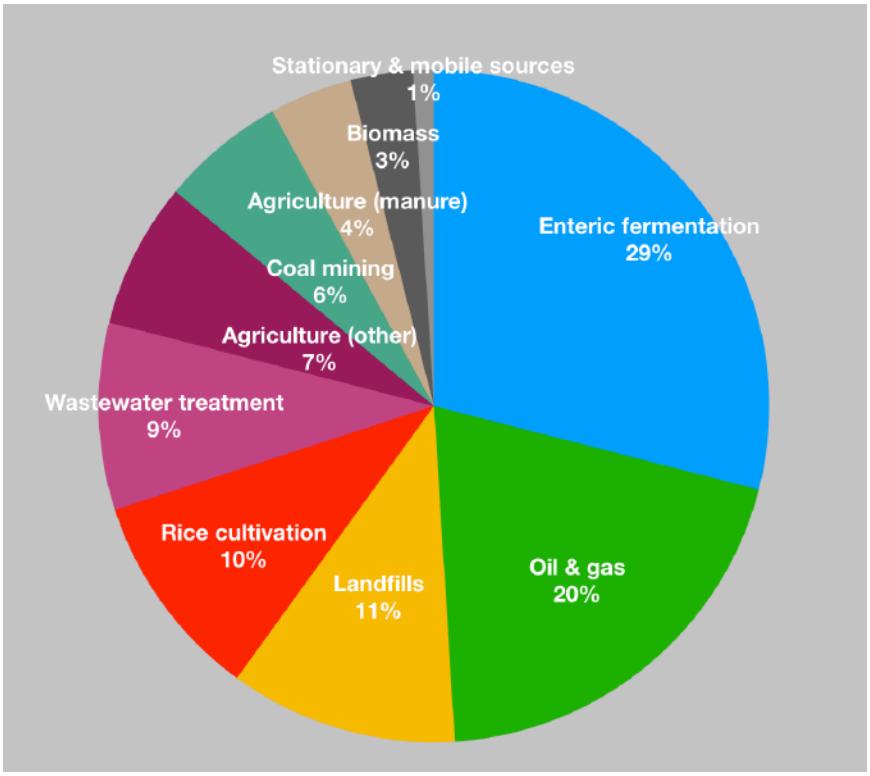

FIGURE 15.3.1 Methane percentage contribution from various sources, 2010. Global annual methane emissions are in the range of 558 million to 736 million metric tons CH_4 per year from the 2003–2012 decade. (Data for this range are from Saunois et al. 2016.) Adapted from the Global Methane Initiative.

dioxide, this significantly reduces its warming effect, since CO_2 is a much less potent greenhouse gas.

Methane seeps naturally from coal beds. Coal mines create openings that allow the methane to escape into the atmosphere. Both active and abandoned coal mines are significant sources, but **degasification pump stations** have proven effective in removing and collecting methane. Coal mines are not usually near natural gas distribution facilities, so the methane captured is typically burned on-site and could be used for heating or generating electricity.

Oil drilling often brings natural gas to the surface along with the oil, and the gas must be vented to the atmosphere to maintain safe pressure in the well. Sometimes this gas can be stored and sold, but where gas distribution facilities are not available nearby, it is often released to the

FIGURE 15.3.2 To the naked eye, no emissions from an oil storage tank are visible (left), but with the aid of an infrared camera, escaping methane is evident (right). Reproduced with permission from UNEP and WMO 2011.

atmosphere. Burning the methane instead (this is referred to as flaring) would significantly reduce its greenhouse effect. The mitigation effect could be further enhanced by capturing the resulting CO_2, which can be pumped back into the ground and stored or pumped into a depleted oil field to enhance oil recovery (which, of course, will produce still more oil).

Leaks in the natural gas production and distribution system should be relatively straightforward to address. Loss of gas from the system represents a loss of profits, and significant leaks can present a safety risk. Companies involved with natural gas production, storage, and distribution are generally motivated to locate and address leaks. A wide range of portable **methane detectors** are now available to help with this task (Figure 15.3.2).

The Oil and Gas Climate Initiative (OGCI), which includes several of the world's largest oil and gas producers, has set a target of reducing the methane intensity of its member companies by 20% by 2025, a very modest goal but a start nonetheless. In contrast, the International Energy Agency estimates that the oil and gas industry can reduce its worldwide methane emissions by 75%—and up to two-thirds of those reductions can be realized at zero net cost.

Methane emissions associated with oil and gas extraction are an important consideration in evaluating the impacts of hydraulic fracturing (often called hydrofracking, or fracking for short). In the United States, hydrofracking over the past decade or so has significantly reduced the cost of natural gas, resulting in a significant shift from coal to oil in

TABLE 15.3.1 Methane mitigation measures

Sector	*CH_4 Mitigation Measures*
Extraction and transport of fossil fuel	Extended pre-mine degasification and recovery and oxidation of CH_4 from ventilation air from coal mines
	Extended recovery and utilization, rather than venting, of associated gas and improved control of unintended fugitive emissions from the production of oil and natural gas
	Reduced gas leakage from long-distance transmission pipelines
Waste management	Separation and treatment of biodegradable municipal waste through recycling, composting, and anaerobic digestion as well as landfill gas collection with combustion/utilization
	Upgrading primary wastewater treatment to secondary/tertiary treatment with gas recovery and overflow control
Agriculture	Control of CH_4 emissions from livestock, mainly through farm-scale anaerobic digestion of manure from cattle and pigs
	Intermittent aeration of continuously flooded rice paddies

SOURCE: Reproduced with permission from United Nations Environment Programme and World Meteorological Organization. 2011. *Integrated Assessment of Black Carbon and Tropospheric Ozone*. UNEP, Nairobi, Kenya.

electric power production. Because natural gas emits only about half as much CO_2 per unit of energy produced compared with coal, this shift could significantly reduce greenhouse gas emissions associated with electricity generation. However, the leakage of as little as 3% of the methane during well completion or production could reduce or even negate the climate benefits of reduced CO_2 emissions and be as greenhouse-gas intensive as burning coal. Studies by different groups have resulted in published estimates of methane leakage rates of between 1.4% and 2.3% of production industry-wide, but emissions from individual facilities can be significantly higher. The extent of methane emissions from hydrofracking is currently a topic of serious scrutiny.

About 10% of anthropogenic emissions are due to wet rice agriculture, in which rice is grown in flooded fields. Studies have shown that periodic short-term draining of the rice fields to expose the soil to oxygen, known as **intermittent aeration**, can significantly reduce methane emissions.

Methane emissions from livestock and poultry manure can be

addressed using covered **anaerobic digesters**, which accelerate the decomposition process and capture the resulting methane, rather than allowing it to escape to the atmosphere. Burning the methane can generate heat or electricity for on-farm use or for sale. California agencies are funding pilot projects to demonstrate the collection and concentration of methane from dairy digesters for injection into natural gas pipelines. Industrial-scale hog farms, meanwhile, are expanding their efforts to reduce methane—partly because such efforts often yield co-benefits in terms of a reduction in offensive odors—after being sued dozens of times and being required to pay neighbors damages for the offensive odor. In a recent North Carolina lawsuit against the largest pork and hog producer, Smithfield Foods, a jury awarded $473.5 million in damages, reduced to $94 million by a North Carolina law capping punitive damages.

Similar to degasification pumps for coal mines, **landfill gas wells** can capture methane from landfills to be burned for heat or energy. Wastewater can undergo **anaerobic wastewater treatment** with installations

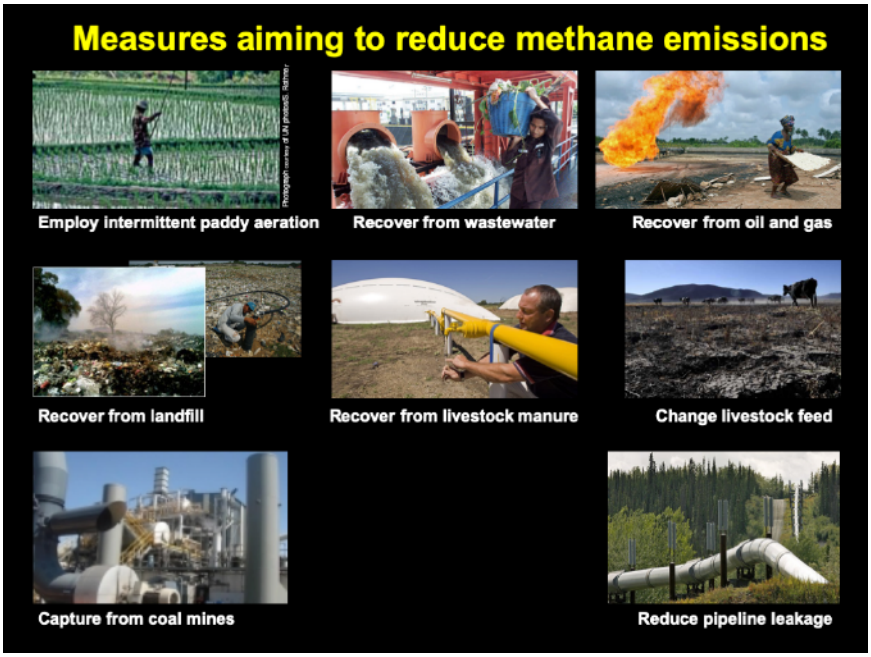

FIGURE 15.3.3 Seven measures that aim to reduce methane emissions. Reproduced by permission from Climate and Clean Air Coalition; data from UNEP and WMO 2011.

that use technology similar to anaerobic digesters, but typically on a larger scale, with the methane captured and used for energy.

Although this chapter focuses primarily on technological mechanisms to remove methane, there are other mitigation strategies that involve societal transformations or changes in ecosystem management. For example, a reduction in meat consumption, particularly lamb and beef, would reduce the associated methane. Similarly, we'll see in the next chapter how reducing food waste could substantially lower methane emissions from landfills as well as the CO_2 emissions associated with the energy required for food production, transportation, and storage.

Table 15.3.1 and Figure 15.3.3 summarize measures that aim to reduce methane emissions.

15.4 Mitigating Tropospheric Ozone

Ozone (chemical formula O_3) has very different impacts, depending on where it is found in the atmosphere. **Stratospheric ozone**, produced naturally in the upper atmosphere through a reaction between oxygen molecules and solar ultraviolet radiation, is vital to human health and indeed to the existence of life on the Earth's land surfaces. The stratospheric ozone layer, at a height of roughly 20 to 30 km, absorbs ultraviolet radiation that would otherwise be damaging or even fatal to life on land. In Section 15.6, we'll see how the Montreal Protocol (1987) led to the phasing out of chemicals that damage the ozone layer.

While ozone in the stratosphere is beneficial to life, ozone near the Earth's surface, called **tropospheric ozone**, has serious negative effects on both human health and agricultural crop yields. It is also a significant greenhouse gas.

As discussed in the Overview, human activities aren't responsible for the direct emission of ozone. However, they do generate a range of **precursor gases** that can react in the presence of sunlight to form ozone. Methane is a key ozone precursor. Other precursor gases include nitrogen oxides (often referred to as NO_x), carbon monoxide, and volatile organic compounds (VOCs). NO_x and carbon monoxide are generated by combustion of fossil fuels in power plants, industrial processes, and vehicle engines. During combustion, NO_x is formed through the reaction of nitrogen and oxygen at high temperatures, and carbon monoxide is formed by incomplete fuel combustion. VOCs represent a whole range of carbon-based molecules, including gasoline, benzene, solvents, and other industrial and household chemicals. Ozone formed by reactions between NO_x and VOCs is a major component of photochemical smog in urban areas.

Catalytic converters are designed to significantly reduce vehicle emissions of NO_x, carbon monoxide, and VOCs. Air quality regulations, including requirements to equip cars with catalytic converters,

have significantly reduced ozone levels in Los Angeles and other urban areas. As discussed in previous chapters, measures to replace fossil-fuel-powered internal combustion engines with electric motors, powered by batteries or fuel cells, would also significantly reduce emissions of ozone precursors. While such measures reduce ozone pollution regionally, they have a relatively small impact on ozone on a global scale.

In contrast, methane reduction has significant potential to reduce tropospheric ozone and its warming impact on a global scale. Since methane is a major ozone precursor, the methane reduction strategies discussed in Section 15.3 are also effective ozone mitigation measures.

Mitigating tropospheric ozone would have significant health and agricultural co-benefits. Ozone can promote asthma attacks and cause respiratory irritation, particularly in children, older adults, and those with existing respiratory conditions such as bronchitis and emphysema. Long-term exposure to ozone can cause permanent inflammation and scarring of the lungs, resulting in respiratory illnesses and premature deaths.

Ozone pollution is a dominant destroyer of agricultural crops. Ozone pollution is estimated to result in the loss of more than 110 million metric tons of crops per year, and it is responsible for 39% of crop losses in North America and 37% of losses in Asia. A UNEP study focused on the world's four main staple crops (maize, rice, soybeans, and wheat) showed that full implementation of the methane reduction measures outlined above would also reduce ozone, avoiding 25 million metric tons of crop losses each year, relative to a scenario of unmitigated emissions; implementing black carbon reduction measures along with methane mitigation could double that figure to 50 million metric tons.

15.5 Mitigating Hydrofluorocarbons (HFCs)

Hydrofluorocarbons (HFCs) are factory-made gases that are SLCPs with comparatively short lifetimes in the atmosphere. They are super climate pollutants with high global warming potentials. They were invented as substitutes for chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs), two groups of chemicals that destroyed the protective stratospheric ozone layer *and* warmed the climate. CFCs were phased out under the 1987 Montreal Protocol on Substances that Deplete the Ozone Layer, and HCFCs are currently being phased out under that treaty. The phaseout of these and related chemicals under the Montreal Protocol has put the stratospheric ozone layer on the path to recovery, with noticeable improvements to the ozone layer expected by the 2030s and closing of the Antarctic ozone hole expected by 2060.

While they do not destroy stratospheric ozone as the CFCs and HCFCs they replaced did, HFCs are the fastest-growing climate pollutant in many countries, and many HFCs have high global warming potentials (GWPs). Because of the climate risk posed by the fast-growing HFCs, a small group of countries began an 8-year effort to phase down HFCs under the Montreal Protocol, culminating in the Kigali Amendment in October 2016, which will take the single biggest bite out of the climate problem so far. Phasing down HFCs has the potential to avoid up to 0.5°C of warming by 2100, and the initial phasedown schedule of the Kigali Amendment will deliver 80%. Getting the remaining 20% will require speeding up the schedule or otherwise encouraging countries to avoid moving into HFCs during their current phaseout of HCFCs—a leapfrog strategy whereby countries move directly into climate friendly substitutes. (Unlike the earlier phaseouts, the Kigali Amendment is a phasedown because some HFCs have very low GWPs; for example, HFC-1234yf, a refrigerant used in mobile air conditioners, has a GWP of only 1.)

TABLE 15.5.1 The most commonly used HFCs according to Montzka et al. 2015, with GWPs and lifetimes from the IPCC Fifth Assessment Report

HFC	*GWP (100-Year)*	*Lifetime (Years)*
HFC-134a	1,300	13.4
HFC-152a	138	1.5
HFC-143a	4,800	47.1
HFC-125	3,170	28.2
HFC-32	677	5.2
HFC-227ea	3,350	38.2
HFC-365mfc	804	8.7

SOURCE: Montzka, S. A., et al. 2015. Recent trends in global emissions of hydrochlorofluorocarbons and hydrofluorocarbons: reflecting on the 2007 adjustments to the Montreal Protocol. *Journal of Physical Chemistry* 119, 4439–4449; IPCC. 2013. *Climate Change 2013: The Physical Science Basis.* Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T. F., et al. (eds.)]. Cambridge University Press, New York, NY.

HFC impacts

HFCs were developed in the 1990s and started to replace CFCs and HCFCs in refrigerators, air conditioners, insulating foams, and other uses. As noted, HFCs are the fastest-growing climate pollutant in many countries, and while their climate impact in 2010 was relatively small, they were projected to increase 30-fold by 2050 if not mitigated through the measures discussed in this section.

The average lifetime of HFCs currently in use is 15 years, but their high GWPs (some are almost 5,000 times more potent than CO_2) mean they have a large impact on the climate in that short time. Unchecked, annual HFC emissions could have the global warming equivalent of 12% of annual CO_2 emissions in 2050 under a business-as-usual scenario, and up to 71% under the strongest of IPCC mitigation scenarios. Additionally, continued manufacture of appliances and foams that utilize HFCs will lead to storage of these pollutants in what are called HFC banks, which will emit HFCs as the products are discarded and will contribute to further warming.

HFC sources

HFCs are used in refrigeration, air conditioning, thermal insulating foam blowing, aerosol sprays, fire protection, and solvents. As an example, in

the United States, air conditioning and refrigeration make up 86% of the country's HFC emissions; this includes commercial refrigeration, mobile air conditioning in cars and other vehicles, and stationary air conditioning in homes, offices, and other buildings. The remaining emissions come from residential and industrial refrigeration, transport refrigeration, aerosol propellants, and solvents.

At what point during their life cycle HFCs are emitted depends on how they are being used. For aerosols and solvents, HFCs are emitted while in use. For foams, HFCs are emitted during the manufacturing process, when they leak out of foam in use as building insulation (off-gas), and when the foam is crushed for disposal later or when it is otherwise damaged. For HFCs used in refrigerators and air conditioners, emissions occur throughout a product's lifetime, including during manufacture, while the appliance is in use, during servicing, and at the end of the appliance's life.

HFC mitigation

Many developed countries have already begun the transition to low-GWP HFCs and non-HFC alternatives, and as developing countries move away from HCFCs, they can leapfrog HFCs to the more climate-friendly alternatives to maximize climate benefits. This leapfrog strategy also helps avoid the buildup of the banks of HFCs in air conditioners, foams, and other products, with the potential to avoid another 53 gigatons of CO_2 equivalent (CO_2eq) between 2020 and 2060.

Alternatives to high-GWP HFCs are readily available for most uses, ensuring a smooth transition (Table 15.5.2). Alternatives include low-GWP HFCs like R-32 with a GWP of 660 and extremely low-GWP HFCs sometimes called hydrofluoroolefins (HFOs), natural refrigerants, and not-in-kind alternatives. For example, HFC-134a, with a GWP of 1,300, has been the most commonly used refrigerant in mobile air conditioners and is quickly being replaced in developed countries by HFO-1234yf, with a GWP of less than 1.

Natural refrigerants include ammonia (GWP near 0), hydrocarbons like propane and isobutene (GWPs less than 5), and CO_2 (GWP of 1). Commercial refrigeration has moved to these low-GWP alternatives, with up to 65% of new installations already using them. Domestic

TABLE 15.5.2 Indicative list of low-GWP alternatives to high-GWP HFCs

Application	*Current Refrigerant*	*GWP*	*Alternative*	*GWP*
Refrigeration (domestic)	HFC-134a	1,300	HC-600 (isobutene)	~3
	HFC-152a	138	HC-290 (propane)	<5
			HFO-1234yf	<1
Refrigeration (commercial & industrial)	HCFC-22	1,760	HC-600 (isobutene)	~3
	HFC-407C	1,774	R-744 (CO_2)	1
	HFC-134a	1,300	R-717 (ammonia)	0
	HFC-404a	3,943	HFCs and HFC blends	<1–1,600
Air conditioners (room)	HFC-410A	1,923	HC-290 (propane)	<5
	HCFC-22	1,760	HFC-32	677
	HFC-407C	1,774	HFC/HFC blends emerging	~350
Air conditioners (commercial)	HFC-134a	1,300	HFO-1233zd	<1
	HCFC-22	1,760	HFO-1234ze	<1
	HCFC-123	79	HFC/HFC blends emerging	400–500
			HFO-1234yf	<1
Mobile air conditioners	HFC-134a	1,300	HFO-1234yf	<1
			HFC-152a	138
			R-744 (CO_2)	1
			R-290 (propane)	<5
Foams	HFC-227ea	3,220	HCs	<5
	HCFC-142b	1,980	CO_2/water	1
	HFC-245fa	1,030	HFO-1234ze	<1
	HCFC-22	1,810	Methyl formate	<25
	HFC-134a	1,300	HFO-1336mzz-Z	2

refrigeration could see about 75% of production using natural refrigerants by 2020. Some room air conditioners are also using hydrocarbons as alternatives, although such natural refrigerants tend to be more flammable, which presents safety concerns and in some circumstances limits their use to smaller appliances. Not-in-kind alternatives include methods

of cooling that do not involve chemical refrigerants, such as improving building insulation and implementing reflective roofs.

The mandated transitions of refrigerants from CFCs to HCFCs and then to HFCs catalyzed energy efficiency improvement of the cooling equipment, and the Kigali Amendment's mandated transition from HFCs to more climate-friendly alternatives presents another opportunity to further improve efficiency. When selecting among alternatives, it is important to consider energy efficiency, as the electricity used to run cooling equipment can be up to 90% of the total carbon footprint when fossil fuel is the source of the electricity. It also is important to consider safety issues, like the flammability associated with natural refrigerants.

Even before the Kigali Amendment was agreed, some leading countries began taking steps to phase down HFCs, including economic and market-based incentives, required practices, import/export licensing, reporting requirements, and taxes and fees. For example, the US has a number of regulations relating to HFCs, curtailing the applications where they may be used. The EU has regulated HFCs for over a decade, strengthening the regulations over time to more aggressively phase down HFCs. Norway instituted a tax-and-refund scheme where a tax was levied on the import of HFCs but was refunded upon proper disposal of the refrigerant. In the US, some states, including California, also restrict HFC use.

15.6 Mitigating HFCs: The Kigali Amendment to the Montreal Protocol

The Kigali Amendment to the Montreal Protocol was adopted in October 2016 and entered into force on January 1, 2019. It has the potential to avoid up to 0.5°C of future warming by 2100, assuming fast ratification and implementation. The Montreal Protocol is widely considered the world's best environmental treaty for successfully solving the first great threat to the global atmosphere—the destruction of the stratospheric ozone layer by CFCs and related chemicals. Its success over more than three decades has prevented an increase in ultraviolet (UV) radiation that otherwise would have led to increased cancers, cataracts, immune suppression, and other problems. At the same time, that treaty has provided more climate mitigation than any other agreement because CFCs and HCFCs are also powerful greenhouse gases; in 2014, *The Economist* ranked the Montreal Protocol as the top of all major measures to reduce climate change. It also is the only international treaty with universal membership of all UN countries, and their membership makes them "Parties" to the treaty. Under the Kigali Amendment, the treaty now mandates the phasedown of HFCs. In 2017, Project Drawdown, a comprehensive analysis of climate solutions, ranked the HFC refrigerant transition as the top solution of 100 solutions to reverse global warming.

History of the Montreal Protocol and stratospheric ozone protection

In 1974, Mario Molina and F. Sherwood Rowland, scientists at UC Irvine, published a study in *Nature* that described the risk to stratospheric ozone from CFCs. As these scientific findings were publicized, they led to consumer boycotts against products such as hair spray containing CFCs in the US, Canada, and Europe, which in turn helped pave the way for national and regional regulations to control CFCs.

But this was not enough to solve the problem and protect the

stratospheric ozone layer. In 1981, UNEP assembled a group of experts to discuss developing an international treaty for controlling CFCs. This led to the Montreal Protocol, which was adopted in 1987 and included a mandatory phaseout of CFCs and related gases, starting with a 50% reduction of production and use within 12 years. The treaty is successful because every country is on board and works toward common goals. The treaty has mandatory requirements to phase out the production and use of specific factory-made chemicals, by specific amounts, by specific dates. At the same time, the treaty implements the important principle of "common but differentiated responsibility," which in this case means that the developed-country Parties are required to phase out the damaging chemicals first and to develop safer alternatives and bring them to scale, which drives down the cost and demonstrates the best way to meet the treaty's obligations for the developing-country Parties. After a grace period of several years, developing-country Parties are required to start their own phaseouts.

The developed-country Parties also provide funding through the Multilateral Fund (MLF) for the Implementation of the Montreal Protocol, to pay the "agreed incremental costs" of the developing-country Parties in meeting their obligations. This funding is negotiated every 3 years and for 2018–2020 was US$500 million. Between 1991 and 2010, the MLF spent US$2.4 billion and achieved emissions reductions of approximately 188–222 gigatons of CO_2eq, which is equivalent to roughly $0.01 per ton of CO_2eq. The phasedown of HFCs may cost $0.22–$0.29 per metric ton of CO_2eq. On a consumer level, a new home air-conditioning system can cost anywhere from $6,000 to $12,000, but the lifetime savings from newer, more efficient refrigerants and equipment can significantly reduce energy consumption, which leads to a reduction in lifetime cost.

The Montreal Protocol is a "start-and-strengthen" treaty because it started modestly, learned by doing, helped the Parties to gain confidence that they could meet their obligations, and then strengthened the control measures time and again. Since its inception, the Montreal Protocol has been amended five times to add new chemicals and adjusted six times to speed up existing phaseouts. The Kigali Amendment of 2016 is the sixth amendment, which adds HFCs to the list of controlled

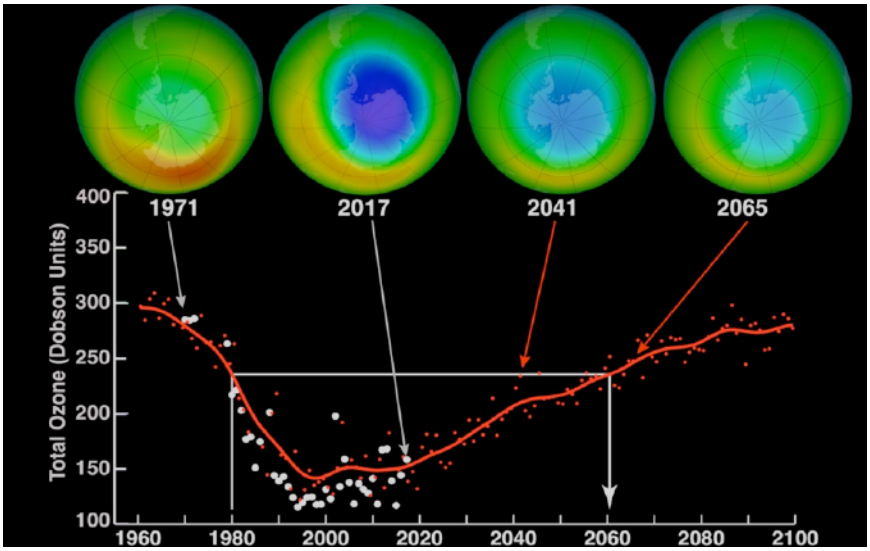

FIGURE 15.6.1 October average minimum ozone over Antarctica over time, measured in Dobson units, which are a measurement of total ozone in the atmosphere. "Since the mid-1990s, global ozone levels have become relatively stable. In fact, because of the Montreal Protocol, model simulations suggest the size of the hole should return to its pre-1980 levels by about 2075. Here, the four globes show monthly-averaged total ozone over Antarctica in October. The graph shows each year's October average minimum (white dots) over Antarctica. The red curve represents a smoothed version of the white dots." Reproduced from NASA's Goddard Space Flight Center.

substances and requires that they be phased down in the coming decades. We'll return to the Kigali Amendment shortly.

The Montreal Protocol has phased out roughly 100 chemicals by nearly 100%. Success of the Montreal Protocol has reduced exposure to UV radiation that otherwise would have led to skin cancer, eye damage and cataracts, and immune suppression. Without the Montreal Protocol, skin cancer would have quadrupled by 2100. The US Environmental Protection Agency (EPA) calculates "that full implementation of the Montreal Protocol is expected to result in the avoidance of more than 280 million cases of skin cancer, approximately 1.6 million skin cancer deaths, and more than 45 million cases of cataracts in the United States, resulting in hundreds of billions of dollars in societal health benefits in the United States over the period 1990 to 2165." The reductions of these cancers and cataract cases have been valued at more than 11 times the costs of phasing out CFCs and other ozone-depleting substances.

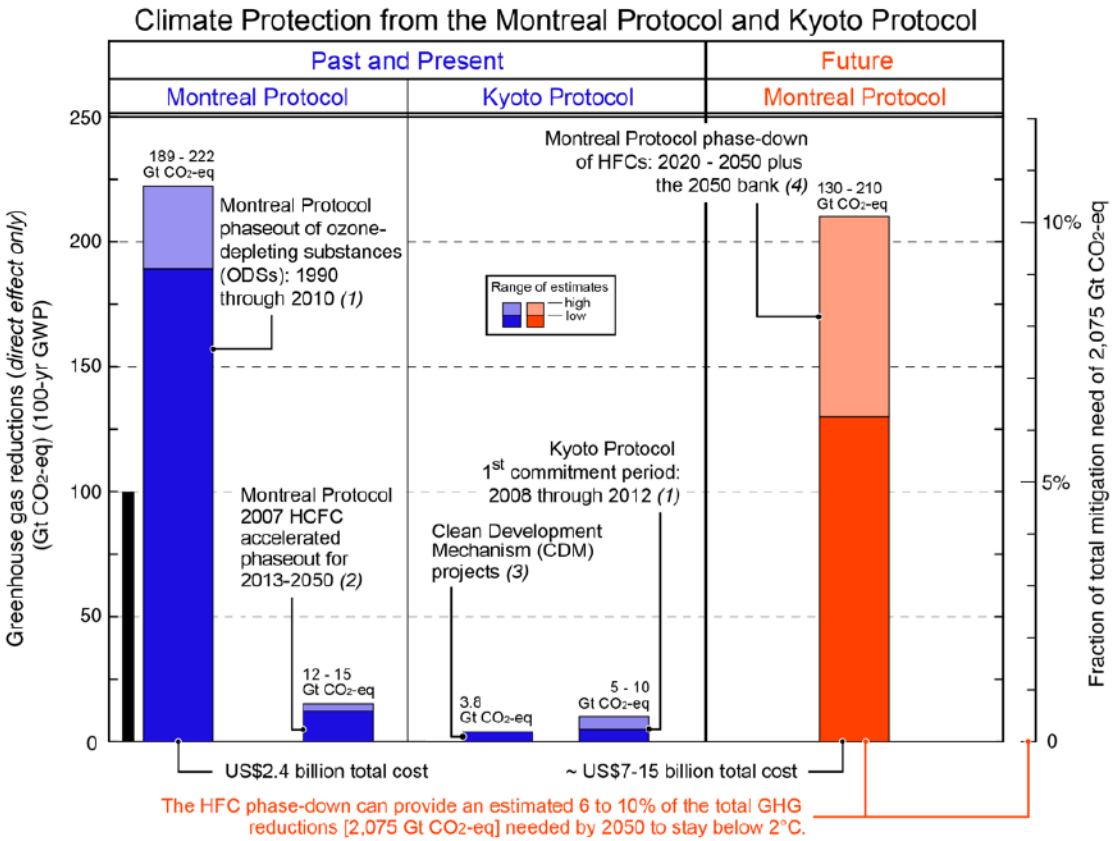

FIGURE 15.6.2 The immense amount of avoided emissions under the Montreal Protocol through 2010, as well as the projected future avoided emissions impact from phasing down HFCs. This figure is based on a similar figure in the Institute for Governance and Sustainable Development's *Primer on HFCs* (available at http://www.igsd.org/primers/hfc/), which contains additional information about the sources referenced in the figure by numbers in parentheses.

In addition to avoiding further damage to the stratospheric ozone layer, the reduction of these ozone-depleting substances has also avoided more climate warming that any other strategy. Professor V. Ramanathan calculated that CFCs and related chemicals were powerful greenhouse gases and published his results in 1975, the year after Molina and Roland published their results. These scientific papers spurred early consumer boycotts and national and regional measures to control CFCs, followed by the Montreal Protocol. This early start to reduce and ultimately ban CFCs not only put the ozone layer on the path to recovery, but also avoided an amount of future warming that otherwise would have been

24–76 gigatons CO_2eq per year—up to twice the amount of warming that CO_2 is causing today. The avoided warming just from the Montreal Protocol is about 135 gigatons CO_2eq, or 11 gigatons CO_2eq per year. The CFC story shows the importance of starting early to address climate pollutants, which we unfortunately did not do with efforts to cut CO_2.

Path to the Kigali Amendment

The path to the Kigali Amendment began in 2009 when the low-lying island country of the Federated States of Micronesia, along with Mauritius, proposed an amendment to the Montreal Protocol that would phase down high-GWP HFCs. Morocco immediately joined the proposal, which was soon followed by a similar proposal from the North American Parties—the US, Canada, and Mexico. Over the next few years, more and more Parties joined in support, and in 2015 India, previously one of the most reluctant Parties, submitted its own proposal, as did the EU, with the Africa Group (representing all 54 countries) also submitting an informal proposal and becoming a strong champion for the HFC phasedown.

Negotiating a treaty or an amendment to a treaty requires consensus among all the Parties, and consensus is built on the foundation of science (in this case, to understand how damaging HFCs are to climate), technology (to understand what substitutes are available to replace HFCs), and economics (to determine what the substitutes will cost and who will pay). Another important factor is competitiveness (to determine which companies located in which countries might benefit from phasing out old chemicals that were soon to lose their intellectual property protection and become commodities that any company could make without paying a royalty to the inventor, and which countries might lose during a phaseout). Over time, more and more of the Parties learned the underlying facts about HFCs and could communicate those facts to their governments and industries, to help formulate their negotiating strategy. At the same time, early movers, including the US and the EU, took specific actions to control HFCs at home. Once companies in these major markets were required to phase down HFCs under national and regional laws and were compelled to develop climate-friendly alternatives, these companies started encouraging their governments

to "multilateralize" the controls to all of the countries of the world to ensure the playing field stayed level (and to open up new markets for alternatives they were developing).

Strong US leadership was critical for building the consensus for the Kigali Amendment. President Obama, Secretary of State John Kerry, and EPA Administrator Gina McCarthy all became champions of the HFC phasedown. President Obama and Secretary Kerry negotiated bilateral agreements with various leaders, starting with President Xi of China in 2013. This was done during the first meeting between President Obama and President Xi, where they agreed on two things: first, to cooperate to reduce the risk from North Korea, and second, to cooperate to phase down HFCs. President Obama negotiated agreements on HFCs with other heads of government, including Prime Minister Modi of India, President Macri of Argentina, and Prime Minister Sharif of Pakistan. Along with the support of the island States and the Africa Group, this ensured that the battle to finish the Kigali Amendment would not be a contest between the rich and poor countries.

A final push came in September 2016 when the White House assembled a "fast start" fund of $80 million to help developing-country Parties phase down HFCs and improve energy efficiency of air conditioners and other cooling devices. Governments provided $27 million, and a group of philanthropic donors provided the other $53 million. This fast-start fund was announced in New York by Secretary Kerry and other ministers, in association with the High Ambition Coalition of more than 100 Parties. The $27 million from governments was later added to the Multilateral Fund, and the remaining funds are being disbursed by the Kigali Cooling Efficiency Program (K-CEP), organized under the ClimateWorks Foundation in San Francisco.

The following month, on October 16, 2016, at 7 AM Saturday, after an all-night negotiating session, the Parties to the Montreal Protocol agreed to the Kigali Amendment to phase down HFCs (Figure 15.6.3). A few minutes after the agreement, after the cheering stopped, the negotiators from Rwanda and Morocco introduced a draft decision to explore how to increase energy efficiency of cooling equipment during the phasedown of HFCs. The Parties agreed to this decision too.

FIGURE 15.6.3 Rwanda's Minister for Environment Vincent Biruta makes the Kigali Amendment official. *Photograph by IISD/Kiara Worth.*

Implementing the Kigali Amendment

As of May 2, 2019, 71 Parties have ratified the Kigali Amendment, which means the amendment entered into force at the earliest date set by the terms of the amendment, on January 1, 2019. Under the initial phase-down schedule, the Kigali Amendment will avoid up to 0.4°C of warming. Faster implementation that leapfrogs over HFCs during the ongoing phaseout of HCFCs can sweep up the additional 0.1°C to achieve the full 0.5°C of avoided warming projected by scientists. Previous phaseout schedules were accelerated by the Parties, and it is anticipated that the Parties will do the same with the Kigali Amendment, especially because climate-friendly alternatives are readily available. A strategy that leapfrogs from HCFCs to climate-friendly alternatives and avoids HFCs also will prevent the buildup of HFC banks in products and equipment, with the potential to avoid an additional 53 gigatons of CO_2eq.

As always under the Montreal Protocol, developed countries (known as non-Article 5, or non-A5, Parties within the Montreal Protocol) will take action first, reducing consumption and production of HFCs by 10% (compared with a 2011–2013 baseline) starting in 2019, with a second

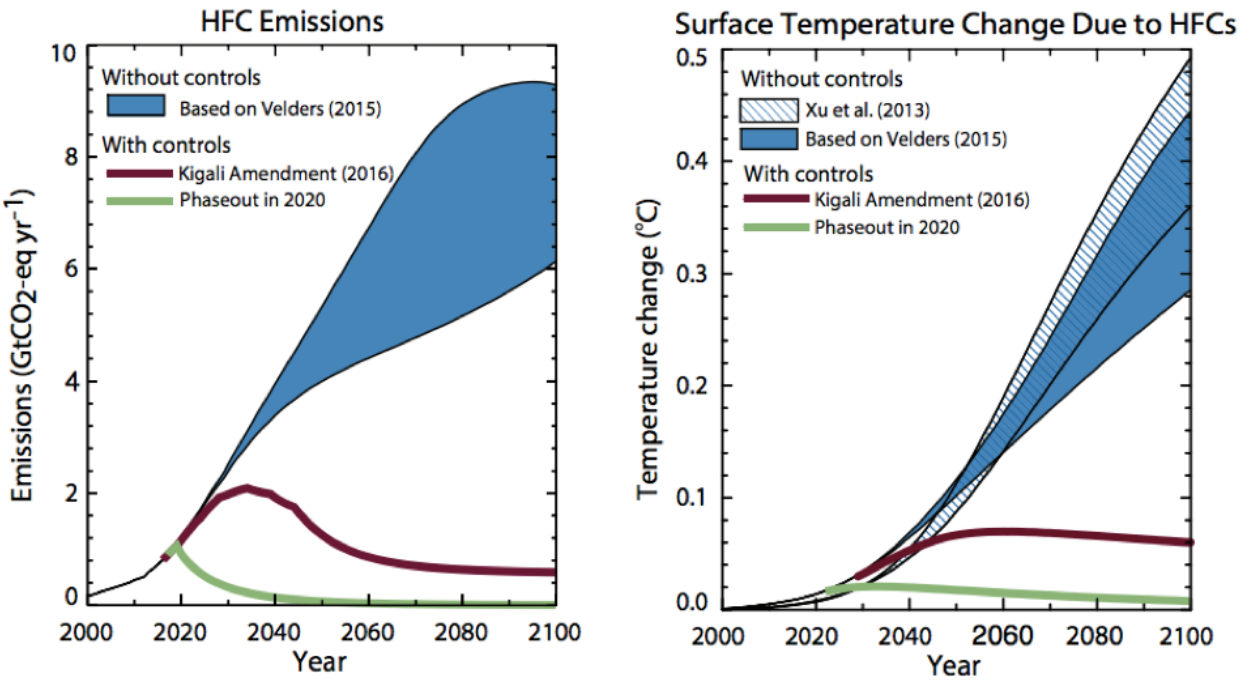

FIGURE 15.6.4 Warming avoided by the Kigali Amendment. Shown are global HFC scenarios without global HFC controls and with full compliance with the Kigali Amendment. Also shown is a scenario in which global production of HFCs is phased out in 2020. Note, the contribution from HFC-23 emissions is not included in either. For comparison of the benefit from HFC mitigation, warming at 2100 from all greenhouse gases is projected to contribute an additional 1.4°C for a moderate-emissions scenario and 4.8°C for a high-emissions scenario, relative to the 1986–2005 global average temperature (which is the baseline used by the IPCC's Fifth Assessment Report and represents warming of 0.61°C above preindustrial temperatures). $GtCO_2eq\ yr^{-1}$ = gigatons of CO_2 equivalent per year. *From WMO 2018.*

group (listed in the footnote to Table 15.6.1) beginning their phasedown in 2020. By 2036, both groups of developed countries will have reduced consumption and production by 85% of the 2011–2013 baseline. Most developing countries (Article 5, or A5, Parties) will freeze consumption and production in 2024 and step down to 20% of a 2020–2022 baseline by 2045. A group of countries with very high ambient temperatures were given a few more years to reach these goals because warmer temperatures may require further improvements in refrigerants and cooling equipment.

TABLE 15.6.1 Phasedown schedule under the Kigali Amendment

	A5 Parties Group1	*A5 Parties Group2**	*Non-A5 Parties Group 1*	*Non-A5 Parties Group2***
Baseline	2020–2022	2024–2026	2011–2013	2011–2013
Freeze	2024	2028		
1st step	2029: 90%	2032: 90%	2019: 90%	2020: 95%
2nd step	2035: 70%	2037: 80%	2024: 60%	2025: 65%
3rd step	2040: 50%	2042: 70%	2029: 30%	2029: 30%
4th step			2034: 20%	2034: 20%
Final step	2045: 20%	2047: 15%	2036: 15%	2036: 15%

*Bahrain, India, Iran, Iraq, Kuwait, Oman, Pakistan, Qatar, Saudi Arabia, and United Arab Emirates

**Belarus, Kazakhstan, Russian Federation, Tajikistan, and Uzbekistan

Non-Article 5 (Non-A5) Parties are developed countries that will begin phasedown in 2019. Article 5 (A5) Parties are developing countries that are given additional time before beginning their phasedown. Some Parties within the Non-A5 and A5 categories are grouped together for a modified schedule that will allow more time for phasedown.

Importance of improving efficiency of cooling equipment during HFC phasedown

At the conclusion of the Kigali negotiations, the Parties also agreed to consider opportunities to improve energy efficiency for even greater climate benefits. While previous transitions under the Montreal Protocol catalyzed improvements in energy efficiency of cooling equipment, this time the Parties were determined to actively promote improvements in efficiency, including promoting new and more advanced components as appliance manufacturers make the switch to low-GWP refrigerants. According to the 2018 quadrennial assessment by the Scientific Assessment Panel of the Montreal Protocol, improvements in energy efficiency of air conditioners and other cooling equipment can double the benefit of the Kigali Amendment, with the potential to cumulatively avoid up to 1°C of warming by the end of the century.

The Economist magazine calls air conditioning one of the great overlooked industries of the world. It asks what the most effective ways are to protect the climate and concludes that it's not to become a vegetarian, or even to replant the Amazon. Rather, the answer is to radically improve air conditioners. *The Economist* notes that phasing down HFCs

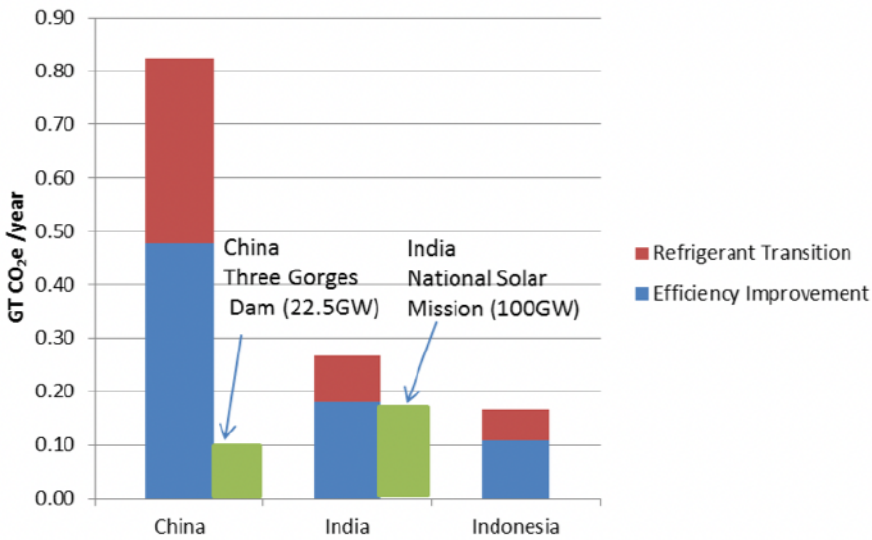

FIGURE 15.6.5 Estimated annual emissions abatement potential of air conditioner stock in 2030. The red and blue represent the refrigerant transition and efficiency improvement benefits, respectively. The avoided emissions are compared with proposed projects, represented by the green bars. *From Shah et al. 2015.*

will avoid the equivalent of 90 billion tons of CO_2 by 2050, and making air conditioners more energy efficient could double that. This compares, they continue, to having half the world's population give up meat, which would avoid 66 billion tons of CO_2, or successfully replanting two-thirds of degraded tropical forests, which would avoid 61 billion tons of CO_2.

With a growing population, an expanding middle class, and a warming climate, the demand for air conditioners and other cooling equipment is growing fast. Hot cities like Delhi and Beijing already use half of their electricity to run air conditioners, and even in France, demand for air conditioners in 2018 grew by almost 200% above 2017. In India, air conditioner ownership has increased from 2 to 5 million units between 2006 and 2011 and is forecast to reach 200 million by 2030. Globally, there are 3.6 billion cooling appliances in use, which will increase to 9.5 billion by 2050. To provide cooling for all who will need it in a warming world—and not just those who can afford it—will require 14 billion cooling appliances by 2050.

Presently, over 1.1 billion people lack access to cooling, which makes it harder to escape poverty, to keep children healthy, to keep vaccines

stable, to preserve food, and to keep economies productive. Already, about 30% of the global population is exposed to life-threatening temperatures for nearly 20 days per year, and heat waves kill roughly 12,000 people annually. As warming continues, deaths from extreme heat could multiply 20-fold by 2050, and by 2100, 75% of humanity could face deadly heat.

In the coming years, mandating energy efficiency alongside the transition away from high-GWP HFCs will be crucial for climate protection. Policies to require stringent energy efficiency can cut future energy demand by at least half. Even a modest 30% improvement for just room air conditioner efficiency can save enough energy to avoid the need to construct up to 2,500 medium-sized, peak-load power plants globally by 2050, according to Lawrence Berkeley National Laboratory. The Rocky Mountain Institute is offering a Global Cooling Prize of $3 million to develop residential cooling technology that has "at least 5x less climate impact when compared to a baseline unit." Improving efficiency of cooling equipment will provide multiple benefits, including making ownership more affordable, more secure, and more sustainable and saving as much as US$2.9 trillion in investment, fuel, and operating costs between 2017 and 2050. This will be particularly important in the hotter regions of the world, where many of the poorest live.

15.7 Conclusion

Successful mitigation of super pollutants, also known as SLCPs, will avoid up to 0.6°C of warming by 2050 (with 0.1°C of this from HFCs) and 1.2°C by 2100 (with up to 0.5°C from HFCs). The short lifetimes of SLCPs mean that fast action yields fast results, which is crucial in the near term because of the accelerating rate of warming we are experiencing. SLCP mitigation bends the curve almost immediately, limiting the warming that will take place during the decades that will pass before CO_2 mitigation takes effect. This will reduce the risk of runaway climate change from self-reinforcing feedbacks that could lead to a "hot house" planet. SLCP mitigation also has co-benefits of reducing impacts to human health and crops from air pollution that is associated with black carbon and tropospheric ozone, which disproportionately affect the global poor.

The direct and indirect impacts of black carbon can be mitigated through already available and deployable solutions in the transportation, residential, industrial, and agricultural sectors. Similarly, the powerful warming from methane—which also reacts in the atmosphere to produce tropospheric ozone, another SLCP—can be mitigated through measures implemented in the fossil fuel industry, waste management, and agriculture. HFCs have helped transition the world away from the CFCs and HCFCs that were destroying the ozone layer, but the climate impact from HFCs must now be eliminated. Fast implementation of the Kigali Amendment to the Montreal Protocol can avoid up to 0.5°C of warming, and improvements in energy efficiency in cooling equipment can double this.

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CHAPTER 16

Enhancing Carbon Sinks in Natural and Working Lands

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CHAPTER CONTENTS

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Learning Objectives

1. **Describe the basic concepts of the terrestrial carbon cycle.**
   You will learn how carbon moves from the atmosphere through plants, to soils, and eventually back to the atmosphere. Understanding the carbon cycle is a critical first step to managing it for carbon capture and storage.

2. **Explain the role of soils, organic matter, and greenhouse gas dynamics in the carbon cycle.**
   Soils are a hidden part of the carbon cycle but play a key role. Understanding what soil is, how carbon enters and leaves soils, and the controls on greenhouse gas production and consumption will help you understand (and invent) viable carbon removal strategies.

3. **Describe the role of plants in carbon uptake, storage, and greenhouse gas emissions.**
   Plants are superstars when it comes to removing atmospheric CO_2. You will learn how plants act as conduits and reservoirs and how some plants and plant management can increase or decrease greenhouse gas emissions.

4. **Identify potential for emissions reduction on working lands.**
   Remember, carbon removal has to be coupled with emissions reduction to bend the curve. You will use your knowledge gained from earlier chapters to explore ways to reduce emissions from agricultural and forestry activities.

5. **Describe carbon recovery and sequestration approaches for working lands.**
   How do we get more carbon out of the atmosphere? You will learn how plants and soils can be managed for carbon removal and storage while they support soil and ecosystem sustainability. We will critically examine case studies of management approaches that are already in use. This information should help you use your creativity and knowledge to develop more approaches for the combined emissions reduction, carbon capture, and carbon storage that are needed to bend the curve.

The material needed to meet these learning objectives will be delivered in the following six sections:

- 16.1 Natural and Working Lands in the Terrestrial Carbon Cycle
- 16.2 Soils, Organic Matter, and Greenhouse Gas Dynamics
- 16.3 The Role of Plants in Carbon Storage and Greenhouse Gas Emissions
- 16.4 Emissions Reduction via Management
- 16.5 Soil Carbon Recovery and Sequestration
- 16.6 What Have We Learned So Far?

Note that when it comes to ecosystem management for climate change mitigation, solutions are rarely simple. Ecosystems, by their very nature, are complex interacting, reactive environments. Nothing is static—they are always changing in response to weather (in the short term), climate (in the long term), big events (for example, fires, hurricanes, harvests), and smaller ones (for example, the gradual shifting of species). Thus, ecosystem management requires a systems approach, and it benefits greatly from long-term monitoring and careful observation. Sometimes ecosystem management also involves trade-offs; understanding how ecosystems function and how they respond to change will help us minimize those trade-offs. This chapter will help you understand some of the complexity of ecosystems, where trade-offs are likely to occur, and how to recognize and minimize negative outcomes.

Overview

Greenhouse gas emissions reduction is a critical component of any plan to slow climate change. However, we have now reached a point where greenhouse gas emissions reduction alone is insufficient to solve the climate change crisis. The primary reason for this is that CO_2 is a long-lived atmospheric gas, meaning that once it arrives in the atmosphere, it is likely to stay there for many years. A small proportion of the CO_2 added through human activities can be retained in the atmosphere for thousands of years! This means that climate warming will continue even with greenhouse gas emissions reduction, because the rate of increase

in atmospheric concentrations of CO_2 exceeds the rate of background removal. However, if we can increase the rate at which CO_2 is removed from the atmosphere, while at the same time reducing emissions, we have the potential to bend the curve.

The Earth's system has built-in ways to remove atmospheric CO_2. On land, the most important mechanism to remove CO_2 from the atmosphere is photosynthesis by plants. Plants, and the soils they live in, are tremendous resources in the battle against climate change. Plants need CO_2 to survive and grow, and they have the "machinery" to remove CO_2 from the atmosphere. We depend upon plants for food, fiber, fuel, and building materials, so we have perfected plant management—also called photosynthesis management—over thousands of years of practice. Soils have the potential to be deep, long-term repositories of some of the carbon captured by plants, keeping it from returning to the atmosphere for years to decades or longer. Finally, managing plants and soils for carbon uptake and storage often translates into more sustainable and productive practices for people and ecosystems.

16.1 Natural and Working Lands in the Terrestrial Carbon Cycle

Natural ecosystems and working lands (those used for agriculture and forestry) play an important role in the terrestrial carbon cycle. Forests, grasslands, crop fields, wetlands—in fact, all ecosystems with plants and soils—exchange carbon dioxide (CO_2) with the atmosphere. Approximately 86% of the Earth's land surface is rural natural or working land, housing approximately 45% of the world's population. Although most of the natural and working lands can be found in rural areas, they are not limited to rural areas. And urban, suburban, and peri-urban areas—even residential lawns and gardens—cycle CO_2. Plants take up CO_2 from the atmosphere during the process of photosynthesis. About half of the CO_2 that plants take up gets released back to the atmosphere via plant respiration, together with oxygen and water vapor. The remaining CO_2 absorbed by plants is converted into plant tissues such as stems, roots, leaves, fruits, and flowers. From CO_2, plants get the carbon they use as a major building block to make and sustain their tissues. Plants are at the base of the food chain and thus provide energy, in the form of carbon, together with nutrients from the soil to most of the rest of the organisms on Earth. Plants feed the world.

How do plants feed the world? Some organisms (for example, herbivores) harvest and eat live plant parts, but most of the carbon and nutrients in plants go to feed microorganisms. Plants regularly slough tissues, akin to animals shedding hair or skin. When plants shed their tissues, or when whole plants die, the tissues get deposited on or in the soil as plant litter. Some of this plant litter subsequently becomes food for microorganisms living in the soil (for example, bacteria and fungi). Like plants, microorganisms play a critical role in the local, regional, and global cycles of carbon. Soil microorganisms use enzymes to help break down plant litter during the process of decomposition. The carbon captured by microorganisms during decomposition is used for energy and to build microbial bodies. Microorganisms also respire

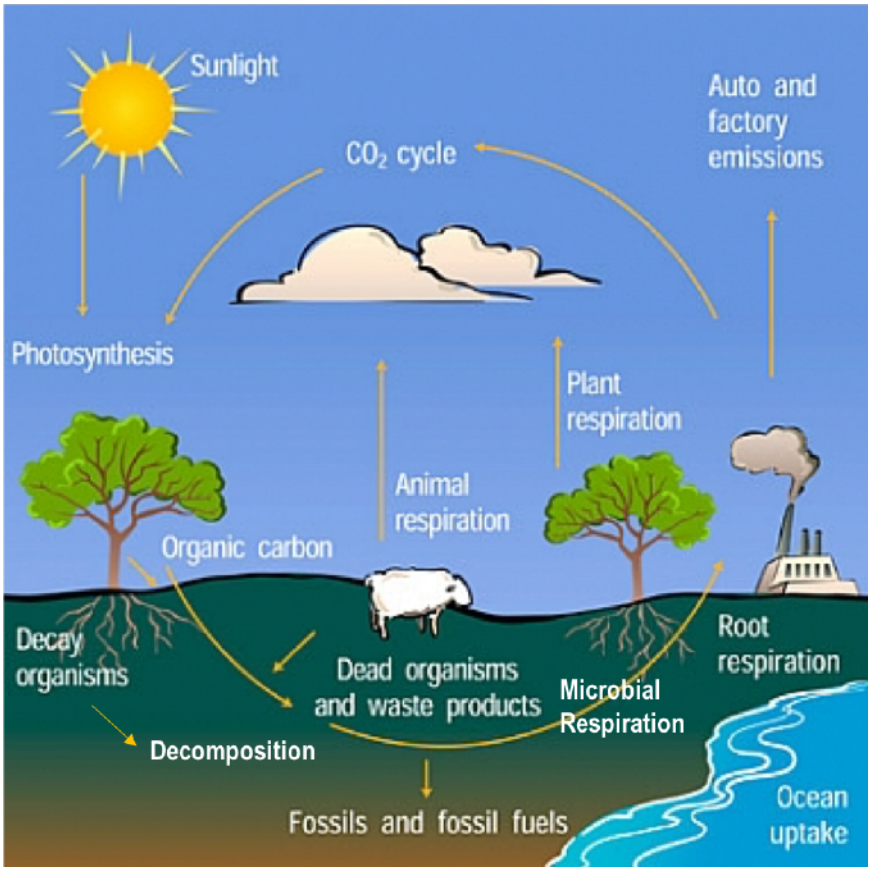

FIGURE 16.1.1 The global carbon cycle. Carbon cycles on the scale of seconds to centuries among the atmosphere, plants, animals, soils, and soil microbes. Geologic reserves cycle carbon on the scale of centuries to millennia. The exception is when humans mine carbon from geologic reserves in the form of coal, gas, oil, and other fossil fuels. The burning of fossil fuels dramatically accelerates the release of geologic carbon to the atmosphere. Adapted from UCAR Center for Science Education.

CO_2, thus completing the carbon cycle by returning some of the carbon initially captured by plants via photosynthesis back to the atmosphere (Figure 16.1.1).

Plants and microorganisms live in every biome on the Earth's surface, and their activity can be clearly seen at a global scale in the graph of atmospheric CO_2 data from Mauna Loa volcano on the island of Hawaii (Figure 16.1.2). There are two prominent features of this graph. The first feature is the steep rise in atmospheric CO_2 concentrations from the

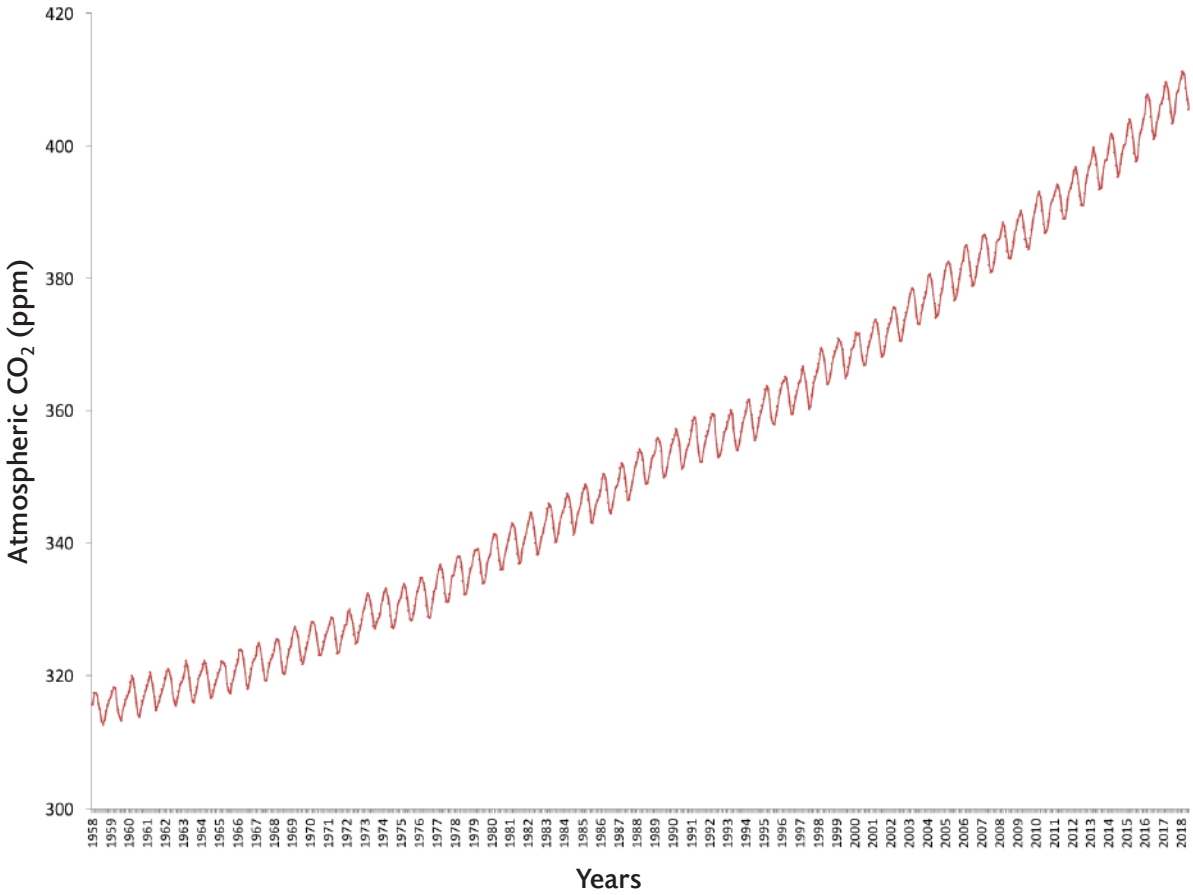

FIGURE 16.1.2 Atmospheric carbon dioxide (CO_2) as measured from the top of Mauna Loa Volcano, on the Island of Hawaii. The upward trend in the data results from human activities that release CO_2 to the atmosphere—the use of fossil fuels, biomass burning, and deforestation, among others. The annual troughs and peaks result from photosynthesis by plants and respiration, primarily by microorganisms. Data from Pieter Tans, NOAA/ESRL; and Ralph Keeling, Scripps Institution of Oceanography.

start of the record in 1958 to present. The long-term rise in atmospheric CO_2 concentrations is due to increasing emissions from human activity. The second prominent feature in the graph is the annual "wiggle" in the atmospheric CO_2 data. The wiggle occurs as a result of the *breathing* of the biosphere. Every time the line goes down, CO_2 uptake by plants has exceeded the release of CO_2 by microbial respiration. This in turn results in the net removal of carbon from the atmosphere and its storage in the biosphere. This annual downturn in CO_2 is a natural process driven

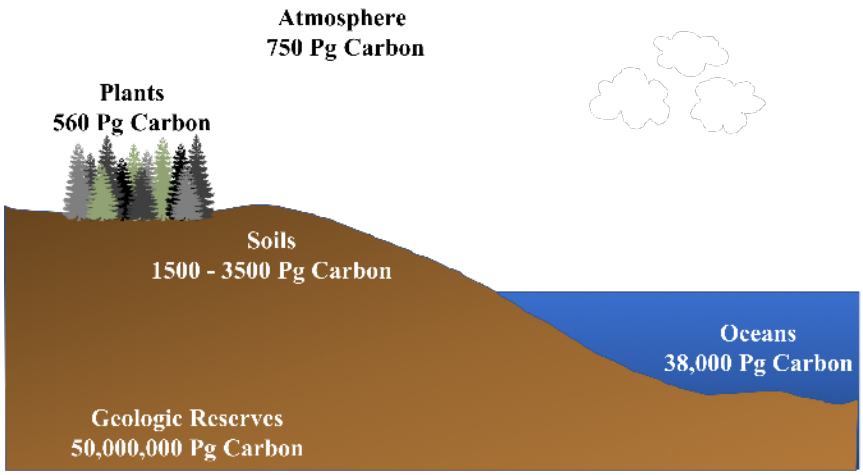

FIGURE 16.1.3 Global carbon stocks. One petagram (Pg) equals 10^{15} grams. Deep rock reserves are the largest pool of carbon on Earth, with oceans storing the second largest amount. Soils are the next largest pool, followed by the atmosphere and plants. There is considerable uncertainty in the exact size of the Earth's carbon stocks, as it is impossible to accurately measure the full pool directly. Estimates are derived from strategic direct measurements, remote sensing (satellite, airplane), and computer models. Data from University of New Hampshire 2008.

by plant uptake of CO_2 during photosynthesis at a global scale. The global minimum of atmospheric CO_2 concentration generally occurs in September or October, which in the Northern Hemisphere occur in summer and early fall. The Northern Hemisphere has more land mass than the Southern Hemisphere and thus more land plants and associated carbon uptake. For this reason, the Northern Hemisphere growing season is the main driver of the annual low point in atmospheric CO_2 concentration.

The annual peak in atmospheric CO_2 concentration occurs when the respiration of microorganisms that live predominantly in the soil exceeds plant uptake of CO_2 from the atmosphere. Soil microorganisms in many parts of the world are active in decomposition all year long and respond to periods of plant litter deposition during the plant growing season and at the end of the growing season when plants drop their leaves or completely senesce. During the growing season, plant uptake of CO_2 exceeds microbial respiration. When plant activity slows or comes to a halt during the Northern Hemisphere winter and early

spring, microbial respiration of CO_2 exceeds plant uptake. This causes the global atmospheric concentration of CO_2 to increase to a maximum, generally in May.

Plants and soils don't just exchange carbon with the atmosphere; they are also a reservoir of stored carbon, together with the atmosphere, oceans, freshwaters, and geologic reserves (Figure 16.1.3). The reservoirs where carbon is stored are also referred to as **pools** or **stocks**. On the land surface, soils are the largest reservoir of carbon. The total amount of carbon in soils is not well understood, because it is difficult to estimate the amount of carbon below the top meter, even though scientists know that deep soils contain carbon. Plants represent a smaller carbon stock but play a key role as conduits of carbon capture from the atmosphere. The interaction among the atmosphere, plants, and soil organic carbon pools can significantly affect the rate of climate change. The more carbon that is stored in soils and plants, the less that is stored in the atmosphere where it can absorb heat and warm the climate. Below, we will explore how carbon is cycled and is stored in soils and plants and how ecosystems can be managed to increase carbon storage to help slow climate change.

16.2 Soils, Organic Matter, and Greenhouse Gas Dynamics

Why should we care about soils?

Soils are literally and figuratively the basis for life on Earth (Figure 16.2.1). Soils provide a substrate for plants to sink their roots into. Soils also provide the nutrients that plants need to survive, and by extension they provide the nutrients for most other living things on Earth. Soils store water. They also filter water by removing minerals and contaminants.

FIGURE 16.2.1 Soil is the basis for life on Earth. Reproduced from © Okea/ Fotolia.

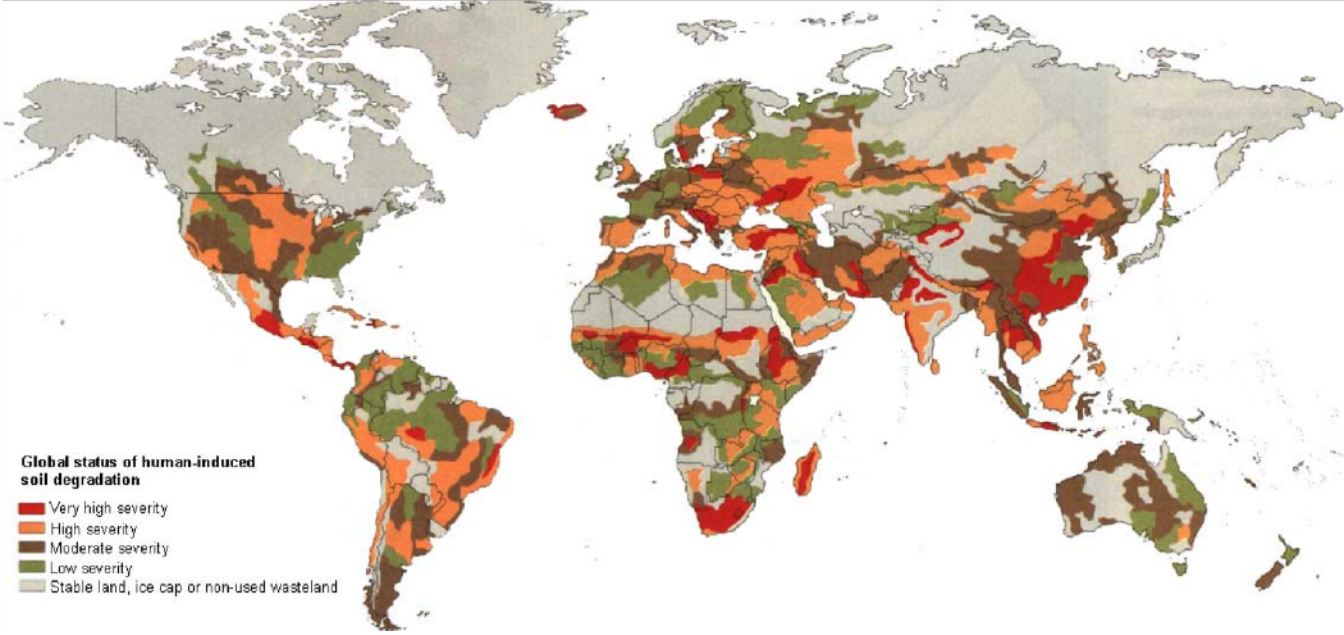

FIGURE 16.2.2 Map of soil degradation globally. The majority of managed lands experience moderate to very severe degradation including soil loss from wind and water erosion, toxicity from pollutants, low nutrient content from over harvesting, and compaction from overgrazing and the use of heavy machinery. Reproduced from the FAO.

In this way, healthy watersheds with abundant and intact soil resources help provide clean water to humans and other organisms. Some groups of soil microbes can consume and break down toxic chemicals, rendering them less dangerous to human and ecosystem health. The sustainability and productivity of agriculture depends on soils. However, much of the world's soils have suffered damage and degradation from poor management (Figure 16.2.2). Erosion, overuse, compaction, and contamination from chemicals threaten the health of soils.

What is soil?

Soils are made up of a complex mixture of minerals and organic matter. The minerals come from rocks that are broken down through the process of weathering. The organic matter in soils comes from plants, microorganisms, and animals. Soils are teeming with life. There are more microorganisms in a teaspoon of soil than there are people on Earth. In addition to live organisms, soils are the repository of microbial by-products and dead microbial, plant, and animal tissues. The organic matter derived from live and dead tissues thus makes up an important part of the soil. As all these tissues contain carbon, storing organic matter in soils is the vehicle for storing carbon in soils.

Soils and greenhouse gas emissions

Soils exchange gases with the atmosphere. These gases include CO_2, methane, and nitrous oxide, the big three greenhouse gases. Microorganisms, roots, insects, and other soil animals that breathe oxygen (that is, aerobic organisms) release CO_2 through the process of respiration. Some soil microorganisms release methane to the atmosphere through anaerobic respiration (that is, respiration in the absence of oxygen), while still other soil microorganisms consume methane from the atmosphere and respire CO_2. Soils are the largest natural source of nitrous oxide, which is produced predominantly by yet another group of soil microorganisms. Both methane and nitrous oxide are very potent greenhouse gases with more warming power than CO_2. Thus, even relatively low methane and nitrous oxide emissions from soils can have a big impact on climate.

Microbes are not the only source of greenhouse gases in soils. In addition to biological sources of greenhouse gases, soils can foster the conditions needed for nonbiological (for example, geochemical) reactions that produce greenhouse gases. Geochemical greenhouse gas production in soils is thought to play a less important role than microbiological processes at a global scale, thus in this chapter we will focus on the microbial greenhouse gas emissions and ways to reduce these emissions.

All ecosystems exhibit some greenhouse gas emissions. The production of greenhouse gases is a by-product of natural microbial processes and an indicator of life. However, some agricultural and forestry activities can increase greenhouse gas emissions from soils. For example, the use of nitrogen fertilizers on agricultural soils can stimulate the production and emission of nitrous oxide. Irrigation, especially flood irrigation, can create the anaerobic conditions needed for both methane and nitrous oxide production and emissions. Plowing and tillage can release stored carbon and nitrogen, making it accessible to microbes that release CO_2, methane, and nitrous oxide to the atmosphere. Agriculture accounts for more than half of the nitrous oxide and methane emissions globally and approximately 25% of the total greenhouse gas emissions worldwide. Forestry and other land uses result in similar levels of emissions.

Organic matter versus organic carbon versus inorganic carbon

The organic matter in soils contains carbon that was originally stored in the atmosphere and subsequently captured by plants via photosynthesis. There is a wide range of **soil organic carbon** (**SOC**) contents in soils globally. This is because both inputs and outputs of SOC are sensitive to a suite of environmental factors:

- **Climate and weather:** temperature, precipitation, storms, drought
- **Geology:** rock type and weathering rate
- **Soil age:** landscape and landform stability
- **Biology:** vegetation, microorganisms, and animals

Carbon capture via photosynthesis differs among ecosystems. The plants of temperate and tropical wetlands and tropical rain forests are among the most productive globally, meaning that they capture the most carbon annually. Wetlands are productive where water and dissolved and suspended nutrients are constantly flowing and providing a regular renewal of resources. Tropical rain forests are productive because their location near the equator promises abundant sunlight and near-constant warm, moist conditions that favor continuous plant growth throughout the year.

The pool of SOC also differs among ecosystems. The amount of organic carbon storage in soils is a function of the difference between carbon inputs and carbon losses. Where organic carbon losses via decomposition and leaching (or other physical removal) equal organic carbon inputs to the soil, the size of the SOC pool remains the same. Where decomposition rates are lower than carbon inputs, SOC can accumulate. Northern peatlands store the most SOC among the world's terrestrial biomes. Although plant growth and associated carbon uptake is low compared with ecosystems like wetlands or tropical forests, the rate of SOC loss is even slower as a result of cold temperatures and unfavorable conditions for microbial decomposition (for example, anoxia). This facilitates the gradual buildup of large quantities of SOC.

So far, we have focused on organic carbon pools. Soil also contains inorganic carbon. Inorganic carbon is primarily made up of calcium and

magnesium carbonates and enters soils through the weathering of carbonate rocks. Soils contain about 1,000 petagrams (Pg; 1 Pg = 10^{15} g) of inorganic carbon (equivalent to 1,000 gigatons) in the top meter, globally, mostly concentrated in deserts and semiarid regions. Increasing atmospheric CO_2 associated with climate change and the increase in soil acidity from certain land uses can result in the loss of inorganic carbon in soils.

Soil organic carbon sequestration

To review, when the rate of inputs of SOC exceeds the rate of losses, SOC accumulates. Another term for this is **SOC sequestration**. Soils have tremendous capacity to sequester SOC. It has been estimated that soils store between 1,500 and 3,500 petagrams of organic carbon. The low estimate of SOC is double the amount of carbon stored in the atmosphere (750 petagrams) and almost three times the carbon stored in vegetation globally (560 petagrams) (Figure 16.1.3). We do not have precise estimates of SOC pools, because soils vary greatly from place to place and are heterogeneous, deep, and largely hidden from view. This makes measuring the total amount of SOC challenging at a global scale.

With so many microorganisms in soils, it is a wonder that any SOC can escape microbial decomposition and become sequestered. However, there are several ways that organic matter and its associated carbon can get stored in soils:

- Organic carbon can chemically react with soil minerals or other organic compounds to form strong bonds. These bonds can be difficult for microbes to break, leading to the persistence of organic carbon in soils.
- Organic carbon can accumulate if it is deposited deep down in the soil. Microbial activity is greatest near the surface of soils (top 10 to 30 centimeters) and declines with depth. This is because most of the carbon and nutrients that microbes need to survive is deposited on or near the surface by plants. However, roots can penetrate to deep soil depths and inject organic matter into soils as they slough tissues. In some seasonally dry environments, like parts of the Amazon basin, roots extend down almost 20 meters. Water can also transport organic carbon into deep soils as it percolates down.

Burrowing animals and insects are good agents of organic carbon transport and deposition into deep soils.

- Organic carbon can persist in soils if conditions are more favorable for plant growth than for microbial decomposition or physical losses. The organic-rich northern peatlands discussed above are an example of where SOC accumulates because microbial decomposition is inhibited by the lack of oxygen in soils and cold temperatures.
- Organic carbon can persist in soils if the organic matter it is derived from is chemically or physically difficult for microbes to break down. This happens with materials like compost, wood, and waxy tissues or in cases where the microbial community lacks the enzymes to break down specific types of chemical compounds.

16.3 The Role of Plants in Carbon Storage and Greenhouse Gas Emissions

Plants as conduits and reservoirs

When it comes to the global carbon cycle, plants are the ultimate carbon-capturing champions. While artificial carbon capture technologies are being developed to address climate change, photosynthesis can be thought of as a "technology" that has been perfected and deployed for over 2 billion years. The rate of atmospheric carbon uptake by plants via photosynthesis dwarfs all other forms of carbon capture. Land plants pull an estimated 120 petagrams of carbon from the atmosphere each year—over 15% of the total atmospheric carbon pool.

Plants, in addition to being the primary conduits for CO_2 removal from the atmosphere, can sequester carbon. As mentioned above, the global terrestrial plant carbon pool stores approximately 560 petagrams of carbon. It is easier to estimate aboveground plant carbon pools than it is to estimate carbon in soils. Plants, and more specifically the reflectance of the chlorophyll in leaves, can be measured from satellites in space. This technique is called **remote sensing** and is a powerful tool for assessing the amount of plant biomass on the land surface. Changes in reflectance over time are correlated with changes in leaf area, which in turn is directly related to rates of plant growth. Thus, satellite imagery repeated over time can be used to estimate how much plant growth is occurring on land. Belowground plant parts, namely roots, are much harder to estimate than aboveground plant parts, as roots are hidden from view. Roots can extend deep into soils. Roots can be large, like the structural roots of trees, or small and ephemeral, like the main absorptive roots of grasses and herbs. Although measuring root biomass is difficult, it is important for understanding the carbon cycle. In some ecosystems there is as much root carbon below ground as is stored in plant biomass above ground. Roots are also important because they are the main conduits for soil organic matter formation.

Roots are generally assumed to be a greater contributor to soil carbon stocks than aboveground plant tissues because roots are already buried below ground and can be more easily captured and sequestered in the soil than aboveground tissues. Thus, roots play a key role as transmitters of carbon into soils.

Forests as carbon sinks and sources

Overall, trees store more carbon than any other plant type. Forests cover about 30% of the total land area on Earth and account for approximately 80% of the terrestrial plant biomass. This means that forests store an estimated 350 petagrams of carbon in their tissues, most of which is in wood. Forests are vulnerable to natural and human-caused disturbance events such as fire, logging, pests, and weather-related disturbances. Some estimates suggest that 60% of the world's forests are in some stage of recovery from the last disturbance event. Forest disturbance often leads to the emissions of greenhouse gases. Deforestation is a big contributor to global greenhouse gas emissions, especially in the tropics. At a global scale, tropical deforestation accounts for about 10% of all greenhouse gas emissions annually. Some of the greenhouse gas emissions from deforestation result from disturbance to soils. Tree cutting and removal can break up soil aggregates, exposing previously trapped carbon to microbial decomposition and providing fuel to microbes that produce CO_2, methane, and nitrous oxide. Greenhouse gases are also released during the decomposition of the plant litter produced from deforestation.

Forest fire and biomass burning is another large source of greenhouse gas emissions. Fires consume biomass and produce CO_2, methane, and nitrous oxide, among other gases. Globally, 2 to 3 petagrams of carbon are emitted to the atmosphere annually from fires. Over 80% of this comes from tropical regions, with approximately 1 petagram of carbon per year coming from savannas (wooded grasslands). Climate change is increasing the frequency and severity of drought in some regions, and this can in turn increase the occurrence of fires.

16.4 Emissions Reduction via Agricultural Management

Management of agricultural lands has historically been a major contributor to climate change, amounting to approximately 25% of global greenhouse gas emissions. When plants and animals are harvested from working lands, the associated carbon and nutrients are harvested as well. Fertilizer can replace some of the nutrients harvested, and plant growth can bring new carbon into ecosystems, but rarely do we replace all the carbon and nutrients that are lost. Fertilization, irrigation, and biomass burning, as well as practices that disturb soils such as plowing and tillage, can increase emissions of all three of the major greenhouse gases. Human land use over the last 12,000 years has resulted in the loss of an estimated 116 petagrams of SOC in the top 2 meters of soil, globally. Deforestation, primarily in the tropics, results in the loss of approximately 1.7 petagrams organic carbon per year from ecosystems. In order to slow climate change, and bend the curve, greenhouse gas emissions from working lands must be reduced. There are several possible approaches for reducing emissions that can yield significant greenhouse gas savings, including improved fertilizer, tillage, water, and residue management, as well as matching crops to appropriate soils and climates, and incorporating fallow periods. Improved grazing land and livestock management, together with better manure management, are additional practices that are known to reduce emissions. Taken together at a global scale, these practices have been estimated to have the potential to save over 3 petagrams in CO_2 equivalents (CO_2e) per year. Below, we detail two examples of approaches that can reduce emissions and offer valuable co-benefits.

Nitrogen fertilizer

Nitrogen fertilizer comes in organic and inorganic forms and is widely used in agriculture to enhance plant growth. Inorganic nitrogen fertilizer

can be a large source of greenhouse gas emissions, from production to field application. The manufacturing of inorganic nitrogen fertilizer is a carbon-intensive activity. A lot of energy is required to convert dinitrogen gas to ammonia during fertilizer production. In 2004, the fertilizer industry used approximately 1% of the world's energy, with 90% of that used to produce ammonia. Producing the 119 million metric tons (MMT) of nitrogen fertilizer applied to soils globally in 2018 resulted in at least 492 MMT of CO_2 emissions (values calculated using Statista 2014). This is assuming that natural gas was used in the manufacturing process; if coal was used, the energy cost was higher. To compound the problem, nitrogen is often applied to fields in excess of plant requirements. This extra nitrogen fertilizer stimulates microorganisms in the soils that make nitrous oxide gas, and nitrous oxide emissions increase exponentially with the amount of nitrogen fertilizer added.

At the field scale, there are several approaches that can lower greenhouse gas emissions from fertilizer use. Careful monitoring of plant requirements could significantly lower the amount of nitrogen fertilizer needed for agriculture. There are important co-benefits from this relatively simple action. Less fertilizer applied means that less fertilizer will need to be produced, lowering the carbon footprint of fertilizer manufacturing. Lower fertilizer application rates will also lower nitrous oxide emissions. More efficient fertilization application could save the farmer money, helping to support a more financially sustainable agricultural industry. And finally, less fertilizer use can help reduce nitrogen runoff and pollution of waterways. Some additional ways to lower greenhouse gas emissions associated with fertilizer use include the following:

- Use low-carbon or no-carbon fuels in fertilizer manufacturing.
- Capture biosolids and wastewaters and convert them to nitrogen amendments; this also helps remove nitrogen pollution from waterways.
- Use organic nitrogen and slow-release fertilizer. If the fertilizer is released slowly, it can result in lower emissions and have a lower overall carbon footprint.
- Use buried or drip irrigation. Supplying only the amount of water

the plant needs can minimize overwatering that can stimulate nitrous oxide emissions.

- Use nitrogen-fixing cover crops. Nitrogen-fixing plants are species that can pull nitrogen from the atmosphere and supply it to soils. Nitrogen-fixing plants in the legume (pea) family are often used as cover crops during fallow periods (see below). Nitrogen-fixing cover crops can also stimulate nitrous oxide emissions but do not result in the energy costs associated with inorganic nitrogen fertilizer production.

The total greenhouse gas savings from these improved practices have not yet been estimated at a global scale, but models suggest the results will be very promising.

Livestock waste

Animal waste is another large source of greenhouse gas emissions on working lands. Animal agriculture accounts for approximately 20% of the non-CO_2 greenhouse gas emissions, globally. Almost half of these emissions come from manure management, primarily on dairies and feedlots. Manure is generally stored in piles or slurry ponds, which create favorable conditions for the production of nitrous oxide and methane. Storage of manure presents additional problems in the form of biological and chemical hazards to human and ecosystem health. Manure applied to fields can stimulate plant growth but has also been shown to be a large source of soil nitrous oxide emissions and to contribute to nitrate pollution of waterways.

Livestock waste is carbon-rich material. One alternative management for livestock waste is anaerobic digestion. **Anaerobic digestion** is the process of controlled microbial decomposition under anoxic (no-oxygen) conditions. The microbes that perform the anaerobic decomposition produce methane gas. While methane is a greenhouse gas, it can also be used as a biofuel and can be captured directly from the digestor. Thus, processing livestock wastes through anaerobic digestion lowers emissions from traditional waste storage and produces a valuable fuel source. It should be noted that when the methane fuel is utilized for energy, CO_2 is the by-product. The CO_2 by-product is considered to be carbon-neutral and not a contributor to climate change. This is because

the livestock waste was derived from CO_2 recently captured from the atmosphere (via the plants that the animals consumed), and in carbon accounting schemes, this relatively fast cycling of CO_2 is considered to result in no net change in atmospheric CO_2 concentrations.

Anaerobic digestion does not completely decompose the livestock waste, leaving a partially decomposed material called digestate. The digestate is nitrogen rich and can stimulate nitrous oxide emissions if applied directly to soils. Composting the residual digestate can reduce nitrous oxide emissions. Anaerobic digestion may not remove harmful chemicals (for example, hormones, antibiotics) or microorganisms (for example, pathogenic bacteria), thus original feedstocks, such as the livestock manure, and the ultimate digestate must be monitored closely to avoid contamination of soils and waterways. As yet, anaerobic digestion is not widely adopted in the US or globally, but policy and financial incentives can increase the use of this technology. Concerns over costs, reliability, and leakage remain, but this technology holds considerable promise for emissions reduction.

16.5 Soil Carbon Recovery and Sequestration

While emissions reduction is a critical step for slowing the climate change crisis, emissions reduction alone is no longer sufficient to solve the problem. The issue is clearly stated in the following quote from the Intergovernmental Panel on Climate Change Report (2014):

> A large fraction of anthropogenic climate change resulting from CO_2 emissions is irreversible on a multi-century to millennial time scale, except in the case of a large net removal of CO_2 from the atmosphere over a sustained period. Surface temperatures will remain approximately constant at elevated levels for many centuries after a complete cessation of net anthropogenic CO_2 emissions. Due to the long time scales of heat transfer from the ocean surface to depth, ocean warming will continue for centuries. Depending on the scenario, about 15 to 40% of emitted CO_2 will remain in the atmosphere longer than 1,000 years.

The difference between emissions reduction alone and the combination of emissions reduction with CO_2 removal is illustrated in Figure 16.5.1. In this figure a hypothetical emissions reduction scenario shows a slower but still increasing trend of atmospheric CO_2 concentrations. What is needed to change this trend? We need to bend the curve! The best way to bend the curve is to combine emissions reduction with CO_2 removal from the atmosphere.

Land-based solutions

Land-based solutions hold considerable promise to help bend the curve, particularly through organic carbon capture, recovery, and sequestration in soils (Table 16.5.1). Well-established agricultural management approaches that have been shown to increase carbon stocks include the following:

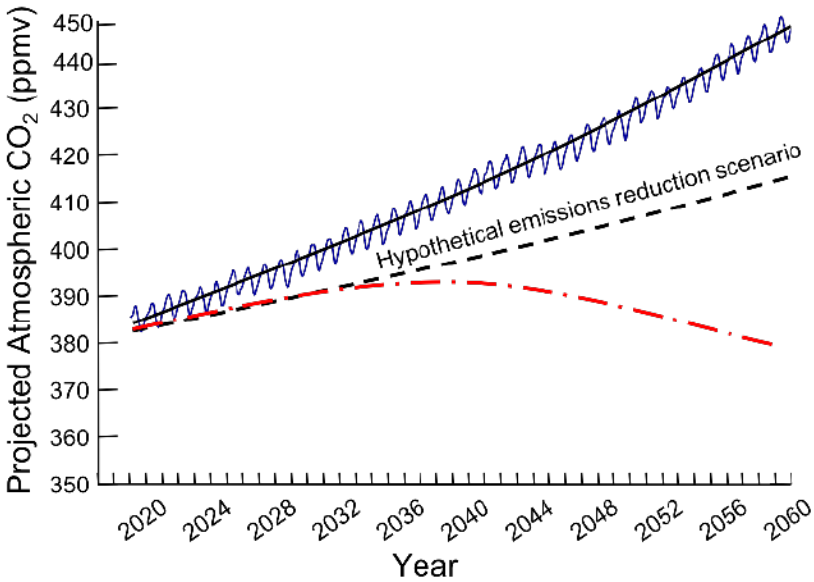

FIGURE 16.5.1 Hypothetical patterns in atmospheric CO_2 concentrations from 2018 to 2060 as a result of different climate change mitigation scenarios. The business-as-usual scenario is depicted in blue with a sold black trend line. A hypothetical emissions reduction scenario, even when optimistic, will still only slow the rate of increase of CO_2 in the atmosphere (dotted black line). Combining emissions reduction with CO_2 removal will help lower atmospheric CO_2 concentrations and bend the curve (dotted red line). (ppmv = parts per million by volume). Image by Whendee L. Silver.

- Reduced or no tillage
- Improved grazing regimes
- Fire management
- Use of cover crops
- Use of plant species with high root allocation
- Conversion from annual to perennial crops
- Crop rotation involving perennials
- Agroforestry
- Wetland restoration
- Fertilization
- Irrigation
- Organic matter amendments

TABLE 16.5.1 Potential global soil carbon sequestration with improved agricultural land management

Management	*Land Use*	*Mean Sequestration Potential ($Pg{\cdot}C{\cdot}yr^{-1}$)*	*High Range ($Pg{\cdot}C{\cdot}yr^{-1}$)*	*Low Range ($Pg{\cdot}C{\cdot}yr^{-1}$)*
Biochar[a]	All	1.05 ± 0.75	1.10 ± 0.70	0.59 ± 0.41
Nutrient, tillage, irrigation[b]	Cropland	0.56 ± 0.14	1.01 ± 0.33	0.48 ± 0.17
Grazing[c]	Rangeland	0.26 ± 0.05	0.77 ± 0.31	0.26 ± 0.11
Combined potential (excluding biochar)[d]	All	0.83 ± 0.11	1.78 ± 0.32	0.74 ± 0.14
Combined potential (including biochar)[e]	All	1.88 ± 0.35	2.89 ± 0.42	1.32 ± 0.13

SOURCE: Adapted from Mayer et al. 2018.

High and low estimates are the mean values of the lower and upper limits of potential sequestration given in the associated references. Values are means plus and minus standard errors. ($Pg{\cdot}C{\cdot}yr^{-1}$ = petagrams of carbon per year)

[a] Griscom et al. 2017, Woolf et al. 2010; [b] Griscom et al. 2017, Lal 2010, Paustian et al. 2016, Smith et al. 2008, Zomer et al. 2017; [c] Griscom et al. 2017, Henderson et al. 2015, Lal 2010, Paustian et al. 2016, Smith et al. 2008; [d] Griscom et al. 2017, Henderson et al. 2015, Lal 2010, Paustian et al. 2016, Smith et al. 2008, Zomer et al. 2017; [e] Griscom et al. 2017, Henderson et al. 2015, Lal 2010, Paustian et al. 2016, Smith et al. 2008, Zomer et al. 2017, Woolf et al. 2010

Land-based solutions that can help mitigate climate change fall into three general categories. The first category includes practices where the primary goal is to slow SOC losses. The second category includes the manipulation of plant species composition to increase SOC capture and associated storage. The third category, using natural and working lands, is the use of soil amendments. Below, we cover each of these in more detail.

Slowing carbon losses in agriculture

Some land use practices result in the loss of carbon from plants and soils. When carbon losses are slowed, emissions are reduced, and carbon storage is enhanced. Examples of land use practices that can slow

the loss of carbon from ecosystems include reduced or no tillage, improved grazing regimes, and fire management.

Tillage is the manual or mechanical practice of turning and agitating soils before planting. It is commonly used in agriculture to reduce weeds, mix soils, and incorporate dead plant material left over from the previous harvest. Tillage also breaks up soil aggregates, exposing soil organic matter to decomposition; tilled fields tend to have lower surface SOC than nontilled fields. Reducing tillage, or doing away with it altogether, decreases the rate of decomposition of soil organic matter and can lead to soil carbon sequestration. Rates of carbon gain tend to be slow, particularly if decreasing the amount of tillage slows the rate of plant growth. Slower plant growth can present challenges to farmers. Furthermore, low- or no-till soils have a greater potential to produce nitrous oxide. From a climate change perspective, the ultimate benefit of reduced- or no-till practices will be a function of the rate of new plant carbon inputs relative to the rate of soil organic matter decomposition and physical soil carbon losses, as well as overall greenhouse gas emissions. Improved tillage practices associated with maintaining soil cover have the potential to save 0.3 to 0.5 petagrams CO_2 per year.

Livestock grazing is another practice that can result in significant SOC losses. Grazing practices vary widely, from a few animals grazed for short periods to continuous grazing of large herds. Overgrazing can decrease the ability of plants to recover and can degrade soil resources, akin to overharvesting of an agricultural crop. Overgrazing can also compact soils and lead to SOC losses via erosion. Changes in grazing regimes that provide opportunities for plant regrowth can decrease the rate of SOC losses. Similarly, restricting herd size and movement during periods when soils are vulnerable (for example, when soils are very wet and thus easily compressed) can reduce SOC losses. Plant regrowth not only increases carbon capture, but also provides additional forage for livestock. Root regrowth can also help hold soil in place and limit erosional losses. Together, improved grazing practices are estimated to have the potential to save 0.2 to 0.7 petagrams CO_2e per year.

Fire leads to rapid carbon losses through the oxidation of plant biomass and surface organic material. By *oxidation* we are referring to the conversion of solid carbon to CO_2 and other carbon gases during

burning. Fire management is challenging. Attempts to suppress fire through management in regions where fire is a natural part of the landscape can have devastating results. Fuels, in the form of dead organic matter or standing biomass, can accumulate in the absence of fire, leading to hotter, more severe, uncontrolled fire events such as wildfires. Fuel management can reduce the chance of wildfire. Examples of fuel management include forest thinning, removal of downed wood, and grazing or mowing of grasslands and woodlands to remove residual dead plant material. Fire management not only decreases the amount of carbon loss via severe fire events, but also facilitates plant growth and associated CO_2 capture. The potential of fire management to lower greenhouse gas emissions and increase soil carbon storage is poorly understood at a global scale. Preliminary estimates suggest that carbon savings of 0.2 to 0.4 petagrams CO_2e are possible.

Plant species–based approaches

The carbon-friendly management of plant species and communities can take many forms, but some of the best-documented examples include the planting of cover crops, use of plant species with typically high root biomass, conversion from annual to perennial crops, crop rotation using perennial plant species, agroforestry, and wetland restoration.

Cover crops can increase carbon capture by increasing the length of time that plants are active in an ecosystem. In some forms of crop agriculture, soil is left bare during the fallow periods in between growing seasons. Bare soil is vulnerable to erosion and associated carbon losses, and the lack of live plants means that CO_2 is not being captured. Nitrogen-fixing cover crops can increase the nitrogen content of the soil, reducing the need for inorganic fertilizer, as mentioned above. Species that tend to build large root systems are particularly helpful for sequestering SOC, as most SOC is thought to be dominantly derived from root biomass.

Similarly, the use of perennial crops, alone or in crop rotations or with agroforestry, can increase carbon capture and sequestration. Annual crops live out their entire life cycle within a single year. Examples of important annual crops include corn, wheat, rice, and soy. Annual plants must grow from seed each year, establishing new root systems and

aboveground plant parts. Perennial plants such as alfalfa, grapes, artichokes, asparagus, and tree crops persist for multiple years. In the case of tree crops, the below- and aboveground plant parts remain on the landscape. In the case of nonwoody plants like alfalfa, the aboveground plant parts may die back or be harvested, while the root system remains and becomes reactivated during the next growing season. There are many advantages of perennial crops from a carbon perspective. Perennial crops often have a longer growing season, as they have greater access to soil resources. A longer growing season translates into greater potential for carbon capture from the atmosphere and storage in soil, even past the time when the fruit or vegetable is harvested. Deeper, more extensive root systems can access water and nutrients not available to annual species. The maintenance of perennial root systems helps hold the soil in place, limiting erosion and associated carbon losses. Perennial species are often used to rehabilitate degraded, overgrazed, or overharvested lands. Although carbon sequestration rates can be slow, owing to lack of nutrient and water resources, the use of perennials can be an effective climate change mitigation approach for degraded soils. Crop selection and conservation agriculture techniques (particularly the use of cover crops) combined can save 0.3 to 1 petagrams CO_2e per year.

Wetland plant species can also contribute to climate change mitigation. Wetlands in some regions have been drained for agriculture because the underlying peat soil is often rich in organic matter and nutrients. However, when peat soils are exposed to the atmosphere and become aerated, the organic matter decomposes rapidly. In the Sacramento–San Joaquin Delta of California, the biggest freshwater wetland in the western US, wetland drainage has led to the loss of approximately 1 petagram of carbon to the atmosphere. The loss of SOC has contributed to land subsidence. In some areas, the land surface has dropped 10 meters or more (Figure 16.5.2).

Wetland restoration has the potential to sequester carbon by restoring peat soils. Estuarine, swamp, and marsh wetlands are among the most productive ecosystems in the world, meaning that they have the highest rates of CO_2 capture and conversion, globally. Plant growth in these wetlands benefits from high soil moisture year round and the

FIGURE 16.5.2 Soil subsidence in the Sacramento–San Joaquin Delta of California. Wetland drainage led to the decomposition of soil organic matter, leading the land surface to drop over time. Reproduced from USGS.

near-constant input of nutrients leached from upslope sources. Wetland restoration could potentially save 0.3 to 1.3 petagrams CO_2e per year. Wetland flooding helps create anaerobic conditions in soils that slow organic matter decomposition. Thus, high rates of carbon capture by wetland plants coupled with low decomposition rates in wetland soils lead to rapid rates of organic carbon accumulation in soils. The anaerobic conditions in wetland soils can also lead to methane production and emissions. The net benefit of wetland restoration for climate change mitigation must carefully consider the balance between carbon sequestration and methane emissions. Wetland restoration also provides many co-benefits, including reduced flood risk and increased downstream water quality.

Soil amendments

Enhancing the soil environment directly is another carbon sequestration approach. Fertilizer, water, and organic amendments are approaches that are commonly used to increase plant growth and enhance soil organic matter and SOC storage. Fertilizer applications, as discussed above, can stimulate plant growth and associated carbon capture. However, nitrogen-based inorganic fertilizers, and even some organic fertilizers, can also result in high carbon costs during production and increased emissions of nitrous oxide from soils. Thus, a full greenhouse gas and carbon accounting is necessary to determine the costs and benefits of fertilization for climate change mitigation.

Irrigation is also used in agricultural ecosystems to enhance plant growth. Irrigation helps land managers maintain optimal soil moisture conditions for plant productivity. Periodic drought associated with natural climate patterns (that is, annual dry seasons) can limit plant growth to the rainy months of the year. Irrigation can be used to lengthen the growing season and to minimize the impacts of rainfall variability. Approximately 89 million acre-feet of water (1 acre-foot = 326,000 gallons) was applied to farmland in the US in 2013. Over 82% of that water was applied to farms in the western US alone, because of the strong rainfall seasonality in the region. Where irrigation increases plant growth, it has the potential to also increase soil carbon sequestration. However, increasing soil moisture can also stimulate microbial decomposition and the loss of SOC from soils. Careful management of the timing and amount of irrigation, as well as the way it is applied (subsurface, drip, or sprinkler systems), can help limit SOC losses. Overwatering can lead to soil water saturation, the development of anaerobic conditions, and the emissions of nitrous oxide and methane.

Transporting and applying water represent some of the carbon costs of irrigation, although the actual emissions are very difficult to quantify. Transport-related greenhouse gas emissions from irrigation depend upon the distance the water has to travel and the change in elevation required to bring water to the site of delivery. Climate change–related increases in drought frequency and severity, particularly in regions like the western US, are likely to result in additional greenhouse gas emissions from water transportation. Estimates of the potential CO_2e costs and savings from improved irrigation are lacking at a global scale.

Organic matter amendments are another land use practice that has potential to help mitigate climate change. Organic matter amendments can take many forms, from residual plant material not utilized from a harvest, such as corn stover, to livestock manure, composted urban or agricultural organic waste, and biochar produced by burning organic materials. Adding organic matter to soils is thought to increase the chances for soil organic matter formation. However, the application of fresh plant material (called green waste) to the soil surface often leads to higher emissions of CO_2 due to the stimulation of microbial activity. This stimulation, call the priming effect, can lead to the loss of some

of the existing SOC stock, although the duration and amount of SOC loss is variable and dependent upon a suite of environmental factors. The application of raw animal wastes has been shown to increase SOC storage but also leads to emissions of nitrous oxide. As nitrous oxide is a much more potent greenhouse gas than CO_2 with regard to atmospheric warming potential, the net benefit of soil amendments of livestock manures can be low or even negative—leading the ecosystem to become a net contributor to climate change.

Composting organic material before land application can significantly decrease the rate of decomposition and greenhouse gas emissions and lead to net carbon sequestration in soils. Composting organic waste also removes the waste from high-emitting sources such as landfills and manure ponds, leading to large greenhouse gas savings. For example, composted green waste applied to just 5% of California's grasslands resulted in a net savings of 28 million metric tons of CO_2e over 3 years. Much of this savings came from reducing methane and nitrous oxide emissions from waste management, while the remainder came from the new carbon added to soil via enhanced plant growth and the additional storage of the compost carbon added as the amendment. Preliminary estimates based on the generation of organic waste suggest that composted organic amendments could save on the order of 2 petagrams CO_2e per year globally.

Biochar is an amendment that is produced from the burning of organic residues and waste. Under some conditions, biochar has the potential to remain for years, decades, or longer, although the actual decomposition rate is dependent upon the chemical and physical characteristics of the biochar, as well as the climate and soil characteristics of where it is applied. Biochar can act as a slow-release fertilizer similar to compost and can improve other soil chemical and physical characteristics, including soil aeration and drainage. This can lead to enhanced plant growth and associated carbon capture and storage. Estimates of the carbon savings from biochar amendments vary widely, as this is a relatively new approach for climate change mitigation in the agricultural sector. Scientists estimate that carbon savings range from less than 1 to over 2.5 petagrams of carbon per year.

16.6 What Have We Learned So Far?

Natural and working lands can both contribute to climate change and help to mitigate it. What is needed to bend the curve? *"Carbon-friendly" land management is key* to reducing emissions and increasing carbon capture, conversion, and storage. *Field-tested solutions are needed*. These must consider the full life cycle of carbon and greenhouse gases to be truly effective. *A systems perspective is critical*. Ecosystems are complex, and thus cross- and multidisciplinary collaborations may be necessary to devise and implement comprehensive climate change solutions for natural and working lands. *In addition to research, training and outreach are important components of successful strategies*. Educating yourselves and others on the concepts of the carbon cycle and our ability to alter it through everyday decisions is perhaps the most effective strategy to solving the climate change crisis. Making decisions about how to fertilize fields and supporting climate-friendly practices with our purchasing power are examples of actions that we can take today.

Summary

- Greenhouse gas emissions reduction is critical for slowing climate change, but emissions reduction alone is no longer sufficient to solve the problem. We must remove carbon dioxide from the atmosphere to bend the curve.
- Ecosystems are complex and management approaches must embrace that complexity to be successful. Trade-offs, for example between carbon sequestration and enhanced greenhouse gas emissions, need to be identified, quantified, and carefully weighed for effective climate change mitigation outcomes.
- Plants need CO_2 from the atmosphere to survive and grow. They convert CO_2 to plant tissues via photosynthesis. The annual pattern

in the drawdown of CO_2 by plants is evident at a global scale in the concentrations of atmospheric CO_2.

- Microorganisms in the soil break down plant litter into soil organic matter. Microbes also respire CO_2, returning some of the carbon originally captured by plants to the atmosphere, completing the carbon cycle. The annual pattern in respiration of soil microorganisms is detectable at a global scale in the concentrations of atmospheric CO_2.
- Plants and soils are reservoirs of carbon. Soils are the largest reservoir of carbon on the land surface. Plants are a smaller reservoir of carbon but are key conduits for moving carbon from the atmosphere to the soil.
- Soils are the basis for life on Earth. They are a complex mixture of minerals and organic matter. They house and feed microorganisms and support plants. They are a source and a sink of greenhouse gases.
- All ecosystems produce some greenhouse gases, as this is an indicator of life. Land management can increase greenhouse gas emissions. Agriculture accounts for approximately 25% of global greenhouse gas emissions.
- Soil organic matter contains carbon that was originally captured by plants. Soil organic carbon pools vary across locations because they are affected by climate, by plant, animal, and microbial species, and by underlying geology.
- Soils can accumulate organic carbon when the rate of inputs exceeds the rate of losses. This is called soil carbon sequestration.
- Photosynthesis can be thought of as a "technology" that has been perfected and deployed for over 2 billion years. The rate of atmospheric carbon uptake by plants via photosynthesis dwarfs all other forms of carbon capture.
- Plants can accumulate and store carbon. Trees and forests store more carbon than other plant life. Forest carbon is vulnerable to fire and logging, as well as pest outbreaks. Tropical deforestation accounts for 10% of annual greenhouse gas emissions globally.

- Emissions reduction from working lands is critical for climate change mitigation. There are several possible ways to lower emissions. Many of these approaches have valuable co-benefits for land owners and managers. Fertilizer and livestock waste management are examples of promising avenues for emissions reduction.
- Soil carbon sequestration holds great potential as a carbon sink. Large areas of the land surface have become depleted in soil organic carbon through management over the last 12,000 years. Many land use practices have already been shown to increase soil carbon storage.
- Soil carbon sinks can be divided into three categories: those that slow emissions and allow carbon to accumulate, those that increase the rate of carbon capture by plants, and those that use amendments to stimulate plant growth, increase carbon storage, and reduce emissions in other sectors.

Sources for the Figures

Figure 16.1.1: UCAR Center for Science Education. https://scied.ucar.edu/carbon-cycle.

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PART THREE

Current Topics

CHAPTER 17

Sea Level Rise from Melting Ice

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UC Irvine

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Learning Objectives

1. Describe how ice sheets melt in the polar regions.
2. Understand the history of melting and the tools used to unveil its recent history.
3. Understand the dynamic effects of melting across socioeconomic levels and how to curb these effects.

Overview

Glaciers and ice sheets in Greenland, Antarctica, and other parts of the world are melting as a result of climate change resulting from human-induced emissions of greenhouse gases. The rates of ice melt have increased by one order of magnitude in the last 40 years and will likely continue to increase rapidly in the next 40 years. At the current accelerated rate of ice melt, sea level will rise by about 1 meter by the end of the twenty-first century, but the actual number will depend on both the rate at which our climate continues to warm up and the rate at which ice sheets undergo catastrophic retreat and melt, especially in the marine-based sectors of the ice sheets. Large uncertainties remain in both processes. Meanwhile, paleoclimate records and basic physics dictate that the current regime of climate warming is unsustainable for ice sheets and that continued warming commits us to multiple-meter sea level rise in the coming centuries. A reduction in the rate of ice melt is possible but entails a massive curbing of our greenhouse gas emissions and the implementation of carbon sequestration to bring carbon concentration in the atmosphere back to lower levels.

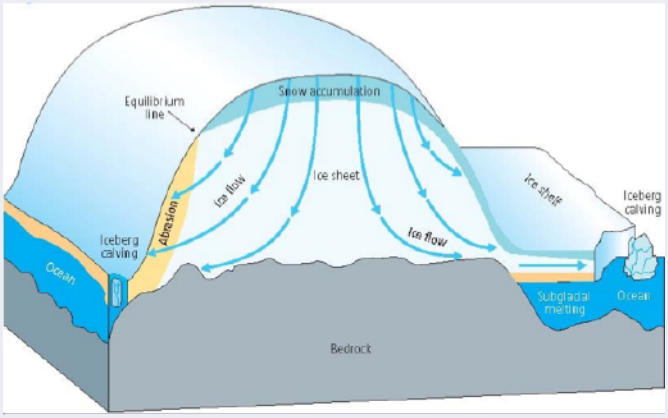
The ice sheets in Greenland and Antarctica contain large volumes of ice, equivalent to a change in global sea level of 7 meters (43 feet) for Greenland and 56 meters (360 feet) for Antarctica if all the ice were to melt into the sea. This is because the ice sheets hold several quadrillion tons of land ice. One billion tons is called 1 gigaton (Gt), and 361 Gt of land ice melting into the ocean would cause 1 millimeter (mm) of global sea level change. One gigaton of water is the annual supply of water for a city the size of Los Angeles and its 8 million inhabitants. We use gigatons to quantify the mass loss of ice sheets.

FIGURE 17.1 Calving front of Getz ice shelf, West Antarctica, with 50-meter-tall ice cliffs. Photograph by Jeremy Hardbeck, NASA.

The average precipitation on Earth is 1 meter per year. Greenland (average precipitation 24 centimeters per year) and Antarctica (average precipitation 17 centimeters per year) qualify as deserts (the Sahara gets 10 centimeters per year). Yet their combined annual cycle of precipitation is equivalent to a 7-millimeter fluctuation in global sea level because they cover such large areas, about 1.7 million square kilometers for Greenland and 14 million for Antarctica.

Ice accumulates in Greenland and Antarctica from snowfall, which slowly densifies into ice and deforms under its own weight to flow toward the ocean along rivers of ice called **ice streams** and glaciers. At the ocean boundary, ice melts in contact with ocean water or is released as icebergs that subsequently melt in the ocean. At the surface, snow/ice mass is removed via wind transport, sublimation, evaporation, and surface melt. Surface melt that does not refreeze in place produces runoff, which reaches the bottom of the glacier, or bed, through cracks and holes (known as moulins). It emerges at the **ice front** (where ice meets ocean water; Figure 17.1) or at the **grounding line** (where ice detaches from the bed and becomes afloat in the ocean) as a buoyant plume of freshwater, often laden with sediments. Runoff in Greenland averages about 300 Gt per year, and the **ice flux** crossing the glacier fronts or grounding lines averages 400 Gt per year. In Antarctica, the ice flux

Greenland
R = 300 Gt/yr
D = 300 Gt/yr



Antarctica
R = 0 Gt/yr
D = 2,200 Gt/yr

FIGURE 17.2 The Greenland and Antarctic ice sheets form from the slow accumulation of snowfall, which densifies into ice, which deforms under its own weight. Snowfall at the poles is low by global standard: 24 centimeters per year in Greenland, 17 centimeters per year in Antarctica. However, the Greenland ice sheet contains enough ice to raise global sea level by 7 meters, and that figure is 56 meters for Antarctica. When 360 gigatons (Gt) of ice melt in the ocean, that raises sea level by 1 millimeter. One gigaton is the amount of water consumed by a large city like Los Angeles in a year. The transfer of mass by the glaciers and the amount of melt at the surface are measured in gigatons per year (Gt/yr). R is the annual runoff production and D is the annual discharge of ice for the ice sheets, averaged for the years 1961–1990 (Greenland in blue, Antarctica in red). Adapted from NASA.

crossing the grounding line is 2,200 Gt per year and runoff is nearly zero at present (Figure 17.2).

Glaciers and ice sheets move from a few centimeters per year near **ice divides** to a few kilometers per year at the front of the fastest-moving glaciers. Around 13,000 years ago, sea level rose 4 meters per century for several centuries. This rapid sea level rise was associated with the collapse of the northern ice sheets, including parts of Greenland, northern Canada, and Scandinavia, but also parts of West Antarctica and, presumably, parts of East Antarctica yet to be identified. During the Holocene, sea level rose, in comparison, very slowly before rising 1.8 millimeters per year in the twentieth century and 3 millimeters per year at present. This rate is projected to increase as climate continues to warm up, land ice melts worldwide, and the oceans continue their **thermal expansion**. While the glaciers and ice sheets already control

two-thirds of the global increase in sea level rise today, we expect greater rates of sea level rise in the future as the ice sheets in Greenland and Antarctica start melting faster. We face the distinct possibility that ice sheets will contribute multiple meters of sea level rise in the future.

Millions of people and trillions of dollars of infrastructure located along the coastlines of the world's oceans will be threatened by as little as 1 meter (3 feet) of sea level rise, which is almost certain to happen by the end of the twenty-first century, and multiple meters of sea level rise are expected in the ensuing centuries. While adaptation may be possible in some places, people in many low-lying underdeveloped countries will have to move to higher ground or to other countries. Moving infrastructure such as industries, roads, housing, seaports, airports, and other critical facilities will cost trillions of dollars.

At present, predictions of sea level rise are affected by two major uncertainties: (1) the rate at which our emission of greenhouse gases into the atmosphere will continue to increase and warm the planet, and (2) the rate at which ice sheets and glaciers will respond to climate warming and collapse, which depends on physical processes that have not been fully elucidated and incorporated into physical climate models. Most current numerical ice sheet models use simplified and incomplete physical descriptions of ice sheet and ocean dynamics that systematically underestimate the risk of catastrophic melting. In the next sections, we will discuss the physical processes of ice melting, the history of melting, and what we can do about it.

17.1 How Ice Is Melting

Surface melt and runoff

In Greenland, ice and snow that melts at the surface of the **ice sheet** is transported by supraglacial rivers, which end up in large holes in the ice, called moulins, that go straight into the ice for hundreds of meters before migrating in a complex set of horizontal and vertical galleries that ultimately connect the water from the surface to the bed (Figure 17.1.1). Water pressure slowly builds up at the bed in early summer and eventually becomes high enough to overcome the overburden pressure of ice, lifting the ice off the bed so it can slide faster downhill. Subglacial water flows beneath the ice along a network of subglacial channels that are initially disconnected. Eventually, the subglacial channels become connected and reach the ocean, subglacial water pressure is released, and ice again comes into contact with the bed, which stops its enhanced sliding. As more meltwater pours down from the surface to reach the bed, the speedup occurs sooner and is larger in magnitude, but it extends over shorter time periods because the subglacial channels become connected sooner. Overall, in Greenland the summer speedup averages about 10% for a period of 2–3 months; that is, enhanced sliding has only a small impact on the annual mass loss from the ice sheet. This enhanced sliding is often presented in news media as a main process of acceleration of ice toward the ocean, but in reality, we have learned that it is not a major process of ice loss.

Other aspects of snow/ice melt are important. A higher production of meltwater at the surface results in the formation of supraglacial lakes that may break up and cause flooding, a natural hazard. In addition, as snow melts, it is replaced by the underlying ice, and as ice melts, it is replaced by standing liquid water. The **albedo** of fresh snow is 90%; that is, it reflects 90% of the incoming sun energy and absorbs only 10% as heat that melts snow. In comparison, the albedo of ice is 35%, so 65%

FIGURE 17.1.1 Ice and snowmelt at the surface of Greenland are transported in supraglacial rivers like this one, which ends up in a big hole called a moulin. The moulin goes 100 meters vertically, then connects horizontally and eventually brings water to the bed. The bed is wet. Water pressure at the bed can be high enough to lift the ice. When that happens, the ice moves faster, at least temporarily. Photograph reproduced with permission from *The New York Times* from Davenport et al. 2015.

of the incoming energy is absorbed. The albedo of liquid water is only 3%, meaning that 97% of the incoming energy is absorbed as heat. As the ice sheet melts away, its surface changes from strongly reflective to strongly absorptive by nearly a factor of 10. This **positive feedback** keeps pushing the ice sheet out of mass equilibrium.

Another positive feedback is the elevation feedback: As ice melts, the snow/ice surface migrates to a lower elevation, becomes exposed to warmer air temperatures, and melts faster. Similarly, as the ice margins get exposed to the atmosphere when ice melts away, more ice melts, and rocks, fine glacial debris, and dust with no vegetation to hold it are exposed. Dust gets blown away onto the glaciers by the prevailing winds, which makes ice and snow dirty, lowering their albedo, and increasing melt.

The largest positive feedback affecting climate warming, however, is a change in ice flow dynamics, that is, the speed of glaciers, as discussed next.

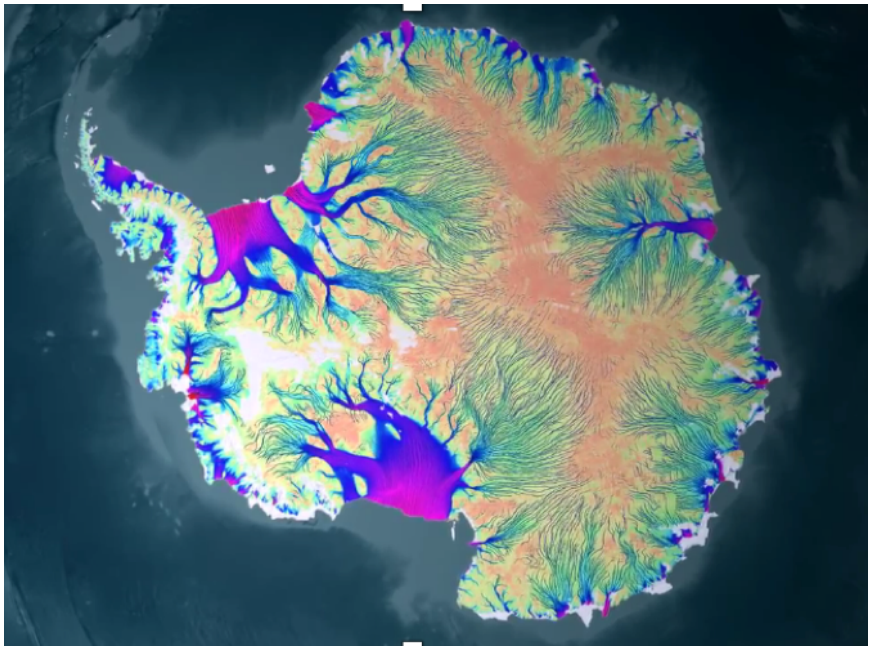


Figure 17.1.2 To a photographer in space, Antarctica looks like a vast white continent with no life. Using radar imagery and tracking the scintillation of the surface, scientists can measure the rate of deformation of the ice with amazing precision—a few millimeters per day. This visualization shows ice flow in Antarctica. Flow speed is highest in purple to red areas and low in brown to green. The rivers of ice, or glaciers, reach far into the continent and drain ice into narrow corridors at a few locations along the coast. The glaciers control the flow of ice into the sea. If they flow slowly, the ice sheet grows; if they flow quickly, the ice sheet shrinks. From Rignot et al. 2011.

Ice discharge

The second major process of "melting" or ice removal from the ice sheets is the rate at which ice is transported by glaciers and ice streams into the ocean (Figure 17.1.2). When ice reaches the glacier front, several scenarios may take place. Ice may melt in contact with ocean waters, or it may break up into blocks called icebergs. In Greenland, it is not uncommon for icebergs to "explode" into a myriad of small pieces during their detachment from an ice face, because the blocks of ice are too small to remain cohesive under their own weight. Iceberg debris generated in a matter of minutes quickly dissipate into the ocean. Ocean water is a very efficient "solvent" of land ice because the melting

point of the seawater-ice mixture is to −2°C, reduced from 0°C for pure water.

As the climate warms up, glaciers produce smaller and smaller icebergs. In Antarctica, where the climate is colder, icebergs are larger and more cohesive and do not explode into a myriad of pieces. They are called tabular icebergs because they form large "tables of ice" several kilometers to tens of kilometers in size afloat in the ocean. They do not flip over as they detach, as the icebergs in Greenland do because they are taller than wide and hence flip to the side when they detach, which helps them break up and melt. In contrast, an Antarctic iceberg will survive for years or decades in the ocean.

Traditional books of glaciology state that iceberg production is the main process of mass loss in Antarctica. We have learned in the last 20 years, though, that a significant part of mass loss proceeds directly from below due to ice melt by the ocean (Figure 17.1.3). This means that ocean warming, or changes in the advection of ocean heat toward the glaciers, or both, is a **climate forcing** that plays a major role in the evolution of glaciers around Greenland and Antarctica. As frontal ice breaks up and melts away, the inland ice flows faster, effectively unplugging the land ice to spill out into the ocean.

Ice that is already afloat in the ocean does not change the mass of the ocean or sea level when it melts; in fact, it lowers sea level (by only 2.6%) due to dilution. Ice that rests on land above sea level does raise sea level when it melts into the ocean, at a rate of 1 millimeter for every 361 Gt of ice.

Iceberg calving

Icebergs detach from glaciers or ice shelf fronts when the tensile stress of ice, that is, the rate at which ice is stretched longitudinally by the speedup of ice flow toward the ocean margin, exceeds a threshold. That threshold depends on ice fabrics, ice temperature, and preconditioning of the ice to break up, for example, the presence of cracks or bottom crevasses. Icebergs may also detach when ice blocks are sufficiently close to flotation that they freely rotate off the ice face and fall into the ocean. In the case of an **ice shelf**, where ice is partly attached to land and partly floating on water, we have also witnessed a domino-like

FIGURE 17.1.3 When ice reaches the ocean, it melts in contact with warm, salty ocean water, and it also breaks into icebergs like this one on Helheim Glacier that is 800 meters tall and 3 kilometers wide. Everyone has heard about icebergs. For a long time, scientists thought that most of the meltwater reaching the ocean was due to the breakup of icebergs. In the 1990s, we learned that a lot of ice is melted from below, by the ocean, orders of magnitude faster than at the surface. Photograph reproduced with permission from Denise Holland.

effect: as unstable blocks of ice detach and rotate off the ice shelf front, they may bang back into the ice shelf and generate more calving events. If cracks preexist in the ice shelf, as in the case of the Larsen B ice shelf in the Antarctic Peninsula, the detaching of an iceberg triggers a chain reaction that breaks up the entire ice shelf in a matter of weeks. Conversely, it would take centuries to re-form these ice shelves if we were to let the land ice expand freely into the ocean again, at the same original speed, until it reaches the former position of the ice shelf front.

Scientists have examined the impact of surface meltwater and its role in hydrofracturing ice. Another process is "ice cliff failure" whereby ice cliffs above a certain height can no longer support the ice pressure, fail, and break off. These two calving processes may explain episodes of rapid sea level change that took place in the past. When applied to the present-day evolution of the Antarctic ice sheet, these calving processes yield a sea level rise greater than 1 meter by the end of the century.

Another form of calving that is important in Greenland but which

has been highlighted only recently is undercutting. In that process, ice melting by the ocean is most effective at depth; that is, the ocean waters undercut the glacier front. The ice above the cut is then not supported by its base, so it breaks up, independent of the tensile stress or height above flotation. This form of calving is driven by the temperature of the ocean: the warmer the water, the higher the melt rate, and the faster the ice is undercut. It is also affected by the production of subglacial meltwater, discharged at the base of the glacier front, which is buoyantly driven up the water column and entrains warm ocean water along the ice face to melt it. In Greenland, the process of undercutting is comparable in magnitude to the mass loss from "dry" calving by tensile stress and block rotation, but the partitioning between the two varies considerably from one glacier to the next.

Understanding how the calving of icebergs changes as a result of climate warming is an important topic of ongoing research. We need to quantify the roles of hydrofracture, the mixture of ice and sea ice that glues large pieces of ice shelf together before they break away from an ice front, fabrics, temperature, and the stress regime at calving margins. We expect the calving rate of glaciers to increase in a warmer climate, but quantifying the increase has remained challenging because of a lack of observations.

The marine ice sheet instability

A most important process of evolution of ice sheets and glaciers is called the **marine ice sheet instability** (**MISI**). This concept was proposed in the 1960s by a number of glaciologists, including Weertman (1974), Thomas and Bentley (1978), and Hughes (1981), and observed in the case of marine-terminating glaciers in Alaska, where it was referred to as the "tidewater glacier cycle," by Meier and Post (1988) (Figure 17.1.4). We had to wait until the 1990s and early 2000s to verify the concept of marine instability in ice sheets, but scientists studying tidewater glaciers in Alaska knew it decades earlier.

If a glacier stands on a **retrograde slope**, that is, where the bedrock slopes downward in the inland direction, there are only two stable states for the glacier: either it reaches the outer edge of that slope and remains stable at that location, or it **retreats** inland until either the bedrock slopes upward or the entire glacier is afloat in water between the

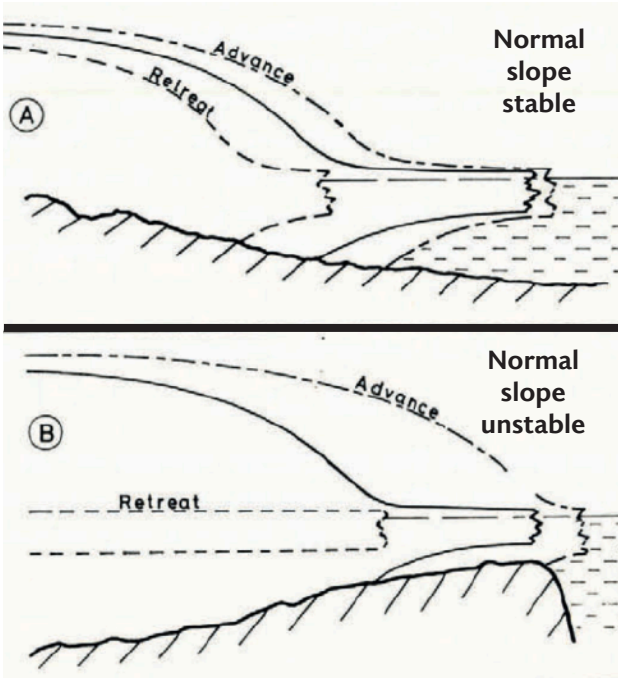


FIGURE 17.1.4 **The most important concept for ice sheets in a warmer world is the concept of marine ice sheet instability (MISI). If a marine-terminating glacier ends in the ocean on a normal (prograde) slope, that is, with bed elevation increasing inland, any glacier retreat or advance will be slow, as there are many stable positions. If the glacier is on a reverse (retrograde) slope, that is, with bed elevation dropping in the inland direction, there are only two stable states: either it reaches the edge of the continental shelf, or it becomes entirely afloat in the ocean. Once initiated, the MISI retreat is in principle (considering one-dimensional geometry) unstoppable.** From Thomas 1979.

glacier and the bedrock. In other words, glaciers resting on retrograde slopes are inherently unstable and prone to rapid retreat. In Alaska, the edge of the slope is a moraine created by the glacier during a prior advance. If the glacier retreats from the moraine because of climate forcing, for example, warmer ocean waters melt the ice faster than in the past, the retreat will proceed rapidly, in a nonclimatic fashion, until the ice front reaches a new bed position where the bedrock elevation rises again in the inland direction. This could be many kilometers inland. For Columbia Glacier in Alaska, the retreat that started in the 1980s will proceed for another 50 kilometers along a retrograde bed. Conversely, if the bedrock slope is prograde (slopes downward in the ocean direction), the glacier retreat will be slow and may even stop.

The effect of a retrograde slope is large because ice deformation exhibits a nonlinear dependence on ice thickness. The strain of deformation of ice varies as the third power of the thickness, and the speed of the ice varies as the fourth power of ice thickness. Hence a drop in bed elevation as the ice front moves inland translates into an accelerating response of the ice tensile stress, with sliding and ice breakup into the ocean. This is the marine ice sheet instability.

In practice, the MISI is complicated by two dimensional effects. The glacier and its floating extension in the ocean—the ice shelf—experience friction along valley walls (lateral shear), islands (longitudinal back-stress), and bumps in bedrock topography (basal friction), so a glacier on a retrograde slope may not be systematically unstable and hence capable of unstoppable and rapid retreat. To address that possibility, precise observations of bed topography, detailed understanding of the ice flow mechanics, proper scenarios of climate forcing, and the usage of a coupled ocean-ice numerical model are essential.

We have already witnessed examples of MISI in present-day ice sheets: (1) the Jakobshavn Isbrae Glacier, the largest discharger of ice in Greenland; and (2) the Pine Island, Thwaites, and Smith Glaciers draining into the Amundsen Sea Embayment of West Antarctica, the largest dischargers of ice in Antarctica. Scientists think that the retreat of ice in these areas is ongoing and unstoppable. There are, however, other sectors at risk of MISI around North Greenland and East Antarctica.

Ocean heat and its impact on ice sheets

How could more ocean heat be brought into contact with ice in a warming climate? The physical processes are the same in the Arctic and Antarctic—ocean heat is driven by wind—but the details differ. In both polar regions, we find cold, fresh water at the top of the water column and warm, salty water at the bottom, about 200–300 meters below the surface in Greenland and 400–500 meters in Antarctica (Figure 17.1.5). This configuration is opposite to that in the tropics, where warm, fresh water sits atop cold, salty water. In polar regions, colder air temperatures cool the surface, and the freezing of seawater forms sea ice, which loses its salt. This produces salty water that sinks to the ocean bottom and participates in the global **thermohaline circulation of the ocean**.

Depending on prevailing winds and the depth of the seafloor around the ice sheets, ocean heat may or may not reach the glaciers. Prevailing winds are affected by climate change. Seafloor depth differs where deep channels have been carved into the seafloor by prior advances of the glaciers. Wind characteristics, depth, and ocean temperature all must be known if they are to be used in numerical ocean and ice models.

When warm seawater reaches the glaciers or ice shelves, it fuels

FIGURE 17.1.5 In polar seas, ocean heat is found several hundred meters below the surface in the form of warm, salty water. Surface waters are comparatively cold and fresh. Winds transport ocean heat toward the glacier, and a thermohaline circulation ventilates the ice shelf cavities as in this figure. Melt rates of 100 meters per year in Antarctica and several meters per day in Greenland are generated in this manner. In the Antarctic, heat comes from the Antarctic Circumpolar Current. In Greenland, it comes from the subtropics. Reproduced from NASA.

rapid rates of ice melt because ocean water has a melting point of −2°C (versus 0°C for freshwater ice) and the melting point decreases with pressure by 0.75°C per kilometer of water, hence it is −3.5°C at 2 kilometers depth. If warm seawater does not reach the glaciers, that is, if the glaciers stand in cold water, ice melts slowly. In Antarctica, the largest observed melt rates are of the order of 100–200 meters per year. In Greenland, the melt rates reach 2–3 meters per day, that is, one order of magnitude larger than in Antarctica. Conversely, in cold parts of Antarctica, melt rates may drop to values as low as 10 centimeters per year. In some places, ice may even cease to melt completely. Instead, typically up to 100 kilometers from the grounding line, seawater may freeze onto the ice shelf bottom, creating a layer of "marine ice." Marine ice may accumulate by about 100 meters over time (decades to centuries).

In the Antarctic, ocean heat originates from the Antarctic Circumpolar Current (ACC), which is a broad area of subsurface warm, salty water that encircles the continent, clockwise, pushed by the westerly winds (Figure 17.1.6). In some parts of the Southern Ocean, the ACC is close

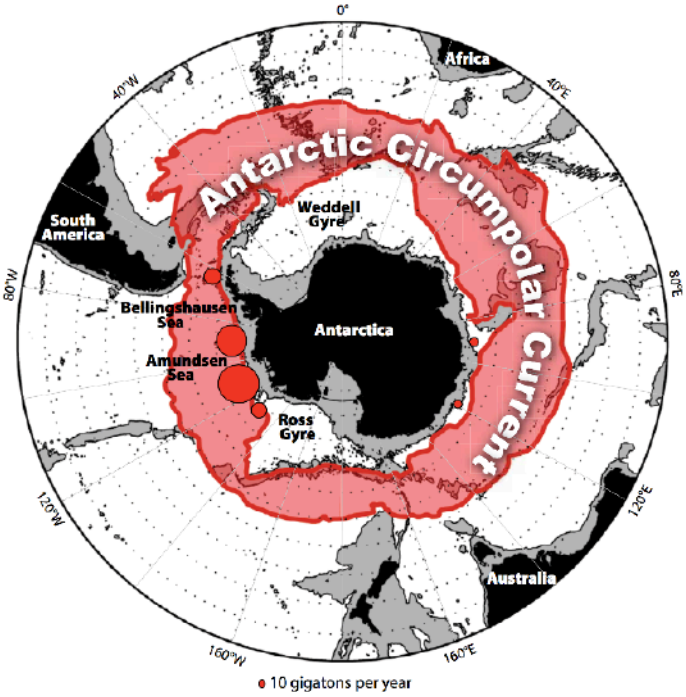


FIGURE 17.1.6 **In Antarctica, ocean heat is contained in the Antarctic Circumpolar Current (ACC). Warm water, about +2°C, is present at 400–700 meters below the surface. At the surface, the water is cold and fresh. Prevailing westerly winds push the ACC in a clockwise direction. The Coriolis force displaces the surface water to the north (left) and displaces the subsurface warm, salty water to the south (right). With climate warming in most of the world and cooling in Antarctica under the ozone hole, the winds are getting stronger and displacing more warm water toward Antarctica.** From Gille et al. 2016.

to the continent, for example, in the Amundsen Sea Embayment of West Antarctica and in the western Antarctic Peninsula. In other parts it is far from the coast, for example, in the Weddell Sea and in the Ross Sea. Since the 1980s, the westerlies have increased in strength and started to contract southward. This is due to an increase in the temperature difference between Antarctica and the rest of the world. Antarctica is not warming as fast as the rest of the world, because a decrease in the ozone concentration in the stratosphere above cools Antarctica, and it experiences a slower rate of warming from greenhouse gas emissions than the rest of the world because of a lack of albedo feedback. As a result of the Coriolis effect, the winds tend to push surface waters to the north (to the left of the wind), which contributes to the slight extension of sea ice cover with time, and to push subsurface waters to the south (to the right), which brings more subsurface ocean heat toward Antarctica's glaciers. As more heat reaches Antarctica's coast, glaciers and ice shelves melt faster from below, which reduces the buttressing force in front of them, leads the glaciers to speed up, and increases sea level.

In Greenland, warm water is transported north from the subtropics

by the Gulf Stream, which is deviated by Iceland to form the Irminger Current, which runs along southeast Greenland, rounds the tip of Greenland, and reaches the Labrador Sea. Some of that warm water makes it into Baffin Bay through Davis Strait, circles counterclockwise inside Baffin Bay, and returns south along the coast of Canada. To the east, a branch of the North Atlantic Current returns cold water from the High Arctic along the east coast of Greenland and meets the Irminger Current southeast of Greenland. These currents contribute to the North Atlantic gyre, which allows warm, salty Atlantic Water (AW) to intrude onto the continental shelf and glacial valleys by following troughs on the seafloor that have been carved by former glacier advances during ice ages. The strength of the North Atlantic gyre is affected by fluctuations of the jet stream, itself affected by climate change.

At present, the Arctic is warming up 2–3 times faster than the rest of the world. As the temperature differential between the Arctic and the rest of the world decreases, the strength of the jet stream is reduced, allowing it to wobble, that is, undergo large excursions and incursions north and south. In some of the lobes of the Rossby waves—global air pressure waves high in the atmosphere—cold Arctic air flows unusually far south, which creates cold snaps along the east coast of the United States, for instance. In other lobes, warm air from the subtropics intrudes far north, which creates unusually warm winters in Greenland. Models suggest that as the jet stream wobbles, the lobes tend to become stationary, hence the unusual flow of cold, and air masses may persist for long periods of time. This simple explanation of Arctic changes is in debate but offers an explanation for changes taking place in the north. If the models are correct, the wobbling will send more warm air and ocean masses toward Greenland than in the past, which will melt the glaciers from above and below faster than in the past.

In both Greenland and Antarctica, the amount of warm, salty subsurface ocean water pushed by the prevailing winds toward the glaciers has been changing in response to climate change, which is caused by human activities.

17.2 History of Melting

Ice sheet mass loss through recent times

Since the early 1990s, scientists have been using a new set of precise, powerful tools to measure the ice sheets—satellites, complemented by dedicated airborne surveys to measure the ice sheets at an unprecedented level of precision. Satellite instruments observe whole ice sheets and collect precise measurements of all their glaciers, from about 800 kilometers above ground, day in and day out, over days to years and decades, in a comprehensive and uniform fashion. These observations are possible as a result of massive technological advances and engineering achievements in remote sensing over the last 40 years.

There are three main ways to measure the ice sheets. In the mass budget technique, we compare the mass added to the continent by snowfall, reconstructed by regional atmospheric climate models, with the mass flux into the ocean along the periphery, obtained by combining ice thickness from airborne radar sounders and ice speed from satellite radar interferometers. The mass budget record goes back to the 1970s. The mass budget technique is difficult to use because it compares two large numbers with large uncertainties, but advanced satellite observations and regional atmospheric climate models constrained by a wealth of meteorological data have permitted us to obtain precise and detailed estimates of glacier changes with this method. The advantage of the mass budget method is that it documents changes in glacier dynamics separately from surface melt processes.

A second method to measure the ice sheets is altimetry in which scientists continuously measure the height of the snow and ice over time. If ice/snow accumulates, the height of the surface increases; if ice/snow melts, the height of the surface decreases. In the meantime, the elevation of the bedrock beneath the ice changes by only millimeters. This technique collects data from ice sheets and measures surface elevation with

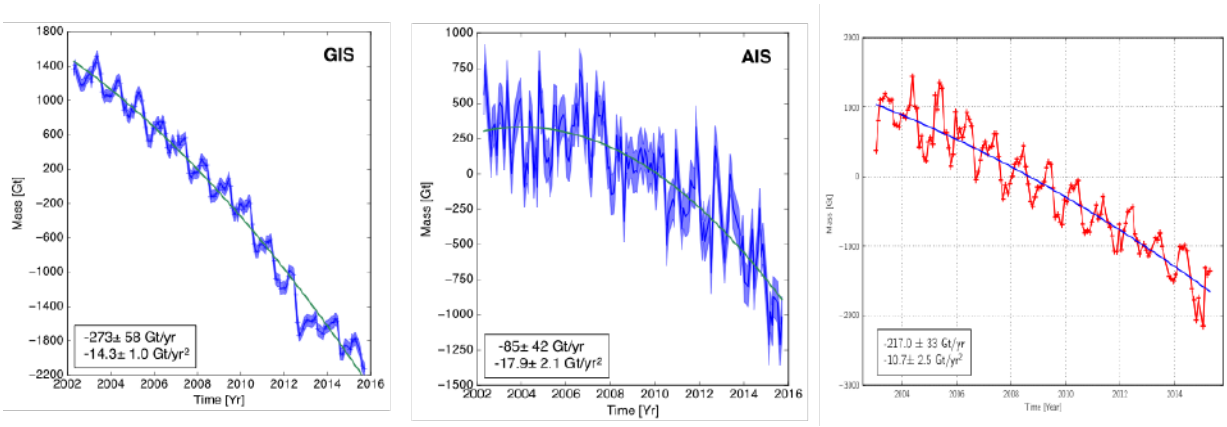


FIGURE 17.2.1 Since 2002, scientists have used NASA's Gravity Recovery and Climate Experiment (GRACE) mission to measure ice mass changes directly from space via changes in the gravity field of the Earth. GRACE has shown that the mass change in Greenland (left) has clear seasonal cycles and is negative; that is, the ice sheets are losing mass. The time series graph has a downward bend in it, showing that the mass loss is increasing with time. In Antarctica (center), the signal is noisier, with no clear seasonal cycles but large interannual to decadal cycles. The mass change is negative there too, and the acceleration is slightly larger than in Greenland. GRACE also measures the mass changes of the world's glaciers and ice caps. The glaciers are melting fast, but their melting rates are accelerating less than those of the ice sheets. Adapted from Velicogna 2009.

meter to decimeter precision (by radar and laser, respectively). A major difficulty of altimetry is in transforming the observed height changes into mass changes, since we do not know a priori whether the changes in height are due to changes in snow (density of 0.3) or ice (density of 0.9). On the other hand, the technique provides a critical view of where elevation changes are taking place, analogous to a warning signal.

Since 2002, scientists have used the time-variable gravity data from NASA's Gravity Recovery and Climate Experiment (GRACE) mission to measure mass changes directly. GRACE has a large footprint, about 350 kilometers, which does not allow it to see small detail such as individual glaciers, but it detects changes in water mass with a precision of 1 centimeter of water on a monthly basis. The measured mass changes in Greenland are so precise that they capture seasonal cycles: gain in mass in winter, loss in mass in summer. In a graph of GRACE data, the seasonal changes in mass do not produce a straight line (Figure 17.2.1).

Instead the line is "bent." This bend means that the mass loss is getting larger every year, or accelerating. The data show that over several years, the ice mass has decreased markedly. For every 361 Gt per year of extra mass melting into the ocean, sea level has risen 1 millimeter. This is more or less how fast Greenland ice is melting into the ocean today. The rate of acceleration shown by GRACE from 2002 to 2017 has been 430 Gt per year per decade.

For Antarctica, the mass change graph is noisier than the Greenland graph, and it shows no seasonal cycle but a large interannual to decadal variability. A few years of observations in Antarctica would not be sufficient to capture the long-term trend in ice mass. However, it can already be determined that overall, the ice sheet is losing mass—not as fast as Greenland and not over the entire periphery, but the time series graph has more curvature, indicating that the acceleration in mass loss is greater than in Greenland. The acceleration was 180 Gt per year per decade in 2002–2017.

With GRACE, scientists also quantify the mass loss of mountain glaciers, a set of about 150,000 glaciers and ice caps around the world. The glaciers and ice caps (GICs) turn out to melt as fast as the ice sheets. They experience a loss that increases by 110 Gt per year per decade. In total, melting ice from Greenland, Antarctica, and the GICs dominates sea level rise. From 2002 to 2017, the mass loss averaged 575 Gt per year with an acceleration of 430 Gt per year per decade. At this rate, we will exceed 1 meter of sea level rise by 2100 if we factor in a 20-centimeter sea level rise expected from the thermal expansion of the ocean. Glaciologists, however, fear that the contribution of land ice to sea level could become larger if major ice sheet instabilities take place.

Ice shelf collapse

How fast glaciers collapse into the ocean remains a central question in projecting the evolution of ice sheets in a warmer climate. In 1995 and 2002, large ice shelves in the Antarctic Peninsula collapsed following decades of slow decay from warm air and ocean temperatures. These ice shelves act like plugs on the glaciers upstream. Once gone, the glaciers are "free" to speed up. In 2002, following the collapse of the Larsen B ice shelf, the glaciers upstream of Larsen B sped up by a factor of 3 to

8. Fifteen years later, the glaciers are still flowing 5 times faster than when an ice shelf was present. The glacier response is therefore rapid, the impact on the mass loss is significant, and the effect is persistent for long periods of time.

As stated earlier, the collapse of Larsen B is an irreversible process on a human time scale. Studies have shown that the ice shelf had been stable during the entire Holocene; that is, it did not collapse in the prior 10,000 years. If the same process were to take place farther south, where larger ice shelves hold large sea level rise potential, the effect on global sea level would be measured in meters instead of millimeters. As an illustration, if all the glaciers around Antarctica were to speed up by a factor 6.5, sea level would rise by 4 meters per century.

Do we know where irreversible mass loss could take place in the ice sheets? In principle, the portions of the ice sheet most sensitive to climate change are marine based, that is, where the base of the ice is grounded below sea level. There the ice will remain in contact with the ocean waters during the retreat and be replaced by an ocean. Among marine ice sheets, the most sensitive sectors are those with a retrograde slope, as discussed earlier. Among the marine ice sheets capable of MISI, those closest to the sources of warm ocean water around Antarctica (and Greenland) are at risk because changing winds will bring more ocean heat to the glaciers.

In Greenland, we recognize three major marine-based basins: (1) the Jakobshavn Isbrae in central west Greenland, (2) the Petermann-Humboldt drainage in central northwest Greenland, and (3) the 79 North–Zachariæ Isstrøm drainage in northeast Greenland (Figure 17.2.2). These basins hold sea level rise equivalents of 0.6 meters, 0.6 meters, and 1.1 meters, respectively. All three basins are currently under attack by climate warming. In 2002, the floating ice shelf that protected Jakobshavn Isbrae broke up in a few weeks, following years of melting from the bottom (due to warm ocean temperature) and above (warm air temperature), and the glacier sped up by a factor of 3. The glacier has been retreating along a retrograde slope at a rate of 0.6 kilometers per year. In the warm summer of 2012, the glacier was flowing at a record speed of 18 kilometers per year, or 54 meter per day, versus 3–4 kilometers per year in the 1990s. Based on the bed topography of

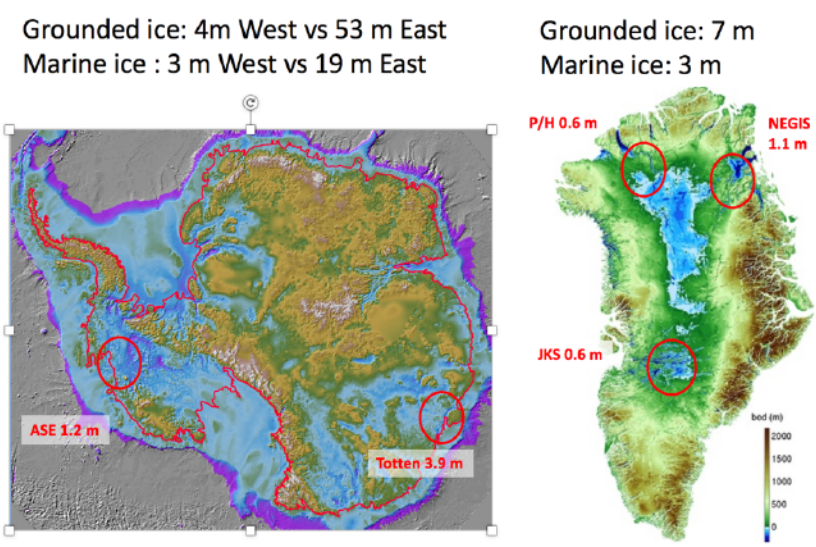


FIGURE 17.2.2 In Greenland, there are three major marine-based basins with retrograde slopes: Petermann/Humbolt (P/H), the Northeast Greenland Ice Stream (NEGIS), and Jakobshavn Isbrae (JKS). All three are currently under attack by climate warming. In Antarctica, the mass loss is mostly from the Amundsen Sea Embayment (ASE), the Antarctic Peninsula, and sectors in East Antarctica (such as the Totten Glacier with a 3.9-meter sea level rise equivalent). Antarctica image from Fretwell et al. 2013. Greenland image from Morlighem et al. 2018.

the glacier, the retreat should continue for decades until the grounding line reaches a bed that is rising in the inland direction, more than 80 kilometers inland.

In the northeast, the floating section of Zachariæ Isstrøm collapsed in 2004 following years of slow decay of the permanent sea ice cover. Eight years after the collapse, we detected a glacier speedup of about 30%. The slower response reflects the geometry of the glacier: the grounding line was anchored on a ridge. As stated earlier, the glacier holds a 0.5-meter sea level rise equivalent. The glacier is now retreating along a retrograde slope for another 10–15 kilometers before the bed elevation rises again. Its neighbor, 79 North Glacier, is retreating more slowly because it is retreating along a prograde bed slope. Both glaciers are retreating for the same reason: warmer-than-usual waters have eaten away the floating section of the glaciers and removed the ice mélange that glues detached pieces of ice shelf together.

The third sector has been the most stable, but in 2010 a series of calving events removed one-third of the floating ice shelf of Petermann Glacier. The ice shelf moved to its most retreated position since the beginning of the twentieth century when first discovered by explorer Lauge Koch. Parts of the ice shelf have thinned by 100 meters in the last 8 years, suggesting that prolonged exposure to warmer conditions will eventually result in the collapse of the ice shelf. This glacier is connected to the interior of the ice sheet via a deep, marine-based channel.

In Antarctica, the northern part of the Antarctic Peninsula does not hold a lot of sea level rise potential, in the range of centimeters, but the southern part holds a lot of ice. At present, the northern part is melting away rapidly, and the southern part is changing slowly. In West Antarctica, the glaciers draining into Siple Coast have been slowly growing with time since the 1970s. This situation is an anomaly in Antarctica and is driven by internal dynamics rather than by climate. As the glaciers thicken, basal pressure rises until ice starts to melt under its own pressure, the bed becomes wet, and ice starts sliding. As ice slides faster and thins, it eventually loses its momentum, slows down, and refreezes to its bed, and the process starts again.

In the northern part of West Antarctica, Pine Island and Thwaites Glaciers hold a 1.2-meter sea level rise potential and stand in warm circumpolar deep water (CDW) at about +2°C. These glaciers drain from a basin below sea level with steep retrograde slopes in the interior. Since the mid-1990s, scientists have seen these glaciers slide to sea faster and thin. Grounding lines have retreated about 1 kilometer per year, or twice as fast as in Greenland, and the glaciers have lost vast quantities of ice to the ocean. Scientists have mapped the bed geometry of these glaciers in great detail since 2002, and we concluded in 2014 that we knew enough about the bed and the ocean conditions to conclude that the glaciers are in a trend of irreversible retreat. Warm water is fueling the retreat. We find no major bumps in the bed that will slow the retreat to a stop. If these glaciers retreat completely, losing all their water to the sea, they will entrain the collapse of the rest of West Antarctica and raise global sea level by 3 meters.

In a spectrum of slow, catastrophic changes, there is also good

news. During a series of colder years (2009–2013) with a 60% drop in ocean heat, the glacier retreat in the Amundsen Sea Embayment slowed down by 1%. A warmer ocean therefore triggers the retreat but a colder ocean can slow it down. This is yet another illustration that MISI is complex rather than one-dimensional. Similarly, as the glaciers retreat in a nonuniform fashion and form new embayments with smaller ice shelves, warm water intrusion is more difficult, which slows the retreat. While the retreat may remain unstoppable, the rate of retreat depends on the rate at which ocean heat is delivered to the glaciers. As colder waters intruded Disko Bay in Greenland in 2017–2018, not only did the retreat of Jakobshavn Glacier stop, the glacier started to readvance.

The West Antarctic ice sheet is not the only source of instability in Antarctica. Other sectors at risk exist in East Antarctica.

East Antarctica has generally been viewed as stable and immune to change because it stands taller on the ground, most of the ground below the ice sheet is above sea level, the surface climate is colder, the bed slopes are not as steep as in West Antarctica, and there is scanty evidence for the presence of warm circumpolar deep water along the coast, due to a lack of observations. Altimeters on satellites, however, revealed that some parts of marine-based East Antarctica have been changing, with major glaciers thinning at rates of 0.4–0.7 meter per year. Other methods, such as the mass budget technique and use of GRACE mission data, suggest that these glaciers are slowly losing mass to the ocean. High-risk areas include the Totten Glacier, which holds a 3.5-meter sea level rise equivalent, that is, more than the marine part of West Antarctica; Denman Glacier, which holds a 1.5-meter sea level rise equivalent; and the sector drained by Cook ice shelf and Ninnis Glacier. Recent oceanographic data revealed that Totten Glacier stands in relatively diluted circumpolar warm water at +0°C. At present, the glacier is retreating on a nearly flat bed. In the inland direction, the bed rises for another 50–80 kilometers. This prograde slope offers a temporary protection from MISI on Totten. Beyond 50–80 kilometers, the basin drops down in the deep and broad Aurora Basin and its large reserve of ice. To the east, Denman Glacier is also at risk, grounded on a ridge at the edge of a deep trough with retrograde slopes, which reaches

one of the lowest points in Antarctica, at 3,500 meters below sea level. These sectors at risk are closest to the sources of warm circumpolar deep water. Ongoing research will have to determine how and where this warm water reaches the East Antarctic coastline and what pathways exist to trigger a rapid retreat of the glaciers.

17.3 What Can We Do?

Impact of sea level rise

At present, the Earth is on a trajectory for a 1-meter sea level rise by 2100. The economic and environmental damages that a 1-meter sea level rise will inflict on humans and ecosystems should not be underestimated. A 1-meter sea level rise will affect our coastlines worldwide, their assets, homes, industries, and airports; populations will have to move inland and entire ecosystems will disappear. Sea level rise will affect our water resources (for example, by salt infiltration), security, and safety; it will force massive immigration of millions of people who cannot afford to move to higher ground. Flooding by rising sea level is there to stay once it occurs. Seawater does not recede after a few days of warm weather, as in the case of a rain storm. Humanity has to think of it as a permanent storm.

Changes in polar ice produce the most dramatic changes in sea level in areas farthest from the ice sheets because of the nature of the readjustment of the crust and gravity field associated with mass removal. Sea level will actually decrease near the sources of melting land ice as the crust rebounds; conversely, the ground will subside far from the ice sheets, hence increasing the rate of sea level rise compared with the global average. The effects of melting in Antarctica and Greenland add up to raise sea levels by about 20% to 30% more at low latitudes than on average around the globe. While the ice sheets may seem remote, they are therefore most relevant to us at low latitudes. Sea level rise will also vary regionally depending on local tectonics, geology, erosion, slopes, tides, and oceanic conditions.

Paleo record of sea level rise

As discussed earlier, there is a possibility for sea level to rise by multiple meters in a warmer future. Sea level rose by 4 meters per century

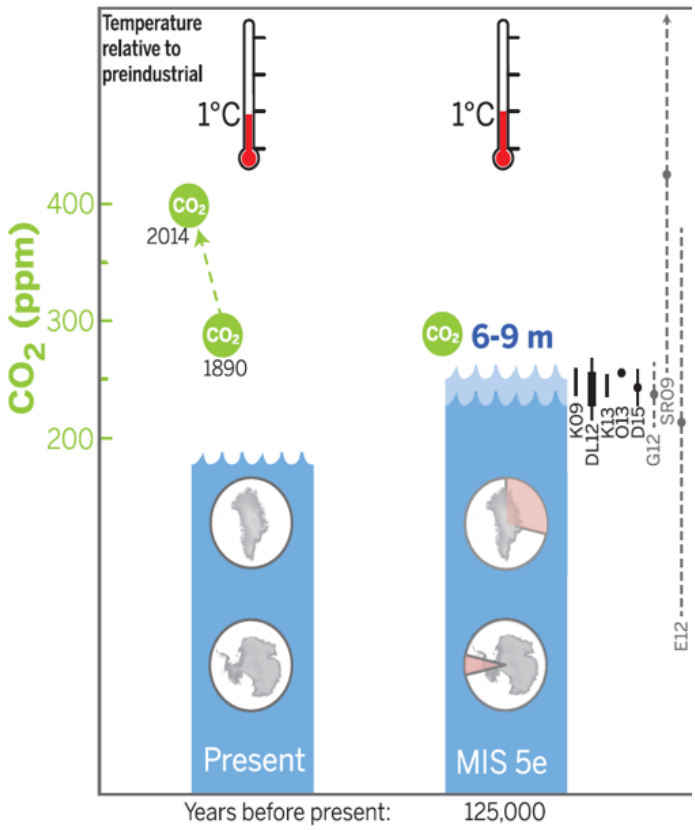


FIGURE 17.3.1 **In the Eemian period, during the last interglacial, temperature at the surface of the Earth was only 0.5°C–1°C warmer than present, but sea level was 6 to 9 meters higher. If the Earth climate reaches a similar state, it is likely that sea level will rise multiple meters again.** Reproduced from Dutton et al. 2015.

about 13,000 years ago during the demise of northern ice sheets and portions of Antarctica. If the climate warms up by 4°C–5°C by the end of the century, the ice shelves in Antarctica will not survive. The world therefore faces the risk of unabated multiple-meter sea level rise if we do not change the course of our greenhouse gas emissions.

A most important finding from the paleoclimate records in recent years is that during the Eemian period, in the last interglacial, when the temperature of the Earth surface was only slightly warmer than present, sea level was 6 to 9 meters higher (Figure 17.3.1). At that time, a large share of Greenland probably melted away, West Antarctica was left as an archipelago, and parts of East Antarctica probably collapsed. If the world commits to a climate system similar to that in the Eemian, it is likely that sea level will rise to a similar level again. Paleo records do not indicate how fast we will reach that state. But they do show that the end

state will be 6 to 9 meters of sea level rise, which would yield a massive redefinition of the world's coastlines and a complete transformation of our polar regions and global climate.

What can we do about this?

There is no benefit to humanity from rapid multiple-meter sea level rise from the collapse of Greenland and Antarctica. The poorest people on the planet will be affected first, but the world's population will be affected as well. Coastal ecosystems and the entire global climate system will change as ice sheet melt threatens to slow down, and eventually stop, the ocean's thermohaline circulation. In 2015, 180 countries signed an agreement to limit climate warming to 1.5°C above the preindustrial temperature. This agreement was a giant step that needs to be confirmed by prompt actions. The world may fail to keep the temperature from rising more than 1.5°C. A recent IPCC report indicates that a world with an increase of 2°C above the preindustrial temperature would be significantly worse than a world with an increase of 1.5°C. Yet limiting warming to 1.5°C may not be sufficient to stabilize ice sheets. We need to make our energy production free of greenhouse gas emissions rapidly. Curbing our carbon emissions is a first step, to be followed by carbon sequestration to reduce the concentration of carbon in the atmosphere to more sustainable levels. Prompt actions on carbon emissions may take 30–40 years to take effect on the climate. They may take even longer to affect the ice sheets, and by that time we will have cumulated a significant amount of sea level change, but we may be able to prevent multiple meters of sea level rise.

Becoming a world with carbon-free energy production and better, equitable, sustainable management of our natural resources comes with large benefits, at all levels of society, especially to the poorest populations of the world. Cleaner air, cleaner water, sustainable use of our natural resources, reduction of conflicts bound to petroleum resources, energy available where the sun shines, new jobs, and new technologies will not only protect the glaciers and ice sheets and their magical beauty, but protect us from massive changes in the climate, permanent damage to ecosystems, loss of biodiversity, and the very existence of life as we know it.

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CHAPTER 18

Atmospheric Carbon Extraction

Scope, Available Technologies, and Challenges

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Learning Objectives

1. Explain the concepts of negative emissions and carbon dioxide removal from the atmosphere—why do we need them?
2. Describe why reducing emissions of greenhouse gases will not be enough to reach our climate goals. You will understand the amount and timing of negative emissions—removing CO_2 from the atmosphere—that will be needed.
3. Define what it means to remove CO_2 from the atmosphere, and what we will do with it to keep it out.
4. List four ways to remove carbon dioxide from the atmosphere and what steps need to be taken to make that removal permanent. You will be able to list the potential costs and volumes of those methods, as well as one potential drawback for each approach. Along with these you will be able to list the accompanying ways to store the CO_2 permanently.
5. Describe the idea of recycling CO_2 to make carbon-based products, instead of using oil.
6. Describe two products that could be made from CO_2 instead of oil. One of the important sources of residual emissions—CO_2 emissions that are very hard to remove from our economy—is the carbon-based products we use every day.
7. Describe how engineered systems remove CO_2 from the air, and identify what their limitations are.
8. Describe the reasons why engineered systems might be important and how they can be used to clean up the atmosphere. Engineered systems are different from natural-based systems like forestry and soil carbon.

Overview

Even after we electrify everything, we will still need to clean up the atmosphere. This is because we have been too slow to implement clean energy technology, and some greenhouse gas emissions will be very hard to ever stop, like carbon dioxide from airplanes. In this chapter I discuss the size of this **negative emissions** challenge and a series of technical approaches we can use to accomplish removing CO_2 from the atmosphere at a scale of billions of tons per year.

The need to remove carbon dioxide from the atmosphere in order to stay well below 2°C total temperature rise is widely accepted today. The climate models can tell us how much CO_2 needs to be removed, and the economic models can tell us how fast changes can be made to existing systems, but the details of these massive new technologies are not well constrained. In this chapter I describe our current understanding of the general classes of technologies, but it will be up to you, today's students and tomorrow's leaders, to establish the details and implement those technologies. You will find that there is considerable uncertainty about exactly which approaches will be the most useful—will reforesting poorly used land be the most critical? Will new, as yet untested, approaches come to the fore? All we can say at this point is that there is no obvious silver bullet, and prudence indicates we should develop and test as many approaches as possible.

Negative emissions methods can be divided into natural solutions, such as increasing forested lands and improving carbon levels in soils, and engineered solutions, such as machines that directly remove carbon dioxide from the atmosphere. In between those extremes are hybrid solutions, such as making biofuels and capturing the CO_2 emitted during that process or speeding up the natural weathering of rocks that removes CO_2 from the air.

All of these approaches require land, and often large amounts of land, either for the technology or growing areas, or for the renewable energy systems to power the more engineered solutions. The trade-offs that will have to be considered are large. Will we turn areas of desert over to solar power to run direct air capture? Will we plant crops, purely to capture their embedded CO_2? And where will we store the

CO_2 removed from the atmosphere? Plants and soils can take up some of it, perhaps a lot with time, but in the short run it is likely that much of the fossil-derived CO_2 in the air will have to be returned to rocks deep beneath the earth. I try to balance these multiple options and give you a sense of the technology development, societal choices, and energy issues associated with cleaning up the atmosphere.

A major issue is how we will pay to achieve these goals. California's current efforts to reduce emissions now include the first mechanisms to pay for negative emissions. I conclude the chapter with an explanation of California's Low Carbon Fuel Standard and how it informs us about ways that we can develop and encourage negative emissions technology development.

18.1 Introduction

Detailed studies of our options to keep the planet livable tell us that the technologies the world is currently focused on—renewables and electrification—will not be enough. We will need to actively clean up the atmosphere—essentially decarbonize it back to a safe level. That is a huge challenge. Figure 18.1.1 shows two scenarios—or trajectories—we have for emissions of greenhouse gases. In yellow is the trajectory for **business as usual**, which represents no change in our current emissions. This is the trajectory of carbon emissions we will follow if we continue our current activities—it will have devastating results for temperature and climate, as you have learned in previous chapters.

Our ambition to keep temperature increase well below 2°C requires us to follow the red trajectory of worldwide carbon emissions. The models tell us it would give us about a 66% chance of staying below 2°C of global total temperature increase. The goal of 1.5°C would be much harder to achieve.

But the range of current tools available—renewables, electrification of transportation, efficiency, basically eliminating almost all fossil fuels—will only give us the reduction shown in brown. These are the massive changes in our energy use and economic activity that the other chapters in this book and the Bending the Curve course have discussed. But it's not enough. Even if we stop all the greenhouse gas emissions represented by the brown field, we won't reach the desired rate of emissions to stay below the 2°C goal. Why is that?

It's mainly because of greenhouse gases like methane, nitrous oxide, and the other heat-trapping gases you have learned about. But it is also partially because some CO_2 is going to be really hard to remove from the economy, like that from airplane fuel. It will be very difficult to eliminate all emissions, and it will take a long time to achieve the maximum reductions. We call these **residual emissions**. Agriculture is

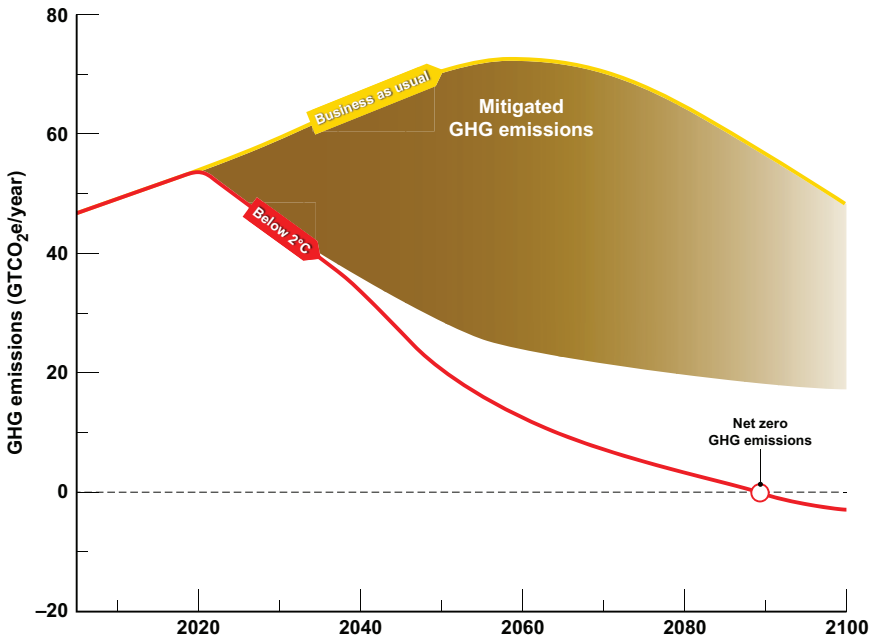


FIGURE 18.1.1 Two trajectories for future greenhouse gas emissions, showing all greenhouse gases (GHGs) as their equivalent in carbon dioxide emissions ($GTCO_2e$). The red curve would give a 66% chance of reaching less than 2°C in global temperature rise. The brown field represents current efforts to reduce GHG emissions. Adapted from Fuss et al. 2018.

a particularly difficult case. For instance, nitrous oxide is emitted from fertilizer use, and of course cattle emit methane. Are we going to stop using fertilizer and eating meat? These are choices that the world could make, but that would represent dramatic changes in our food system and agricultural economy. Other chapters have discussed how to address these problems, but we expect some emissions to remain.

And it's worse than that. We've already put so much CO_2 in the air that we would need negative emissions, shown in blue in Figure 18.1.2, even if we could get our current emissions to zero, which we can't do, because of the residual emissions. But the sum of the slow action and residual emissions is large—10 billion tons by 2050, 20 billion tons by 2100.

One approach for dealing with residual emissions is to create **negative emissions**, basically removing CO_2 from the atmosphere. (In this chapter we expressly limit the phrase *negative emissions* to CO_2 that is

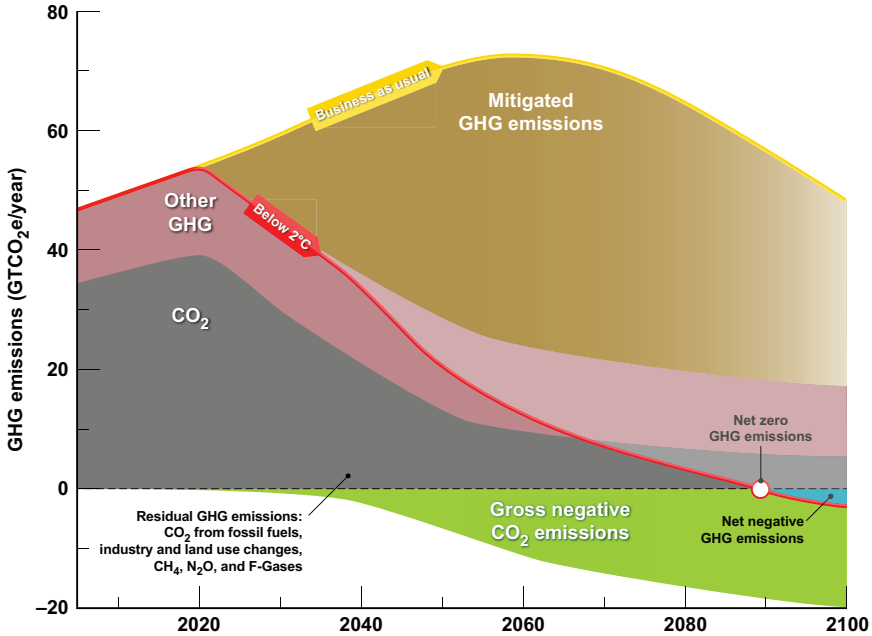


FIGURE 18.1.2 **The green wedge represents the negative emissions—removal of CO_2 from the atmosphere—required to offset residual emissions from other greenhouse gases and unmitigated CO_2 and to keep worldwide greenhouse gas emissions below that required to meet a 2°C future. ($GTCO_2e$ = GHG equivalent in CO_2.)** Adapted from Fuss et al. 2018.

removed from the atmosphere—and not any of the *reductions in emissions* that you have learned about previously). The green wedge in Figure 18.1.2 represents the required negative emissions in order to meet the trajectory of well below 2°C emissions. (The trajectories shown in Figures 18.1.1 and 18.1.2 represent averages of many models that change the rates of electrification, efficiency, and other economic parameters to achieve the 2°C future at the lowest cost to the world economy given today's knowledge of technology options.)

The green wedge, the required negative emissions, grows in slowly to represent realistic growth rates of the technologies required to remove CO_2 (even though we do not yet have a good understanding of those technologies, as we will discuss in this chapter). But the size of the required negative emissions is daunting—we will need to remove around 1 billion tons in 2030, 10 billion tons in 2050, and 20 billion tons in 2100. That means between now and 2050, we need to create an industry to

clean up the atmosphere that moves twice the material of today's oil industry. In 2030, the 1 gigaton we need to remove per year is about equal to the weight of all humans on Earth, or the weight of all the corn we harvest each year.

How will we create the negative emissions required to meet a 2°C future, or better yet to keep temperature rise significantly lower than 2°C? We have to find the right technologies, and then quickly get them to scale. We have to create technology that can address negative emissions and also to understand how full-scale negative emissions ecosystems—capture, transportation, and storage—can be created. We have to catch billions of tons of CO_2 at an affordable price. A really important aspect is how we encourage and enable the creation of businesses that can do this job. You don't move billions of tons of anything without businesses that make money, even if that money is from taxes or government subsidies (like our trash removal today). Most importantly, we need to do all of this in a way that does not do unacceptable damage to the people and natural environment of the Earth that we are seeking to protect.

This chapter discusses these challenges and how we might go about addressing them. I address the major issues associated with the removal of carbon and its ultimate permanent storage. Five methods are listed here with approximate values for how much annual negative emissions they might provide:

1. Regrowing forests (1–5 billion tons per year).
2. Putting CO_2 back into soils as soil carbon (450 billion tons total, but slowly, at 2–5 billion tons per year).
3. Using biomass to remove CO_2, either while making fuel and energy, or to restore soil carbon (2–5 billion tons per year).
4. Enhancing the natural reactions of minerals with the air (2–4 billion tons per year).
5. Directly removing CO_2 via chemistry and machinery, that is, direct air capture (limited only by the availability of renewable energy to power the devices, but probably 2–5 billion tons per year).

The biomass and direct removal methods generate CO_2 that must be stored permanently out of the atmosphere. These approaches also have limitations. I describe two in detail:

1. Making carbon-based products from CO_2 instead of oil (1–5 billion tons/year).
2. Putting CO_2 underground as liquid (unlimited capacity but expensive).

Some consideration has been given to increasing the rate of biological uptake in the oceans by fertilizing plankton or enhancing the growth of large algae (like kelp), but those methods are subject to even more environmental conflicts than the seven activities listed above, and an adequate estimate of how they might affect our negative emissions activities is not yet available.

18.2 Capturing CO_2 from the Atmosphere

Trees

Trees are the first form of natural carbon storage that most of us think of when we imagine removing carbon dioxide from the atmosphere. There are at least *three trillion* trees on Earth, and they hold about 500 petagrams of carbon, or in more common terms, 500 billion tons. When we talk about living organisms, we talk about carbon as the chemical species, C (molecular weight 12), as opposed to when we talk about the atmosphere, where carbon takes the chemical form CO_2 (molecular weight 44 with the addition of the two oxygen molecules). The 500 billion tons of carbon in forests (trees, roots, and dead material) came originally from CO_2 in the air: 500 × 44 / 12 = 1,833 billion tons of carbon dioxide, or roughly about twice as much CO_2 as exists in the atmosphere today.

FIGURE 18.2.1 Aspen grove, Rocky Mountain National Park. National Park Service photograph by J. Westfall.

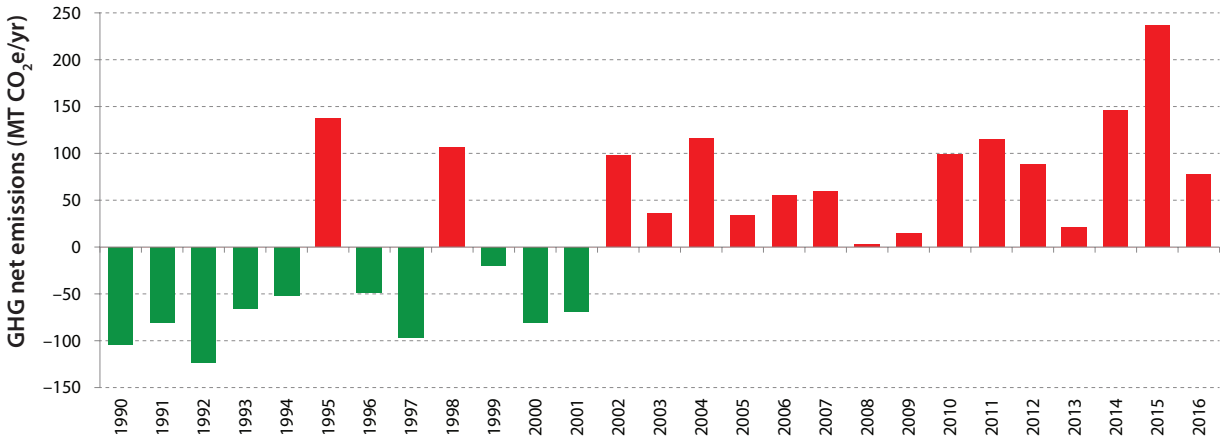


FIGURE 18.2.2 Gain and loss of carbon from Canada's forests in recent years. Since 2002, Canadian forests have been emitting carbon dioxide, not absorbing it, because of fires and insect kills. (MT CO_2e = million tons of carbon dioxide equivalent.) Data from Natural Resources Canada.

Adding more forested area to the Earth is an obvious and fairly rapid way to remove carbon dioxide from the atmosphere, and reforesting land that has been denuded by logging or clearing for agriculture is the first option for negative emissions. This is happening naturally in places like Maine in the United States, where former farmland has been allowed to return to forest, and because of conservation activity in places like Bhutan, where in 2016 at the request of the king, 108,000 trees were planted to honor the birth of the new prince, Jigme Namgyel Wangchuck (the number 108 is auspicious in Bhutan's Bhuddist tradition).

There are two important limitations to how much CO_2 we can remove by reforestation. The first is the total land area to be covered in trees. We can't cover farmland that is in active use, or much of our urban landscape. This limits the total CO_2 that can be removed to about 100 billion tons, although some estimates are as high as 260 billion tons. The second limitation is the rate of growth, and this restricts the rate of removal to between 1 and 3 billion tons of CO_2 per year. The good news is that this is a relatively inexpensive option, with costs as low as \$10/ton of CO_2 removed.

Climate change is hard on forests, however. Figure 18.2.2 shows the carbon uptake and loss from Canada's extensive forests. Despite being mostly undisturbed by direct human activity, Canada's forests are

currently *emitting* CO_2, not absorbing it. In California, trees are also dying at a rapid rate because of drought and insects. In 2010 there were fewer than 5 million dead trees in California's forests; today there are more than 145 million. Maintaining healthy forests will be a major challenge in the Anthropocene, and using forests as a negative emissions sink requires us to solve the forest health challenge. We can't just assume that planting trees, and ignoring existing forests, will achieve a climate benefit.

Soils

Soils store a large amount of carbon in the form of decaying plant matter, organic chemicals derived from plants and soil organisms, and also a large pool of living organic matter such as microbes and fungi. In healthy soils these compounds are in constant flux. Plants absorb CO_2 and grow roots; roots exude chemicals that are absorbed by the microbial community, which is preyed upon by viruses; new microbes consume the decaying plant and animal matter, emitting CO_2; and some soil organic material becomes associated with soil minerals. This results in a constant flux of carbon in and out of healthy soils, such that the carbon content of soils is never static but is a **stock and flow problem.** Soils that are rich in organic matter have healthy ecosystems and *vice versa*, as you learned in Chapter 16.

The rich soils of the US Midwest were formed by these processes operating around the roots of **perennial plants**, such as grasses, that live for multiple years (as opposed to the **annual plants** that die and regrow from seeds every year, like most of our crop plants). These perennial plants typically put down deep roots—often 4 meters deep—in search of reliable water. **Switchgrass** is one of the most common of the perennial grasses of the Midwest.

Agricultural practices like plowing can decrease soil carbon by exposing it to the atmosphere, which causes it to oxidize to CO_2 and be lost. An even larger loss of carbon can occur from rich surface soils washing or even blowing away, as they did in the US Dust Bowl of the 1930s. Similarly, harvesting a crop like corn and then leaving the ground uncovered for the winter allows organic matter to be lost by all these mechanisms and discourages the healthy microbial activity that forms

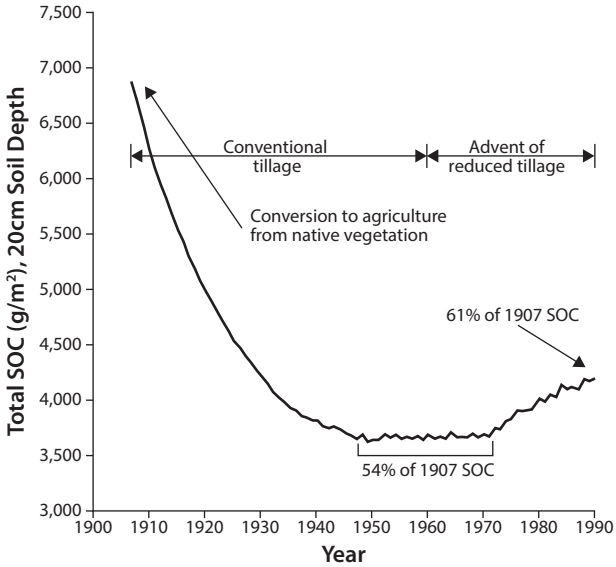


FIGURE 18.2.3 Soil organic carbon (SOC) in the central US. Conventional tillage is plowing every year, without using cover crops in winter. Reduced tillage uses things like no-till planting, cover crops, and contour plowing to reduce erosion and runoff. Adapted from Donigan, A. S., Jr., et al. 1994.

good soils. Today farmers seek to diminish these effects by using soil conservation plowing that decreases erosion, no-till agriculture where seeds are planted without plowing, and cover crops in winter to avoid bare soil and reduce loss of organic material.

When American farmers began plowing the soils of the prairies, they rapidly released carbon from the soils. Figure 18.2.3 shows how the loss continued until recent years, when the new soil management practices were put into place.

These kinds of soil carbon losses have occurred around the world and are responsible for approximately 133 billion tons of carbon loss from farmed land, which represents about 450 billion tons of CO_2 in the atmosphere. If we could return that carbon to soils, it would increase their productivity while decreasing the carbon dioxide in the atmosphere. Since soils formerly had these carbon contents, we assume they could be returned, but the challenge is: how fast can that occur? This is a major target for negative emissions studies, because returning that carbon to agricultural soils would erase much of the excess CO_2 in

the atmosphere today. As you can see in Figure 18.2.3, it is possible for the soil to slowly regain carbon, but can we regain all of it? And, can we greatly speed up the process? Research in this area includes better farm practices, which you learned about in Chapter 16, using perennial crops instead of annual crops, and finding ways to encourage deep root growth. Changing the plants we grow today to do more for soil carbon enrichment—through deeper roots or genetic modification to increase root growth and longevity—is an active research area. There is not yet an obvious silver bullet—much work needs to be done.

Biofuels and carbon dioxide capture

An important link between forestry, agriculture, and negative emissions is the production of biofuels. Today in the United States 10% of automobile fuel is the biofuel ethanol, produced from corn and increasingly from other lignocellulosic feedstocks like corn stover, which is the cornstalks left over after the ears of corn are removed. That ethanol is made by **fermentation** in which yeast breaks down the sugar in the corn, turning it into ethanol and CO_2 in about equal parts. Today that carbon dioxide is simply allowed to bubble out of the vat and return to the atmosphere where it started at the beginning of the growing season. If we could catch that CO_2 and permanently keep it out of the atmosphere, it would be an easy form of negative emissions. Since the CO_2 bubbling out of the fermentation vat is nearly pure (it has some water vapor in it), it is relatively easy to capture. Today much of the CO_2 in fizzy drinks comes from that source. Of course, *that* does not constitute negative emissions, since it immediately returns to the atmosphere when we drink the beverage.

The production of other biofuels also emits carbon dioxide. **Anaerobic digesters** that process manure, sewage, and food waste create methane for use in vehicles or in our natural gas pipelines, and carbon dioxide is a by-product. That CO_2 has to be separated from the methane before it can be used, and today the CO_2 is simply dumped into the atmosphere. This represents another readily obtained negative emission. Typically, one carbon dioxide molecule is created for every two methane molecules in an anaerobic digester. Decomposition of trash in landfills creates a similar mix of gases. Today we try to control the methane

emissions from these sources because it is such a potent greenhouse gas. Capturing and storing the CO_2 can turn this control into a double benefit.

Another way to obtain energy from biomass is to burn it for electricity. This is an old way to make electricity, but now we can consider also capturing the CO_2 and putting it underground. This leads to a negative emissions concept that is prominent in recent Intergovernmental Panel on Climate Change (IPCC) reports—**bioenergy carbon capture and storage**, or **BECCS**. An attractive aspect of this approach is that in principal all of the carbon in the biomass could be captured, yielding the maximum amount of negative emissions. A challenge is that the electricity generated by burning biomass is relatively expensive compared with solar and wind power—typically about 12¢ per kilowatt hour (kWh) compared with 5¢. The added cost of capturing the CO_2 from a biomass power plant would today increase the cost of the power by at least 50%, to 18¢ per kWh, making it dramatically more expensive as a source of electricity. The question to be asked is, How much are we willing to pay to remove carbon dioxide from the atmosphere, and is this a practical way to do it? We could certainly subsidize BECCS power to achieve this goal, but since biomass power plants are struggling to be competitive today, it seems that this will be an expensive and potentially less attractive way to remove carbon dioxide from the atmosphere.

Much of the biomass that could be burned for electrical power can also be processed into liquid fuel by using a variety of methods that heat the organic material to extract organic molecules. One method is **pyrolysis**, or the rapid heating of organic material, as mentioned in Figure 18.2.4. This volatile organic material comprises most of the smoke from typical fires. Pyrolysis attempts to keep the volatile organic material from burning by performing the heating rapidly in an oxygen-free or low-oxygen environment. The released organic chemicals, called **bio-oil**, are then condensed and processed into fuel in a refinery, much like fossil petroleum is made into gasoline.

Once the volatiles have been removed, pyrolysis leaves behind a carbon-rich residue that is fundamentally charcoal and has been labeled **biochar**. Typically making up about 20% of the original weight

FIGURE 18.2.4 The smoke coming off a pile of burning leaves is volatile organic compounds being cooked out of the biomass. It could be condensed to form a biofuel in a process called pyrolysis. Photograph by Jorge Royan via Wikimedia.

of the biomass, this material can be added to poor soil to enrich its water-holding and nutrient properties, as well as encouraging microbial activity by providing a substrate for growth. This carbon is the major opportunity for negative emissions when pyrolysis is used to create fuels from biomass. Although the carbon in the fuel (from the volatiles) is rapidly returned to the atmosphere for net neutral emissions, the biochar can be stable for as long as hundreds of years (this is highly dependent on the soil environment), providing negative emissions.

The practice of adding charcoal to poor soil through deliberate burning campaigns has been used by agricultural societies for centuries. In Brazil, soils labeled by European settlers as *terra preta* ("black earth") are now known to have been deliberately created by the Indigenous people as an enrichment process for depleted rain forest soils. However, pyrolysis is in its infancy as a *combined* negative emissions and energy technology, with many issues yet to be worked out. One perceived advantage is the ability for pyrolysis facilities to be relatively small and be economically located near the source of the biomass. A major cost in any biomass-to-energy system is transporting the biomass. Trucks can typically carry biomass about 50 miles before the costs begin to overwhelm

the profitability of the operation. This is particularly important for forest biomass such as the **slash** that is left over from logging operations that are often far from potential places to use biomass. Currently these small trees, limbs, and unmarketable wood are piled up and burned in the forest (have you heard the term *slash and burn*?). This material could be converted into bio-oil and transported to refineries, where it could be made into transportation fuel. If the biochar is left in the forest soils (or otherwise permanently stored out of the atmosphere), the resulting transportation fuels can be **carbon negative**; that is, even after burning the fuel, the net impact on the atmosphere is that carbon dioxide has been removed (discussed in Section 18.4).

The final method for converting biomass into energy with ultimate negative emissions is **gasification.** In this approach the biomass is heated to high temperatures, above 1,200°C, in the absence of oxygen, and it breaks down into a mixture of hydrogen, carbon monoxide, and carbon dioxide called synthesis gas. This process has been used industrially for more than 180 years. The synthesis gas can be converted, using catalysts, into organic chemicals and fuels or even burned directly to generate heat or electricity.

This is an interesting way to create hydrogen for a modern carbon-free economy. Running the conversion process in such a way as to generate maximum amounts of hydrogen and carbon dioxide, and minimal carbon monoxide, is a good way to make hydrogen. The carbon dioxide can then be separated from the hydrogen with either solvents or membranes, leaving pure hydrogen for energy use, as well as pure carbon dioxide for permanent storage out of the atmosphere. Gasification plants tend to be large in order to achieve efficient operations, and industrial development in the past depended on coal as the feedstock. It is hard to get enough biomass in a small radius around a gasification plant to keep it operating efficiently (without excessive distances for trucks to travel, which is an additional cost and which generates additional pollution), but modern developers are trying to overcome these hurdles. Like burning biomass for direct energy production, gasification is in principal capable of capturing all of the carbon, for maximum negative emissions.

Biomass negative emissions benefits and limitations

I discussed biomass and soil negative emissions methods first in this chapter because they have many positive attributes, but they also have some significant limitations.

On the positive side, we can improve soils while also harvesting biomass, yielding double benefits. These approaches tend to be the least expensive of negative emissions technologies because the plants have done the hard work of accumulating CO_2 and solar energy for us. Afforestation, biochar, and soil carbon enhancement all can be done for less than \$100/ton of CO_2 removed, and they have, respectively, maximum capacities of 4 billion, 2 billion, and 5 billion tons per year worldwide, capable of making a significant dent in our 20-billion-ton need.

Each of these methods requires land, however, which is also needed for other purposes. Producing the food we need is the primary competition with energy uses—of course it is the good-quality land that is best for both needs. If farmers are paid higher prices to grow energy-related crops, then they will grow less food. The US Department of Energy has estimated the amount of biomass that could be provided in the United States for energy purposes in 2050, without reducing food production. The 2016 *Billion-Ton Report* found that it was realistic to expect that in 2040, the United States would have about 1.5 billion tons of biomass available for energy or negative-emissions-related use, without significant impact on food production or other land uses like housing and transportation. This amount of biomass could be used to create all of the airplane fuel used in the United States.

That 1.5 billion tons of biomass includes trash, sewage, manure, crop residues like almond shells and straw, and also growing new crops like poplar trees or switchgrass on land not suitable for high-value agricultural crops. About half of that total would be from those new energy crops, so the impact on food and water needs to continue to be evaluated. Not surprisingly, the trash resources are located in cities, and the agriculture-based biomass is in the center of the country, where agriculture is vibrant and widespread (Figure 18.2.5).

Since biomass tends to be around 50% carbon (waste like sewage can be much less, however), 1.5 billion tons would represent about 750 million tons of carbon. In the form of the carbon dioxide that was

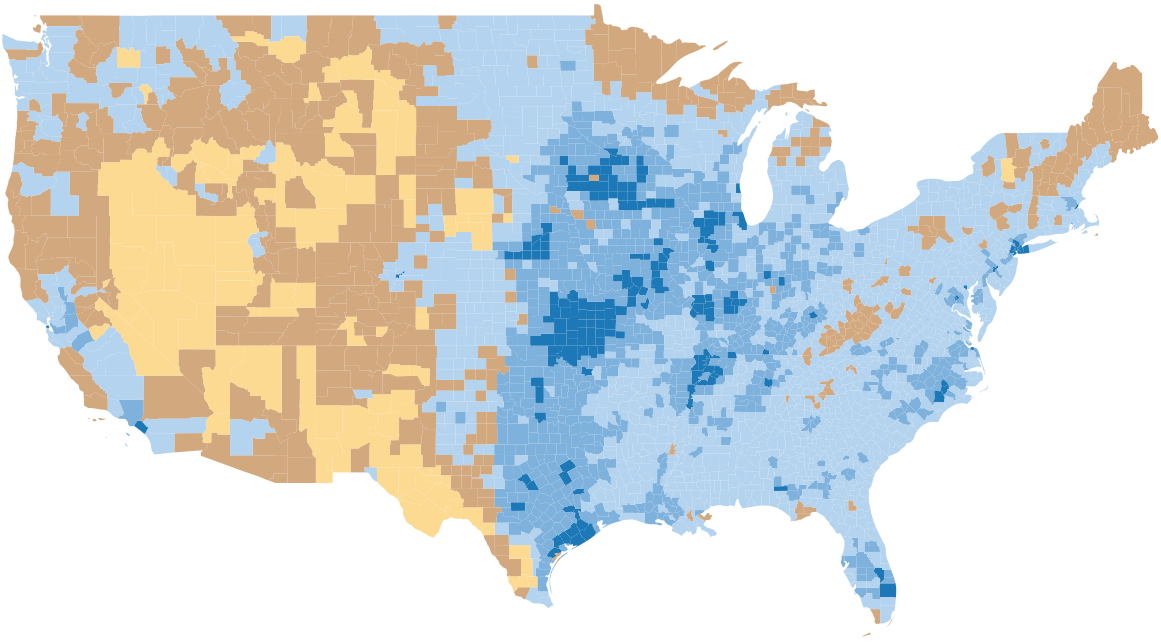


FIGURE 18.2.5 Summary map of biomass resources in 2040 in the United States available at a cost less than $60/ton of dry biomass. Map colors show the available tons of dry biomass (dt) per square mile of area. From US Department of Energy 2016, Figure ES4.

pulled from the atmosphere to make the biomass, this would be about 1.5 / 2 × 44 / 12 = 2.75 billion tons of carbon dioxide (remember that carbon and carbon dioxide have molecular weights of 12 and 44, respectively). While it is infeasible to assume that *all* of that biomass could be collected, and that energy crops could achieve their maximum contribution with no impact on other important aspects of society, it is clear that biomass could be a very real contributor to US negative emissions.

In countries with significant biomass-based industry like the timber harvesting in Sweden and Finland, there may be significantly more options for negative emissions using existing resources. These countries get a significant amount of their energy supply from wood waste today, and capturing the CO_2 from that combustion could be a very substantial component of their greenhouse gas activities, by some estimates making both countries carbon negative overall. Europe is investigating

using its trash for negative emissions in a project called Northern Lights, where the CO_2 from the trash-burning facility in Oslo, Norway, will be captured for true negative emissions, expected to come on line in 2022.

Some plans for negative emissions involve growing additional energy crops, such as switchgrass or poplar trees, entirely for the purpose of bioenergy with carbon capture and storage. These plans face serious criticism today because of the competition for land and water, and the impact on food supplies. Most current assessments conclude that the most obvious sources of biomass are those that are thrown away today. However, the future need for negative emissions may require us to evaluate whether additional biomass resources can be brought to bear on the problem without undesired consequences.

Direct capture of carbon dioxide from the atmosphere

Carbon dioxide can be removed from the air with strong chemicals like sodium hydroxide (known as caustic soda, or lye) and liquid amine or ammonia solutions. Both of these work because they are chemical bases, while CO_2 is an acid. The stronger the base, the more reactive it is with the acid carbon dioxide. Carbon dioxide is not an acid until it dissolves in water, at which point the reaction occurs to create carbonic acid (H_2CO_3), a weak acid:

$$CO_2 + H_2O \leftrightarrow H_2CO_3 \qquad (1)$$

Carbonic acid, H_2CO_3, can give up a proton (H^+) to react with a base like sodium hydroxide, NaOH, yielding water and two new ions in solution, and releasing heat (chemical energy):

$$H_2CO_3 + NaOH \leftrightarrow H^+ + HCO_3^- + Na^+ + OH^- \leftrightarrow H_2O + Na^+ + HCO_3^- \qquad (2)$$

A solution of sodium hydroxide will spontaneously absorb carbon dioxide by reactions (1) and (2), releasing heat and heating the solution or surrounding air. The solution will only contain the air's carbon dioxide, and not all the other gases—oxygen, nitrogen, argon, etc.—that were mixed with the carbon dioxide. If you heat that solution—add back into the system the heat that was released in dissolving the CO_2 (plus a little extra heat, of course; no chemistry is free!)—pure CO_2, plus some water vapor, will bubble out of the solution. This way of making pure

FIGURE 18.2.6 The Climeworks direct air capture facility near Zurich, Switzerland, uses 18 modular capture units to remove CO_2 from the air. The purified CO_2 is then used to enhance the growth of vegetables in the greenhouses in the background—not really negative emissions yet, but a demonstration of the costs and issues associated with separating CO_2 from air. This facility catches about 1,000 tons of CO_2 per year. Photograph by Roger Aines.

CO_2 has been known for more than 100 years and was used to make dry ice and carbonated drinks before other sources of CO_2 became available from industry. If you use amines or ammonia in place of sodium hydroxide, a similar reaction occurs.

These reactions are being used to harvest CO_2 from the atmosphere in experimental systems we call **direct air capture**, or DAC. Today they are relatively expensive to operate because of the heat that has to be added to the system to release the CO_2 in pure form, and because the systems need to be large to harvest significant amounts of CO_2 from air. In this book, we are very worried about CO_2 at a concentration of 415 parts per million (ppm) because of its blanket effect, but to a chemical engineer, 415 ppm is a very low concentration and requires large, expensive machines to both contact the air with the solution to catch the CO_2, and process that solution once it is enriched in CO_2.

A variety of schemes are being tested today to examine whether this direct air capture can realistically be used to remove CO_2 from the air. Most estimates place the current cost at around \$600/ton of CO_2

removed, with the possibility in the future of decreasing to $300 to $100/ton. Barring dramatic breakthroughs, direct air capture will always be more expensive than the biomass-based systems we previously discussed. But an advantage of direct air capture systems is that they are only limited by the amount of space we are willing to allocate to their operation and the amount of carbon-free energy we can supply to run them (obviously you cannot use something like coal-fired electricity to power such an endeavor, or you will emit more CO_2 than you catch).

Jennifer Wilcox has evaluated the amount of energy needed for direct air capture systems, and it is significant. Today's methods require about 250 megawatts (MW) of power supply to remove CO_2 at a rate of 1 million tons per year. A 250 MW solar farm is among the largest built today. The area required for a direct air capture facility would predominantly be for the energy production, and not for the actual capture devices (like those in Figure 18.2.6). For scale, the Topaz Solar Farm in California takes up 7.3 square miles of land and generates 550 MW of peak power. Considering intermittency (the solar farm produces no power at night), this would be about what is needed for 1 million tons of direct air capture per year. While it is certainly possible to allocate large areas of land for renewable power for direct air capture, this will be a major land use challenge. Today direct air capture methods are being studied and seriously evaluated, even though their large-scale operation may be many decades in the future. If we are lucky and work hard at other options, we may not need direct air capture to meet our climate goals, but if we need it in 2040 or 2050, it will be too late then to start developing it.

Carbon mineralization

Next, a brief mention of the mechanisms that the Earth uses to control CO_2 in the atmosphere, and how we might speed them up. Limestone, or calcium carbonate, $CaCO_3$, is the most stable s*olid* form of CO_2 in the earth. Its stability is attested by its use to construct buildings, particularly beautiful facades. But even as the most stable solid form of a CO_2-containing substance, it will still dissolve slowly in rainwater and turn into *bicarbonate*, HCO_3^-, in solution, which is even more chemically stable than limestone and is one of the most important ions in seawater.

Marine organisms use bicarbonate to form their shells and solid structural elements (like coral).

Bicarbonate and calcium carbonate come from the weathering of rocks containing calcium. These rocks tend to come from deep in the earth and are brought to the surface by volcanism (in basalt like that found in Hawaii) or faulting and plate tectonics, which can bring up large slabs of rock from deep in the earth called **ultramafic rocks**. Some examples are shown in Figure 18.2.7. These rocks are dissolved readily by seawater for the same reason that CO_2 is absorbed by a sodium hydroxide solution—the calcium dissolves to form calcium hydroxide, which reacts by the same mechanisms as sodium hydroxide (see equations [1] and[2]) forming calcium ions and bicarbonate in rivers that empty into the ocean. There the bicarbonate builds up until marine organisms like corals precipitate it into their homes and bodies, which eventually turn into limestone rock, permanently storing the CO_2. This natural cycle of CO_2 in the air reacting with rocks, forming calcium and bicarbonate ions that travel to the ocean in rivers, where they eventually precipitate into solid calcium carbonate shells and skeletons that accumulate on the ocean bottom and turn into limestone rock, has been the primary control on the average amount of carbon dioxide in the atmosphere throughout time. (This process does not acidify the ocean, because the acidity of the CO_2 was neutralized by the base in the rock—ocean acidification occurs when CO_2 in the air dissolves directly into the ocean and, as in equation [1], turns into carbonic acid.)

Researchers are examining whether this process can be speeded up, either by circulating water through rocks and dissolving the calcium or by grinding up calcium-rich rocks and reacting them with air and rainwater. This is an attractive approach because it mimics the processes already active in the earth and, most importantly, uses very little added energy because the reaction of CO_2 with dissolved calcium hydroxide actually releases energy (heat). There is no need to heat the solutions up again, as the direct air capture facilities must do to recover pure CO_2, because in this **carbon mineralization** or **enhanced weathering** approach the CO_2 forms either solid calcium carbonate or dissolved bicarbonate like that already in the ocean.

Much needs to be worked out before the benefits of this approach

FIGURE 18.2.7 Lawrence Livermore National Laboratory scientists examine ultramafic rocks in Washington state. These rocks are rapidly reacting with CO_2 and breaking down to calcium and bicarbonate ions, leaving clays and unreacted blocks of rock behind. This site is a landslide—as the rocks break down, they lose structural integrity and slide downhill. Photograph by Roger Aines.

can be estimated, but since ultramafic rocks are found in a wide variety of locations, including California, it is worth pursuing. Current estimates are that a process like this is less expensive than direct air capture and could be quite inexpensive. Since it is still quite uncertain, we estimate that the costs would be from $50 to $200 per ton removed, and the capacity would be several billion tons per year.

Ocean carbon uptake

Finally, a brief mention of one of the earliest ideas for removing carbon dioxide from the air: enhancing the primary productivity of the oceans.

In this approach, fertilizer would be applied to encourage the growth of plankton, which upon their death would sink to the abyssal depths of the ocean where carbon is out of contact with the atmosphere. This approach has proven to be difficult to experimentally test, because of limitations imposed by international treaties and also public opinion objecting to addition of the fertilizer components, like iron, to the ocean. However, the extraordinary size of the oceans, and therefore the amount of CO_2 that could be absorbed by this method, makes this an interesting option to continue evaluating.

18.3 Storing CO_2 Removed from the Air

After we remove CO_2 from the air with the methods described in the previous section, it still needs to be permanently stored. Biochar provides one means of storage, as does mineralization. Biological means such as soil carbon or trees provide other important forms of storage that have to be maintained to keep their integrity—you can't plow up the soil or cut down the trees in the future without losing some or all of the benefit. Our estimates of the maximum capacity of these systems are in the range of 10 billion tons per year. That is an outstanding start but not enough. And some of the important systems, like bioenergy and direct air capture, generate pure CO_2 that still needs another storage form.

Recycling CO_2 into carbon-based products

Many of the carbon-containing products we use every day are made from petroleum, including carpets, fabrics, and plastics. The availability of carbon from petroleum has made these products easy to make and inexpensive, but there is no fundamental reason that they cannot be made from carbon sourced from carbon dioxide. The important difference is that in general energy must be added to CO_2 in order to make the reduced-carbon chemicals that can be used in things like polymers (Figure 18.3.1). The good news today is that energy is increasingly abundant and inexpensive because of renewable sources. We can expect that in the future the energy to turn carbon dioxide into organic chemicals and make things like carpet fiber will be a small fraction of the total cost of the product.

Researchers are working today on the catalysts and electrochemical systems required to achieve this chemistry, with promising results. Worldwide, we produce enough chemicals (other than fuels) to take up about 1.4 billion tons of CO_2 (Table 18.3.1) if we completely replace petroleum as the carbon source. In principal those chemicals could all be produced using CO_2 processed with the use of renewable electricity,

TABLE 18.3.1 Possible chemicals and building materials that can be made from CO_2, and the maximum amount of CO_2 that would be utilized

	Carbonate Materials		*Chemicals and Fuels*		*Durable Carbon Materials*
	Binders/ Cement	*Aggregates*	*Commodity Chemicals*	*Fuels*	*Fiber, Nanotubes, Graphene*
Market size (GT/y)	4	44	0.5	2.5	~0.0001
	Portland cement (2016)	Non-metallic minerals (2017)	Upstream chemicals (2013)	Transport fuels (2016)	Carbon fiber (2018 est.)
CO_2 demand	0.1–1	1	1.4	7.7	?
		Waste streams			
CO_2 abatement	Unclear—indirect benefits	Reduced emissions likely—negative emissions possible	Reduced emissions possible—negative emissions possible	Reduced emissions possible	Unclear—indirect benefits

NOTE: The estimates in this table are highly uncertain. GT = gigatons.
SOURCE: Prepared by Sean McCoy, University of Calgary, based on analyses in ICEF. 2017. *Carbon Dioxide Utilization (CO_2U): ICEF Roadmap 2.0*. LLNL Report LLNL-TR-739322. https://www.icef-forum.org/platform/upload/CO2U_Roadmap_ICEF2017.pdf. Used by permission.

but the amount of electricity would be gigantic—as much electricity as the world produces today! Clearly we need more efficient methods, which seem very likely, given progress in catalysis and electrochemistry.

The lifetime of the materials we make from industrial chemicals is of primary interest when we discuss negative emissions. For instance, it is not realistic to think of fuels as contributors to negative emissions, since they are burned soon after being made. But polymers, fabrics, and plastics have longer lives, although they are still not permanent. Researchers are currently evaluating the benefits of producing these intermediate-life materials and the amounts of CO_2 removal from air they represent.

While we might think of organic chemicals as the principal place CO_2 could be used in our economy, it turns out that construction materials are another large possible sink. Concrete is composed of an aggregate material like gravel, which is held together with cement. That cement is mainly portland cement, which uses calcium hydroxide as the primary binding chemical. When water is added, the calcium hydroxide reacts with sand and fine rock in the aggregate mixture to form new minerals

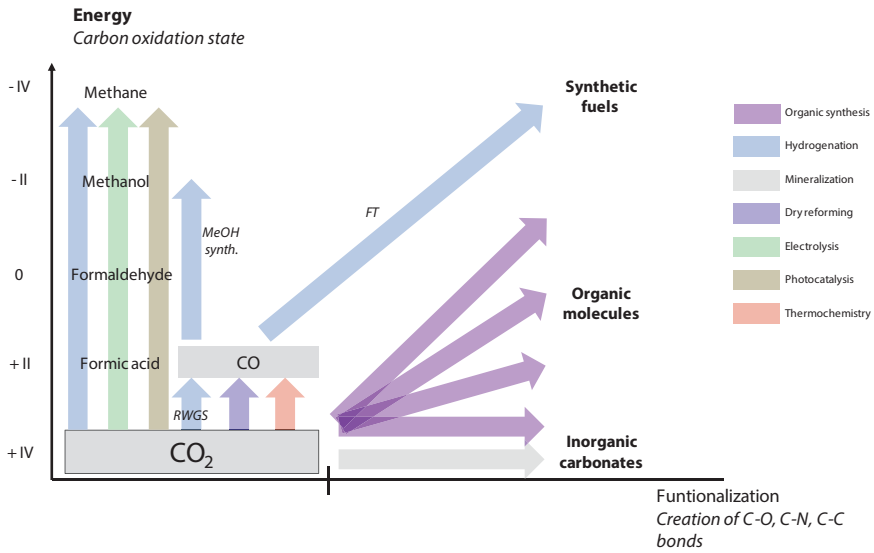


FIGURE 18.3.1 CO_2 is a low-energy form of carbon: energy must be added to chemically reduce the carbon molecule in order to make organic chemicals that are used in products and fuels today. Image from French Ministry of Energy and Environment.

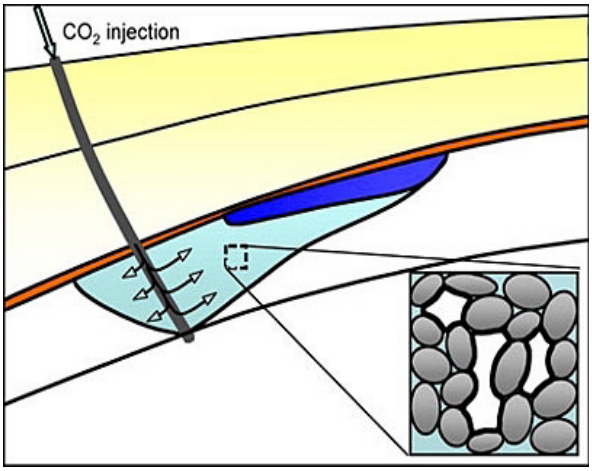
that bind all the material together. Production of calcium hydroxide is a major contributor to emissions, as it involves burning the CO_2 off limestone.

Remember calcium hydroxide from our discussion of carbon mineralization? CO_2 can also be permanently stored in cement and concrete, where instead of reacting all the calcium hydroxide with water and sand, as is currently done, we react some of the calcium hydroxide with carbon dioxide, also forming strong, stable minerals that bind the material together. While this substitution does not *reduce* the amount of CO_2 in the atmosphere, it does offset some of the emissions from calcium hydroxide production. That CO_2 is still emitted, but the net greenhouse gas total is reduced because some CO_2 is added to the resultant concrete. However, the gravel or other aggregate that goes into the concrete is another story. If that aggregate could be made from calcium carbonate produced from atmospheric CO_2 and calcium from wastes, minerals, or the ocean, that could be a very large contributor to negative emissions (Table 18.3.1).

FIGURE 18.3.2 An oil pump at sunset. Image by skeeze from Pixabay.

Geologic storage

An important form of storage will be injection of liquified CO_2 deep into the earth in rocks like those that oil was produced from originally (Figure 18.3.3). When it is injected at depths greater than 1,000 meters (about 3,000 feet), the pressure is sufficient to keep the CO_2 in a liquid state. (Chemists will recognize this as a **supercritical** state where the distinction between liquid and gas is no longer meaningful, but the material's properties are very much like a liquid.) This is about as dense as oil (a little less dense than water), with about the same viscosity. Thus, if we inject CO_2 into an old oil field, or rocks similar to an oil field, the CO_2 will stay there permanently as the oil did. (Of course, some oil leaks out naturally, as on the beach in Santa Barbara, California, but those oil deposits are very shallow, only a few hundred feet below the surface.) The US Department of Energy has conducted extensive tests



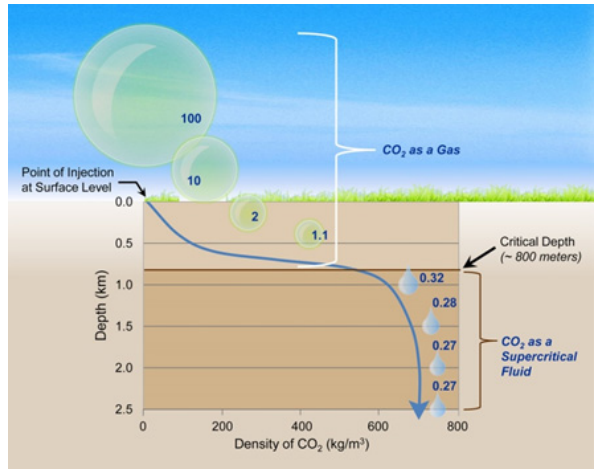


FIGURE 18.3.3 (Left) Underground storage of CO_2 as a liquid can be done at depths greater than 3,000 feet (1,000 meters) where the pressure keeps the CO_2 in supercritical state with properties very similar to those of oil. The CO_2 fills the space in between sandstone grains. Image reproduced with permission from Reuben Juanes, MIT News. **(Right) The volume taken up by CO_2 gas decreases as you add pressure to it, as happens when it is injected deep into the earth. At depths greater than 800 meters it converts into a supercritical liquid with much higher density than the original gas, taking up a small amount of space in the subsurface.** Image from US Department of Energy, National Energy Technology Laboratory.

of this approach, placing 16 million tons of CO_2 underground in a series of experimental sites that have been carefully monitored. No leaks have been observed in 10 years of experiments in the US, nor in 20 years at the Sleipner site in Norway, which is an offshore platform that injects CO_2 beneath the seabed.

This form of CO_2 storage can put very large amounts of CO_2 safely away from the atmosphere. The US Geological Survey and the National Academies estimate that about 3,000 billion tons can be safely stored in rocks under the United States. This number, of course, needs to be verified for individual sites and projects, but there appears to be more than adequate capacity for the US to store negative emissions in, under, and around old oil fields and similar rocks.

The technical issues associated with storing CO_2 underground are very similar to those of oil production, which involves very similar wells, surface equipment, and safety procedures. This is good news because

the skilled workforce required to rapidly scale up geologic CO_2 storage already exists in the oil industry. As the use of oil declines in the future, there is an opportunity to reemploy those workers in the carbon storage workforce, doing very similar jobs and in the same places where they do them today. This is valuable for a **just transition**, that is, the conversion of jobs in the old economy to jobs in the new economy that are similar in skills, location, and pay to the old jobs. If it is not possible to make these transitions, the workforce ends up suffering while the climate improves. Geologic storage is one opportunity to make a just transition for workers in the oil fields.

As with oil activities, there are safety issues with geologic storage that are being addressed in the ongoing demonstration programs. Leakage is always a concern, but to date it has not been observed (and it has been the primary focus of monitoring science). Earthquakes are also a concern, since changing the pressure on fluids underground (such as CO_2) can change the forces holding faults locked and cause induced seismicity, where the fault slips and an earthquake occurs. This effect is limited by the size of the fault—short faults can only make small earthquakes, while long ones like the San Andreas in California are capable of massive earthquakes. Clearly any CO_2 storage activity needs to take place well clear of large faults. Small faults are common in oil fields, however, and the mechanics of those faults are well understood. They often form barriers to underground fluid flow, trapping oil. They are also relatively easy to locate using seismic methods. This is another area where the expertise and monitoring equipment that was developed for the oil industry can be put to use in safely storing CO_2 underground.

Another concern is that leaking CO_2 might affect groundwater, making it slightly acidic and potentially releasing metals at higher levels than originally present. This could occur in large leaks, but in general the CO_2 is stored much, much deeper than groundwater. All CO_2 is stored below 3,000 feet, while most groundwater is held at depths of only several hundred feet. The US EPA has strictly regulated CO_2 underground storage on the basis of protecting groundwater. They require that wells be constructed to protect from leakage and that CO_2 can only be stored in rocks where the native groundwater is not drinkable (it must have greater than 10,000 ppm total dissolved solids, basically salt, rendering

it undrinkable). Leaks that just return CO_2 to the atmosphere are not a safety problem, just a climate problem.

Geologic storage is one of the climate technologies that generate public concern because it is unfamiliar and occurs out of sight. However, it looks like managing the CO_2 content of the atmosphere will require geologic storage, so it is important to develop the safety and monitoring procedures appropriate for public confidence. As with many issues in climate technology, as a society we must balance the possible risk of a new technology against the known hazard of the effects of climate change. Learning about risks and being prepared to control and mitigate them is extremely important.

18.4 The California Story: Paying for Negative Emissions

California's progressive policies on greenhouse gas control (Chapter 9) present the first major opportunity in the world for mechanisms that can be used to *pay* for the development and implementation of negative emissions technologies, especially in the early phase when new technologies and businesses are being developed.

A lot of discussion focuses on the ultimate cost of the climate technologies we will need, and that is a very important topic. But since many of these technologies will not be in full use until midcentury, and not built out until the end of the century, it is difficult to estimate total costs. The year 2100 is about as far from now as we are today from 1939. Some very important things have changed that could not have been guessed then! But do we wait for those miracles to happen? Of course not. We get started, we create new technologies and policies,

FIGURE 18.4.1 The first California hydrogen fueling station fed directly from an active industrial hydrogen pipeline. Photograph from US Department of Energy.

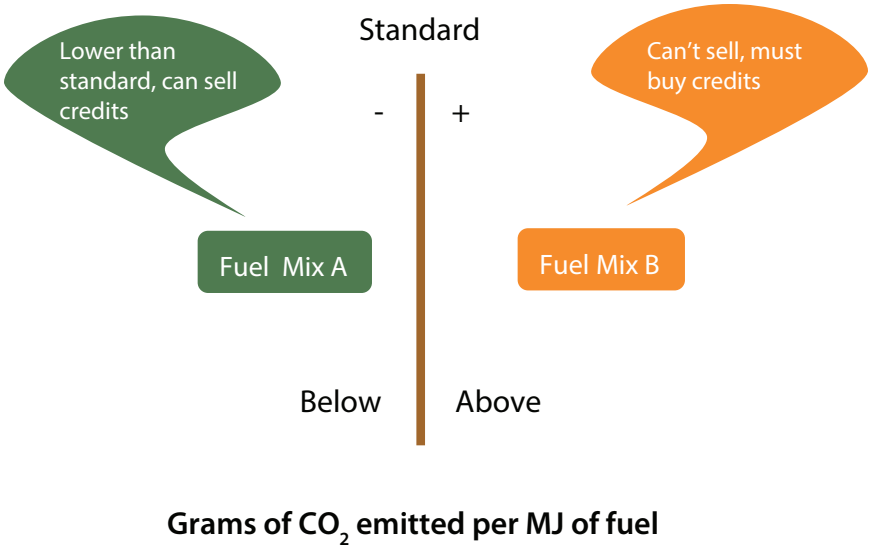


FIGURE 18.4.2 **Low Carbon Fuel Standard mechanics.**

and perhaps most importantly, we create businesses that do these jobs at large scale as we did with renewable energy.

California's ambition is to reach economy-wide net-neutral greenhouse gas emissions by 2045 (as you learned in Chapter 9). Let's take a look at how negative emissions will play a role in California's efforts to deal with its thorny transportation emissions problems through a policy known as the Low Carbon Fuel Standard. This policy controls the ultimate carbon dioxide contribution of fuels to the atmosphere by controlling their **carbon intensity**, or the total amount of CO_2 (and other greenhouse gases) that are emitted by producing, transporting, and ultimately using the fuel. For biofuels this includes agricultural emissions and even the change in land use required to make the biofuel. For petroleum fuels it includes the energy required to pump and refine the fuel. Conventional gasoline emits about 101 grams of CO_2 per megajoule (MJ) of energy content by this analysis. Each year California decreases the allowable carbon intensity of fuels sold in the state by a little more than 1%, so by 2030 it will be 20% less than the 101 gram/MJ baseline.

If a fuel seller has a product, like a biofuel, that has a lower carbon intensity than the standard (such as fuel mix A in Figure 18.4.2), they are allowed to sell the fuel, and it generates *credits*, measured in tons

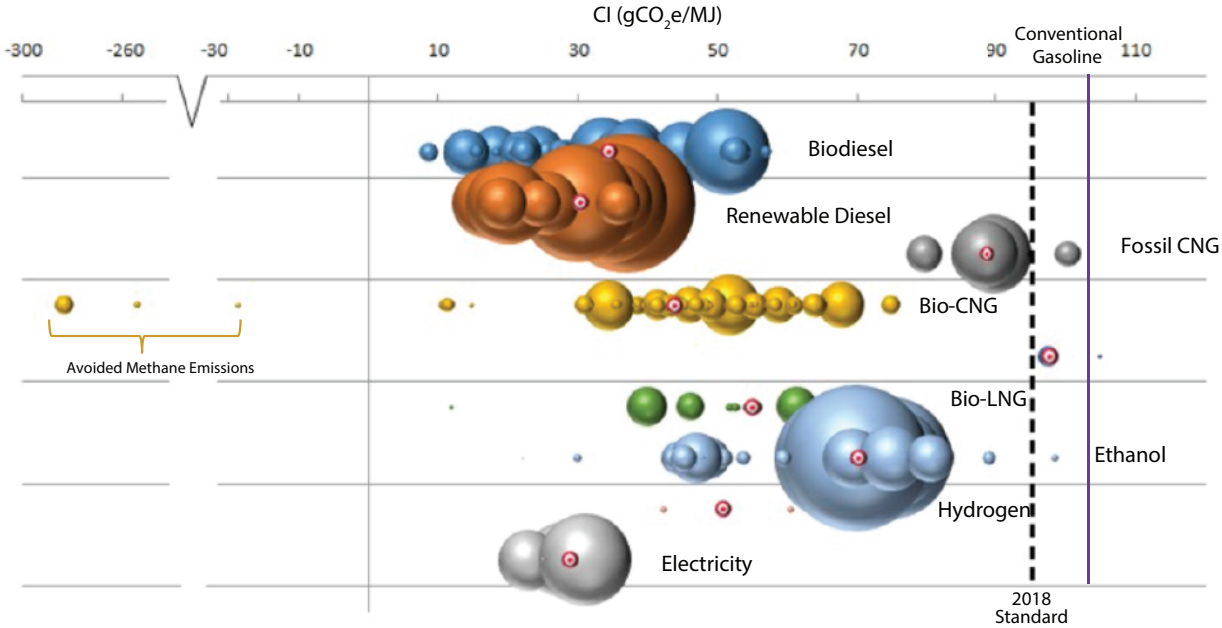


FIGURE 18.4.3 Carbon intensities for all the transportation fuels sold in California in 2017. The size of the bubble indicates the volume of fuel sold. Reproduced with permission from the California Air Resources Board.

of CO_2 avoided compared with the standard. On the other hand, if a seller wants to sell a product like conventional gasoline that is above the standard (like fuel mix B in Figure 18.4.2), they have to *buy* credits in order to offset the overage amount.

This presents the opportunity to create fuels that are carbon negative and to get paid for the fact that producing and using those fuels removes CO_2 from the atmosphere. Figure 18.4.3 shows the carbon intensity of all the fuels currently used for transportation in California. Some biologically derived compressed natural gas (Bio-CNG) has extremely negative carbon intensities, as low as −280 grams CO_2/MJ fuel. This is because that fuel is made from manure (as I talked about in Section 18.2). The previous practice was to let the manure sit in open ponds, emitting methane, which is a potent greenhouse gas. The Low Carbon Fuel Standard gives the farmers credit, as a negative emission, for *stopping* that emission. This isn't quite how we have discussed negative emissions in this chapter (it doesn't actually remove carbon from

the atmosphere). The farmers are being given credit for eliminating this emission that would have been one of the residual emissions shown in Figure 18.1.2, so California counts it as negative.

However, when carbon capture is employed, it will be possible to push many of those carbon intensities to below zero—that is, those fuels will have negative emissions. The California Low Carbon Fuel Standard, as of January 2019, allows producers to reduce the carbon intensity of fuels by capturing CO_2 from the fuel production pathway and *permanently storing it underground*, as we discussed in Section 18.3. For the ethanol in Figure 18.4.3, that additional carbon dioxide removed from the system would amount to a decrease of about 40 grams CO_2/MJ—not enough to get to zero or below, but a significant decrease. On the other hand, with more-carbon-efficient biofuels like Bio-CNG from anaerobic digesters, capturing and storing the carbon can reduce the carbon footprint to below zero. For fuels like those proposed to be made from forest biomass, this can be significantly below zero—a liquid fuel whose use decreases carbon dioxide in the air. The trading of Low Carbon Fuel Standard credits provides a way for businesses to make money making better biofuels for California and also to get a start on negative emissions, working out the details of the best technology and business practices.

The guidelines go a little further as well, authorizing direct air capture as a way to generate Low Carbon Fuel Standard credits. A company can set up a capture site anywhere in the world, capture and store CO_2, and sell the credits in the California market. (The basic premise is that CO_2 emitted by a car in California goes all around the world—capturing it anywhere and keeping it out of the atmosphere is exactly the same as not emitting it in California to begin with.) The current price for credits—about $190/ton at the time of writing—is probably not enough to pay for direct air capture yet, but it will be sufficient to encourage development of negative emissions from fuel production and is the highest price for carbon in the world today.

18.5 Summary

I've discussed a number of possible ways to achieve the negative emissions we will need to stay well below a 2°C total temperature rise. There is no single technology that can do it all—or even a small handful of approaches. We will need many different techniques, and all will need to achieve heroic scales—on the order of billions of tons of CO_2 per year—in relatively short times.

Figure 18.5.1 summarizes most of the technologies we have discussed in this chapter. Achieving 20 billion tons per year of negative emissions would require almost all of these operating at full capacity, and probably more beyond that.

Ultimately the removal of CO_2 from the air is very similar to trash collection in cities today. It is an activity that we must do to maintain a livable environment. We simply will have to pay for it. Some technologies

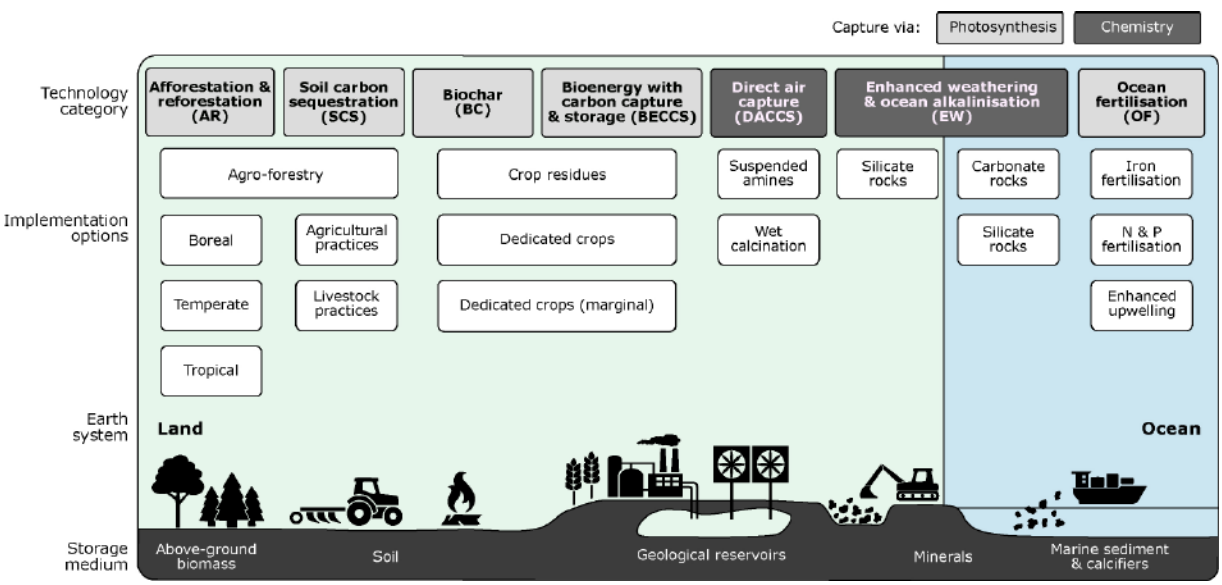


FIGURE 18.5.1 Summary of negative emissions technologies. From Sabine Fuss, Mercator Institute.

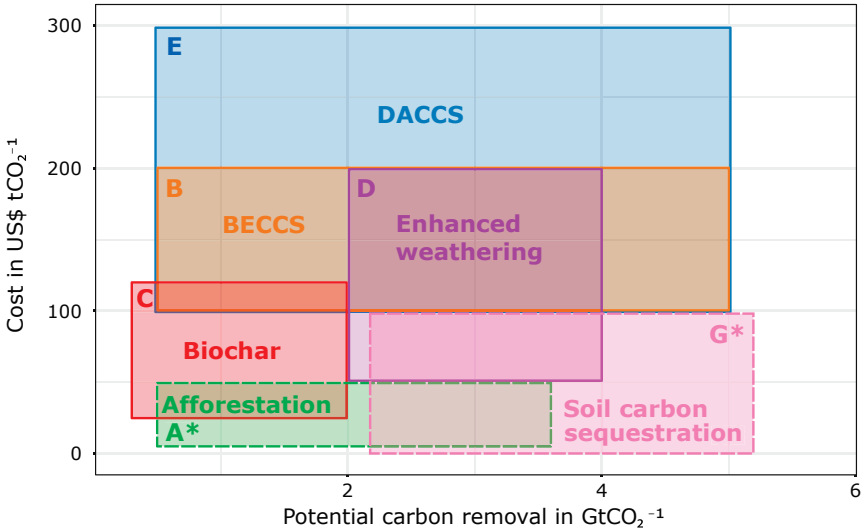


FIGURE 18.5.2 Potential costs and capacities of a number of prominent negative emissions technologies. From Sabine Fuss, Mercator Institute.

to reduce CO_2 emissions, such as renewable energy, generate a useful product (electricity), and once renewable energy reached the price of fossil fuels it became easier to replace the fossil sources. But achieving negative emissions does not replace an existing technology, and so it is harder than developing renewable energy. There is no price incentive for negative emissions, because the price we have been paying to dump CO_2 into the atmosphere is zero!

Figure 18.5.2 from the Mercator Institute in Germany gives one current estimate of the range of costs, and potential volumes, for the major negative emissions options discussed here. At this point it is not possible to produce precise estimates; the impacts of land use, energy, and cost have not been established, and the technologies are still being developed. The natural options such as afforestation and soil carbon sequestration are most likely to be the least expensive but do not add up to the 20 billion tons we will need at the end of the century. Nor does this estimate give options like bioenergy with carbon capture and storage, or direct air capture, an unlimited estimated capacity; they will ultimately have limits due to land use and cost of capital to build them. It appears most likely that we will need many, if not most, of these approaches (and some not yet invented!) to achieve our climate goals.

We could estimate the average from Figure 18.5.2 as around $100/ton of CO_2 removed (averaging the cost of the less expensive technologies and hoping that we need a minimum of direct air capture). At that cost, which seems achievable by the end of the century, the 10 billion tons required in 2050 would cost the world $1 trillion per year—a huge number, but only about 1% of today's world gross domestic product (GDP) of $100 trillion. (By 2050, world GDP is expected to be about $220 trillion.) The United States, with a GDP today of about $18 trillion, spends on the order of $200 billion to manage its garbage—a remarkably similar 1%. Can we spend 1% of our world economy cleaning up the mess we have made of our atmosphere over the last 200 years? Let's hope we can.

And the path that we follow is not just a function of negative emissions options. As you have learned throughout this book, there are dozens or even hundreds of choices that society has to make about the rate of carbon-free energy adoption, energy efficiency, land use, population, and many other factors. Each of these choices contributes to the pathway that we take through future climate space. That path is not yet decided, and society is grappling with the mechanisms to weigh and implement the various options. By reading this book, you have made yourself an educated contributor to that discussion. Whether they be technological, organizational, political, inspirational, or real muscles, you are now ready to apply your muscles to bending the curve.

Negative emissions technology and evaluation are just in their infancy today, rather like renewable energy was in the 1970s. Some of the directions we need to take are clear, but the details of technology combinations, system approaches, and overall trade-offs are not yet apparent. What is obvious is that cleaning up the atmosphere to levels we consider livable will be a massive effort—one that the students of today (you readers of this book) will spend their careers making successful. It is no small effort and will likely be the most important science and technology effort of this century. Go forth and succeed!

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CHAPTER 19

Local Solutions

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Learning Objectives

This chapter has four main learning objectives, the accomplishment of which will enable you to do the following:

1. Explain localization. Explain why so many global scientific organizations and international agencies are now claiming that the commitments and actions of cities and other local subnational entities (for example, counties, port districts, metropolitan planning organizations) are vital to averting climate change disaster on a planetary scale.
2. Describe green infrastructure. Describe how green infrastructure is being used in local climate action plans and ecological landscape design to address flooding and drought while meeting climate change mitigation and adaptation goals on a bioregional scale.
3. Analyze natural climate solutions. Identify potential benefits of natural climate solutions (for example, urban agriculture, food forests, carbon farming) and hybrid solutions that couple human and natural systems (for example, community composting, anaerobic biodigesters, aquaponics) from social justice, economic efficiency, ecological sustainability, and resilience perspectives.
4. Define *rooted university*. Assess from an ethical standpoint the current and potential role of universities in creating and helping to advance climate change solutions. List one or more ways you can improve science-society relations by linking climate change knowledge and action through community engagement.

This chapter will also examine the power of narratives and framing to help you become a good climate change solutions communicator. The chapter content you'll need to meet these learning objectives is organized in four sections:

- 19.1 Localization and the Bioregional Transition
- 19.2 Green Infrastructure and Climate Action Planning
- 19.3 Natural Climate Solutions and Hybrid Approaches
- 19.4 Rooted Universities and the Green Infrastructure Nexus

Overview

The combined impact of anthropogenic climate change and ecological degradation worldwide poses an existential threat to humanity. Significant global and national efforts are underway to accelerate climate change mitigation and adaptation. But there is a rising concern that these efforts may be too little too late. The Intergovernmental Panel on Climate Change (IPCC) and many other reputable science-based organizations are sounding the alarm. That is, that much more needs to be done, and quickly, if we are to avert devastating climate disruption. The fact that Earth's land, water, and ecosystems are subject to mounting cumulative stresses from unsustainable development practices greatly complicates matters.

This chapter focuses on what we can do about this problem, now and going into the future. We'll be exploring local solutions that involve people working together where they live and work. This raises some key questions for you to ponder: Which of these place-based solutions should we try to better understand, rally around, improve, and share? Which factors are most essential to the success of solutions? Is it the science and technology; community engagement; cultural, political, and/or economic system change; some combination of these? This chapter concentrates on identifying and examining climate change solutions that are local and bioregional. In particular, we will concentrate on natural climate solutions and green infrastructure.

Natural climate solutions can remove significant amounts of carbon from the atmosphere through better stewardship of natural and working lands. Examples include land management practices that increase carbon storage and/or avoid greenhouse gas (GHG) emissions through ecological restoration, wetland protection, regenerative agriculture, community composting, carbon farming, and reforestation. Natural climate solutions are taking place in both rural and urban environments. The results are sometimes mixed (good and not so good) and thus need to be more closely studied and understood.

Green infrastructure incorporates the functioning of natural systems like trees, soil, and waterways into human-built systems designed to improve environmental services (for example, storm water management

and flood control, ecological conservation, and drought-resistant landscaping in the public realm). Green infrastructure provides solutions to climate change through physical planning and design that integrates ecological systems, land use, and the built environment. Green infrastructure is included in a growing number of climate action plans.

Natural climate solutions and green infrastructure are woven together in this chapter as part of a bioregional approach taking into account local-global and urban-rural relationships. The term *bioregion* is a place-based concept that is not solely urban nor solely rural; it is a territorial space composed of **urban-rural linkages**. The bioregional frame enables us to think about a city-region as a functioning whole including relationships among urban centers, towns, and natural and working lands. Strengthening urban-rural linkages through a bioregional approach can help bolster support for climate change solutions.

Bioregional imagination helps inspire ideas, innovation, and civic engagement needed to create an equitable green economy with good jobs while improving community health and well-being, minimizing waste, and regenerating ecosystems. Along such lines, this chapter presents the idea of a bioregional transition and points to what some universities are doing to help navigate this transition. One example is the creation of a **green infrastructure nexus**, a social and technical concept that provides a narrative that values justice and democracy in science-society relations. Our prospects for successfully "bending the curve" depend on our strengthening democratically inclusive and informed participation in sustainability science, planning, and design.

The green infrastructure nexus can help society meet human needs (for example, for food, water, energy, resilient and healthy life space) while supporting local and bioregional development that is climate friendly, resilient, and regeneratively sustainable. This chapter encourages you to ponder whether something like a green infrastructure nexus, supporting natural climate solutions along with other approaches, can help bring about a climate-friendly land ethic and rooted democracy.

Much of the technical data and observations provided in this chapter are derived from assessments, special reports, and conference proceedings published by the National Academies of Sciences, Engineering, and Medicine; Intergovernmental Panel on Climate Change; United Nations;

and university centers and institutes. Other sources include scholarly literature spanning the social, natural, physical, and life sciences; arts and humanities; and engineering, management, planning, and design. Chapter sections that highlight particular cases unfolding in Southern California and Northern Baja California, Mexico, are mostly derived from the author's direct engagement and participant observation in these cases over the course of three decades.

19.1 Localization and the Bioregional Transition

Localization is a development process that favors investment inside a particular locality for the benefit of that locality and the people, plus other life, living within it. In a localizing process that addresses climate change, efforts concentrate on identifying and enabling behavioral and physical changes needed to bring about more climate-friendly development. This includes carbon-neutral ways for people to collectively build, dwell, and **adapt-in-place** together.

Localization is a territorial process that generates place-based policies, plans, and activities. The aim is to create resource-conserving, waste-minimizing, and regenerative systems of production, consumption, distribution, and exchange. The number of organizations implementing localization strategies is growing. In the USA, the New Economy Working Group (a multipartner, action-oriented think tank) highlights the possibility and potential of localized living economies that support a healthy biosphere. Ecotrust, based in Portland, Oregon, operates an environmental bank, an ecosystem investment fund, and a range of programs in fisheries, forestry, food, farms, and Indigenous affairs. On a global scale, Bioneers, a group of social and scientific innovators, grows social capital by building local and bioregional and community-based alliances. The Bioregional Center for Sustainability Science, Planning and Design (based at UC San Diego) is doing civically engaged research and education focused on the transborder San Diego–Tijuana bioregion. The Bioregional Center works closely with the Global Action Research Center, known as the Global ARC. The Global ARC has a busy localization agenda linking research and action in community gardens, **food forests**, community composting, watershed protection, green infrastructure, and the establishment of a community-university partnership-led neighborhood environmental learning hub. The Global ARC's food forest planted in an underserved, low-income community in Southeast San Diego has proven to be an especially good way to join concerns about climate and

food systems. The definition and role of food forests in this context are described in more detail in Section 19.3.

The localization narrative now has a long list of tools and concepts (and yes, ample jargon) upon which to draw. Prominent examples include *locavore*, *locavesting*, *slow foods*, *food justice*, *green infrastructure*, *adapting-in-place*, *eco-districts*, *biocapacity*, *ecological footprint*, *business alliance for local living economies (BALLE)*, *local ownership and import substitution (LOIS)*, *community-based natural resource management (CBNRM)*, *relocalization*, and *reinhabitation*.

Localization on the world stage

Global leaders and initiatives that are tasked to address climate change have begun to stress the importance of local engagement by actors that are jurisdictionally less comprehensive than an entire country (that is, nation-state). This includes subnational actors such as cities, counties, port districts, and metropolitan planning organizations. A clear example can be seen in the proceedings of the United Nations Climate Change Conference of the Parties (COP). The COP is an annual meeting of nearly all the world's nation-states and other organizations that formally come together to assess climate change efforts on the world stage.

The COP was established to track the degree to which nation-states worldwide are complying with the 1992 United Nations Framework Convention on Climate Change (UNFCCC). At the COP's twenty-first annual meeting (COP21) held in Paris for 10 days in 2015, 195 nations reached a milestone agreement that has gotten a lot of media coverage. COP21's Paris Agreement commits all of the participating parties (member states) to holding the increase in the global average temperature to well below 2°C above preindustrial levels and to pursuing efforts to limit the temperature increase to 1.5°C above preindustrial levels. This one-half-degree difference is significant. Keeping the increase under 1.5°C improves our chances to avoid devastating climate change impacts.

Glocalizing commitments to reducing carbon emissions

COP21's agenda and activities recognize that *local and regional governments play a critical role in global climate action*. The Climate Summit for Local Leaders that took place during COP21 produced a declaration by

city and regional leaders from five continents announcing their cities' and regions' commitment to tackle climate disruption. Those who signed the Paris City Hall Declaration—including mayors, governors, premiers, and other local government leaders—committed to collectively deliver up to 3.7 gigatons of reduction in urban greenhouse gas emissions every year over the period 2015–2030. Meeting this goal would significantly help to close the gap between current national commitments and the 2°C emissions reduction pathway identified by the scientific community.

The Paris City Hall Declaration constitutes a promising case of **glocalization**—defined in the *Encyclopedia Britannica* as "linguistic merger of *globalization* and *localization* to describe processes that simultaneously exhibit both universalizing and particularizing tendencies in contemporary social, political, and economic systems." The Paris City Hall Declaration draws attention to urban and regional networks worldwide, including the Compact of Mayors, the Covenant of Mayors, and the Compact of States and Regions. These *glocal* networking efforts are mobilizing commitments that specify local carbon and other GHG emission reduction targets for national and global benefit.

The Climate Summit of Local and Regional Leaders that took place at COP23 in 2017 culminated in a commitment by 1,019 local and regional governments from 86 countries, representing 804 million people, to reduce 5.6 gigatons of CO_2 equivalent emissions by 2020 and 26.8 gigatons of CO_2 equivalent emissions by 2050. COP24 held in Katowice Poland in 2018 concentrated on clarifying the details and protocols necessary to make the Paris Agreement operational. COP24 established a working group to support local and Indigenous communities in their efforts to strengthen Indigenous and local knowledge systems, enhance the engagement of local communities and Indigenous peoples in the UNFCCC, and process and integrate their considerations into climate change policy and action.

In addition to COP conferences where support for local and subnational solutions to climate change is rising, support for localization of this sort can also be seen in other global networking endeavors. More than 9,000 cities and local governments representing roughly 800 million people worldwide have joined the Global Covenant of Mayors for Climate & Energy—a voluntary accord whereby cities can commit to make

a low-carbon future one of their top priorities. Other examples include work coming out of the UN's Habitat III, Union of Concerned Scientists, and the Catholic Church. Pope Francis wrote "On Care for Our Common Home," a widely read encyclical letter focused on climate change as a moral issue, especially insofar as climate change disproportionately affects the world's poor living in vulnerable cities and towns.

The new urban agenda and the bioregional transition

The globalization of local efforts to deal with climate change is a harbinger of what may be unfolding in some places as a **bioregional transition**. Organizations seeking integrated approaches to climate change have begun focusing world attention on urban-rural linkages and interdependencies. One of the top priorities listed on the Cities and Climate Change Science agenda produced during the forty-eighth IPCC meeting in 2018 is a clarion call for greater depth of understanding and commitment to improving holistic systems approaches to climate action planning. Specifically, the Cities and Climate Change Science agenda calls for more research to better understand the diverse interdependent links and resource flows throughout natural, built, and social systems and between urban areas and the rural hinterlands. This kind of research begins to look at bioregions as a useful territorial concept where urban, rural, natural, and working lands can be examined as interacting systems.

Bioregional solutions to climate change connect efforts in urban areas with related efforts and/or concerns in adjacent and nearby rural areas. Rural areas are made up of rural settlements, working lands, and waters (for example, farms, ranches, fisheries) and wildlands (natural and conserved spaces such as parks and forests). Bridging and improving urban-rural linkages is crucial if we ever hope to improve communication and public reasoning necessary to address climate change. This argument is well articulated globally in Habitat III's New Urban Agenda.

The New Urban Agenda operationalizes Goal 11 of the UN's 2030 Sustainable Development Goals. Goal 11 aspires to make all cities and human settlements on Earth inclusive, safe, resilient, and sustainable. The New Urban Agenda emphasizes the importance of the "urban-rural continuum." This emphasis constitutes an important relational shift in perspective that sets aside the simplistic dualism of urban versus rural

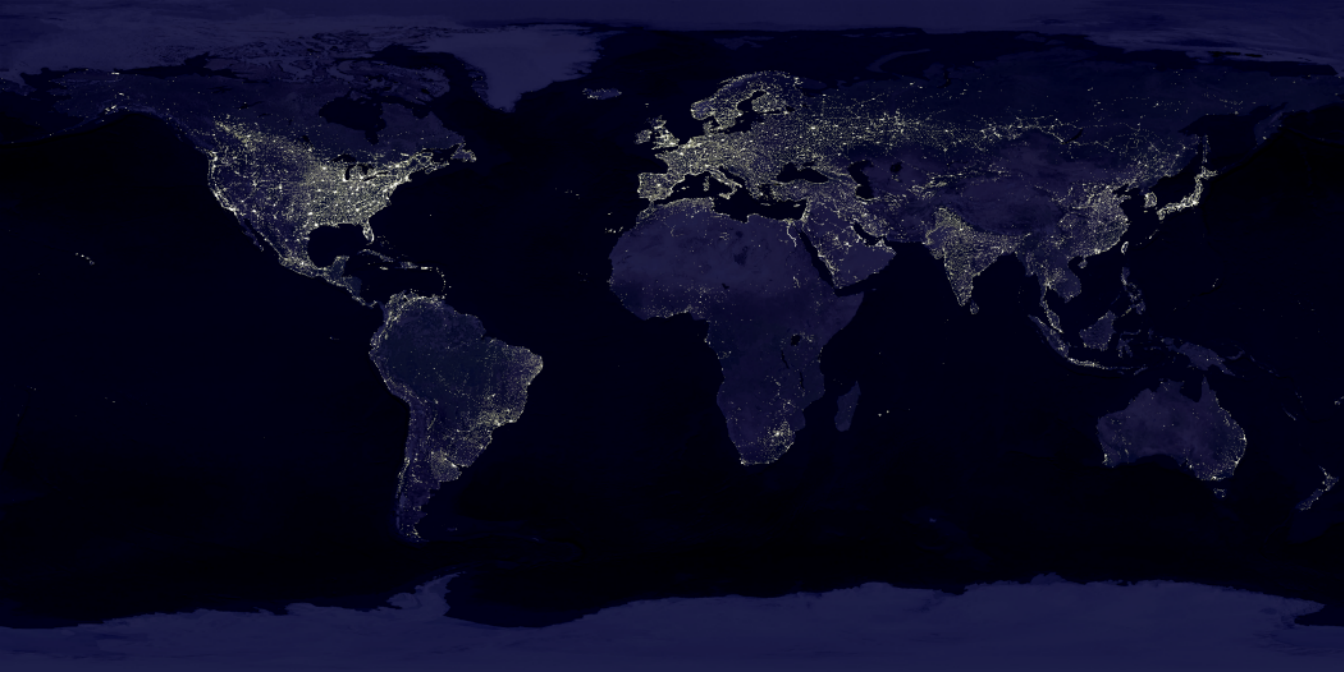

FIGURE 19.1.1 **City lights at night.** Reproduced from NASA.

(the urban-rural binary). It may prove useful to view this shift as the beginnings of a bioregional transition in how we humans build and dwell together collectively on Earth.

Drivers of the bioregional transition

Local and bioregional approaches to climate change benefit from globalized science and technology (for example, climate change modeling, transnational cyberinfrastructure, mapping, and data visualization technology). Science helps put things into perspective. NASA created a widely shared image showing Earth's city lights from space (Figure 19.1.1). The city lights on the image show how urbanization tends to concentrate along coastlines. The United Nations reports that roughly 10% of the world's population (at least 600 million people) live in coastal areas that are less than 10 meters above sea level. And approximately 40% of the world's population (about 2.4 billion people) live within 100 km (60 miles) of the coast. This puts many people in harm's way as sea level rises. And the global human population continues to grow rapidly.

The world's human population in 2018 was 55% urban and 45% rural. The UN projects that the urban population will increase to 68% of the total by 2050. The sheer number of people involved is staggering. Between 2018 and 2050 an additional 2.5 billion people will populate the world's cities. It is hard to grasp such magnitude. So, imagine this.

The city of Los Angeles has roughly 4 million inhabitants. It is the largest city in California, and the second largest in the USA (behind New York City). Every single year, from 2018 to 2050, roughly 78,000,000 people will join the ranks of the world's urban population. That translates into an *annual population increase* of about 20 LA-sized cities! This dramatic urban growth surge will take place mostly in Asia and Africa. The growth will include population increases from rural-to-urban migration. The growth will also stem from births within existing cities and the creation of new cities (perhaps most dramatically in China, where hundreds of new cities with more than a million inhabitants each are expected to populate the landscape). The Cities Alliance warns that meeting the infrastructure and construction needs of this urban population growth over the period from 2018 to 2050 may use up more than three-quarters of humanity's global CO_2 budget if climate change is to be limited to less than 1.5°C. The institutional, economic, and societal stresses happening in the wake of rapid urbanization in many parts of the world where infrastructure and public services are inadequate is one of many factors motivating urban and regional planners to focus on urban-rural linkages from a bioregional perspective.

Figure 19.1.2 illustrates global and regional factors that may give rise to a bioregional transition in some places around the world. The drivers of the bioregional transition are multiple and complex, combining problematic stresses as well as opportunities, including (1) the intensification of climate change as global demand surges for meeting basic human needs such as food, water, energy, and dwelling space; (2) mounting institutional, economic, and societal tensions, including inequality; (3) culture change within universities where demand is rising for equitable, civically engaged research and education that is problem-solving and solutions oriented; and (4) disruptions good and bad happening in the wake of newly emerging modes of knowledge production, data science, multimedia communication, networking, and cyberinfrastructure.

Together these stresses, as well as opportunities, are stoking interest in localized, place-based solutions to climate change. The **bioregion** as a unit of analysis is gaining traction as a territorial framework to address urban-rural linkages. *Bioregion* as a term combines the Greek word for "life" (*bios*) with the Latin word for "territory" (*regia*) and the Latin

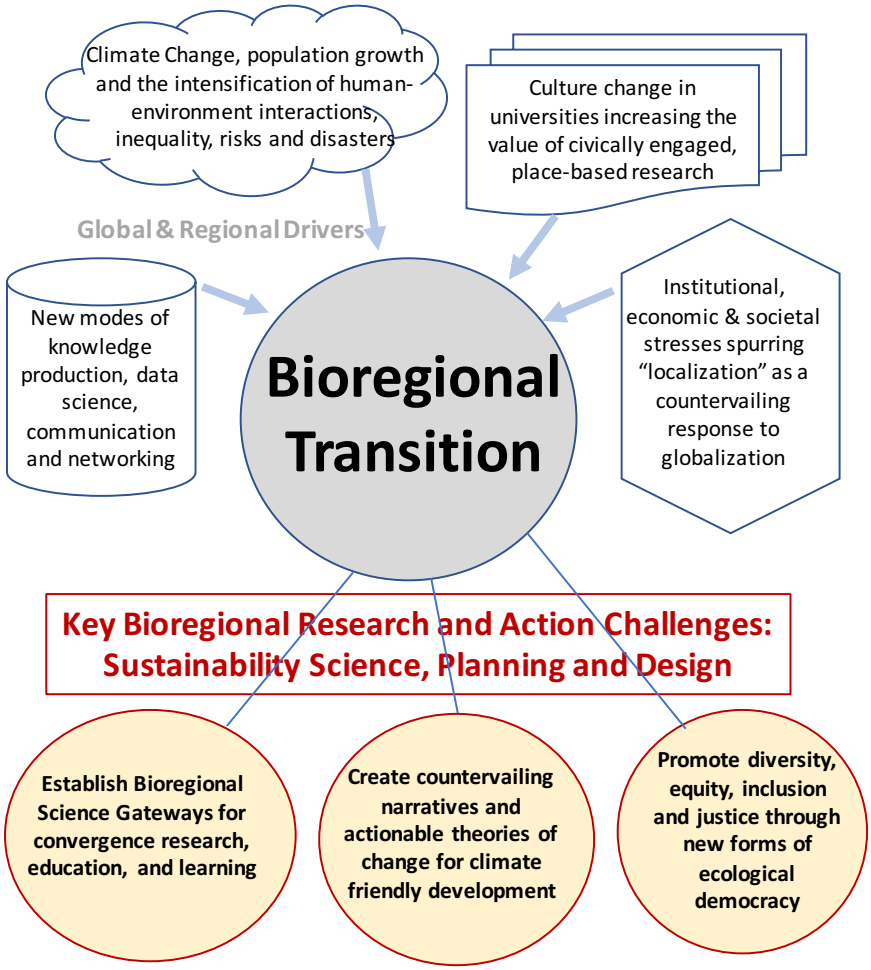

FIGURE 19.1.2 **The bioregional transition.** Illustration by Keith Pezzoli.

term for "ruling/governing" (*regere*). *Bioregion* thus means "life territory or life place." A bioregion is a region broadly defined by its physical, human-built, sociocultural, and economic attributes. The physical attributes of a bioregion include its geographic, ecological, and hydrological contours/systems giving shape to its landscapes and watersheds. Other physical attributes include climate, flora, fauna, soil, and water. The human-built attributes of a bioregion include the area's infrastructures and human settlement patterns.

Bioregionalism is an action-oriented field of study focused on enabling human communities to live, work, eat, and recreate sustainably within Earth's dynamic web of life. The bioregional approach to climate

change solutions calls for establishing just, ethical, and ecologically resilient ways to (re)connect people with one another and with the land. *Bioregionalism's core commitments include* (1) rebuilding urban and rural communities—at a human scale—to nurture a meaningful sense of place and to secure healthy attachments and rootedness among community inhabitants; (2) integrating nature and human settlements in ways that holistically instill eco-efficiency, equity, and green cultural values into systems of production, exchange, consumption, and daily life; (3) making known (and valuing) the way natural and working lands, ecosystems, and rural dwellers and resources enable cities to exist; (4) developing authentic community-based participatory processes that empower just and equitable civic engagement in local and regional planning, visualization, and decision-making; and (5) building global trans-bioregional alliances and knowledge networks to support sustainable place making around the world.

Bioregional ethics: local place-based attachments

Bioregional ethics begins with the following premise: Human beings are social animals. If we are to survive well as a species, we need sustainable human-nature relationships and healthy place-based attachments in ethical living arrangements with one another *and* with the land, waters, habitat, plants, and animals upon which we depend. Figuring out how to meet this need in socially just, ecologically regenerative, equitably inclusive, and climate-friendly ways is the paramount ethical as well as practical challenge of the twenty-first century. This is especially challenging, given how modern civilization's globalized, hypermobile economy and large-scale migratory flows of people worldwide have made it increasingly difficult for people to form healthy place-based (rooted) attachments. Yet, stable, rooted attachments of this sort (including a sense of belonging to, and affection for, a particular place) are arguably necessary for societal well-being and environmental stewardship.

A **rooted community** is a community that identifies and supports aspects of social and political rights (for example, mutual aid, communitarianism, place-based attachment) that the liberal paradigm has neglected. Peter Marris provides us a wise suggestion in this regard: "Instead of thinking about social justice only in terms of the equal treatment

of equivalent units, it acknowledges the right of each community of people to a familiar habitat, like creatures in the natural world. It recognizes the attachments which bind people to each other and to places, and out of which evolve the unique meaning of each person's life." Wendell Berry—a widely noted farmer-philosopher, poet and writer, conservationist, environmentally minded public intellectual—eloquently made the same point during his highly acclaimed Jefferson Lecture. Berry's lecture, titled *It All Turns on Affection*, provides a strong moral and ethical critique of the presumption held by too many that cities can be improved by pillage of the countryside. Berry argues that we need to do a much better job understanding and valuing the multiple ways—ethically, culturally, economically, ecologically—that the fates of cities and towns are inextricably bound together.

There is a disconnect in how we arrange our urban and rural settlements and life support systems on Earth. For sure, resource-intensive industrialism worldwide has generated great wealth, even lifting millions of people out of extreme poverty. But it is also a highly uneven process that in many cases uproots people for lack of secure and stable connections to land and jobs. The relative abundance generated by globalized factory farming as an adjunct to industry has made it hard for many small-scale farms to survive. At the same time, many city people experience poverty and insecurity trying to meet their needs for food, water, and shelter.

The increasing volume of migratory flows of rural people—from degraded lands, expulsions, and lack of job opportunities—join the stream of urban migrants fleeing from violence in war-torn areas and from devastation caused by increasingly powerful storms and other mega-scale disasters, especially in coastal areas. These heavy migratory flows could eventually overwhelm existing legal and institutional systems designed to handle challenges posed by immigration and refugee needs. The prospect that "climigration" (migration forced by climate change) may get heavier increases this risk. What all of this points to is the need to transform how we go about urban *and* rural development.

Localization informed by a globally minded bioregional perspective is one way to address the daunting problems facing human civilization right now, including climate change. Localization can help us "connect

the dots" linking cities, towns, infrastructure, and working lands that are bound together by geography, ecology, and culture. Identifying, understanding, implementing, and sharing local and bioregional solutions in the form of green infrastructure and natural climate solutions is a good start.

19.2 Green Infrastructure and Climate Action Planning

Water is one of the most essential elements of life. Green infrastructure and climate action planning, if done well, can help ensure a secure and reliable flow of water to meet the needs of cities and agriculture, among other thirsty entities. The stakes are high. Researchers from the Center for Environmental Systems Research (University of Kassel, Germany) and the Nature Conservancy (Washington, DC) did a comparative study that examined climate change and urban growth globally. They found that rising levels of competition for water are pitting the needs of cities against the needs of agriculture. The study projects that urban water demand will increase 80% by 2050 in 482 of the world's largest cities. Over the same period, the deficit in available urban surface water is expected to increase.

The water-climate-energy nexus

In the case of California, nearly 10% of the state's GHG emissions come from the energy-intensive water system. Pumping, treating, and heating water consumes approximately 20% of statewide electricity use—and 30% of business and home use of natural gas. The San Diego region is actively seeking ways to supply water more efficiently, capture storm water using climate-smart tactics, and foster integrated regional watershed management. Green infrastructure is one of the favored approaches.

California's 2018 Fourth Climate Change Assessment Report published data projecting that an increase in the number of extreme weather events will likely bring more torrential downpours and flooding to many parts of California and nearby Mexico. Green infrastructure includes rain gardens, bioswales, permeable pavement, rainwater harvesting, and other naturally designed features created to conserve or enhance land, wetlands, and ecosystems. Green infrastructure that reduces flooding while making more efficient use of water saves money and energy in ways that reduce a city's carbon footprint and vulnerability.

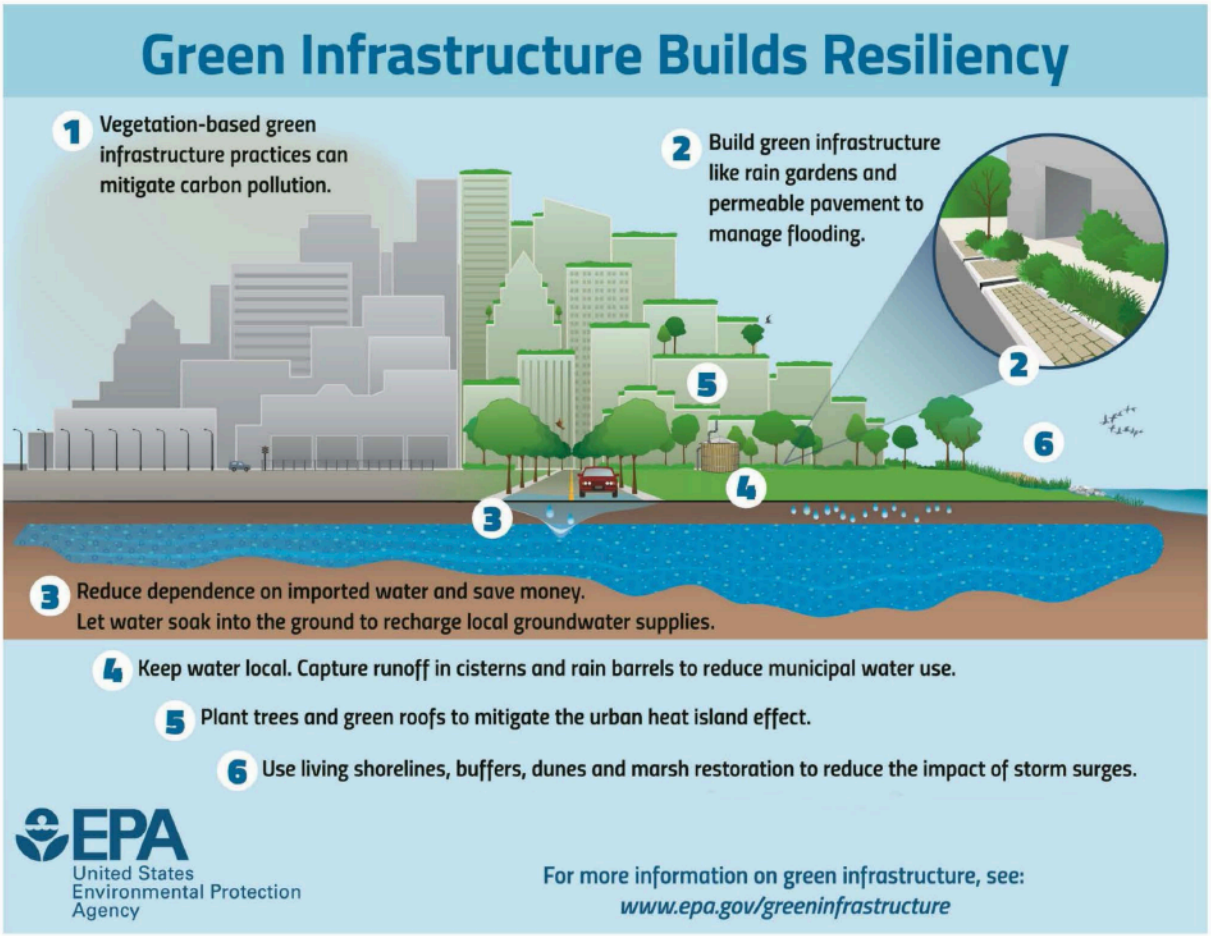

FIGURE 19.2.1 **Green infrastructure builds resiliency.** Reproduced from the EPA.

Green infrastructure can play a significant role in climate change mitigation and adaptation while enabling ecosystem regeneration. Green infrastructure incorporates ecosystem functions into human settlements and working lands. Serious efforts are now being made to incorporate green infrastructure into municipal climate action plans. Green infrastructure programs and policies in the US have mainly focused on improving water systems. But that is changing.

The US Environmental Protection Agency has expanded the definition to describe an array of products, technologies, and practices that use natural systems, and/or engineered systems that mimic natural processes, to enhance environmental quality and provide utility services. Figure 19.2.1 shows elements of green infrastructure that builds urban resilience. Green infrastructure defined in this way may include urban and rural networks of green spaces and other natural elements such

as rivers, lakes, forests, and canyonlands that connect villages, towns, cities, and working lands.

The concept can be stretched a bit further to include community composting facilities, green roofs and green walls, and green streets and alleyways, among numerous other clever ways to couple human and natural systems in the provisioning of utilities and public services. Designed well, green infrastructure can use a combination of vegetation, soils, and natural processes to manage water and create climate-friendlier, healthier urban environments. These systems can range from micro to more macro scales—from household rain gardens and green roofs up to large tracts of undeveloped natural lands.

Green infrastructure can help cities adapt to storm events and flooding, as well as drought, through climate-smart design that integrates human-built infrastructure (engineered systems for handling storm water) with natural environmental features (for example, watershed hydrology, ecosystems services). This can be accomplished in ways that join concerns about climate change, equity, justice, and health where people live.

Water quality, supply, and infrastructure improvement

In November 2014, California voters approved Proposition 1 (Prop 1), The Water Quality, Supply, and Infrastructure Improvement Act of 2014. Prop 1 authorized $7.5 billion in general obligation bonds for water projects including surface and groundwater storage, ecosystem and watershed protection and restoration, and drinking water protection. Prop 1 included $510 million in funding to improve integrated regional water management (IRWM) throughout the state. The Prop 1 IRWM Grant Program is administered by the State of California's Department of Water Resources, which is funding projects that help meet the long-term water needs of the state.

Integrated regional water management (IRWM)

The Prop 1 IRWM Grant Program provides support for "disadvantaged community involvement" in the grant process. The State of California defines **disadvantaged communities** (DACs) as those areas throughout California that are most negatively affected by a combination of

economic, health, and environmental burdens. These burdens include poverty, high unemployment, and health conditions like asthma and heart disease, as well as air and water pollution and hazardous wastes.

The state's Office of Environmental Health Hazard Assessment developed the California Communities Environmental Health Screening Tool ("CalEnviroScreen") to identify DACs in California, in part to help target DAC-eligible localities where a certain percentage of the state's cap-and-trade funding is required by law to be awarded (directly benefiting the people inhabiting that particular place). The law specifies that 25% of the revenue available from cap-and-trade sources must be used within communities designated as disadvantaged—the justification being that these communities are likely to be more vulnerable and thus especially hard hit by climate change.

In 2018, the State of California Department of Water Resources awarded a $1.17 million Prop 1 IRWM grant to UC San Diego, as part of a regional cluster of Prop 1 IRWM grants compiled and facilitated by the San Diego County Water Authority. San Diego's 2019 IRWM strategic plan includes efforts to address climate change through more effective water resource management, including ways to enhance the resiliency of local water resources while reducing greenhouse gas emissions. UC San Diego IRWM researchers teamed up with the San Diego Housing Commission—a major grant partner. This 2018 collaborative grant is titled Disadvantaged Community Planning Project (DAC): Alternative Non-Potable Water Supplies, Xeriscape Design and Flood Prevention for DACs. The DAC grant is a good example of localization involving water systems and green infrastructure that can help bend the curve.

The DAC project has an integrated design approach that includes a strong public health component, a research translation process for community residents, and water-conserving methods that include xeriscape design, flood control, water use management, and urban agriculture. UC San Diego and the San Diego Housing Commission joined forces with the Scripps Institution of Oceanography, Public Health Alliance of Southern California, San Diego Food System Alliance, and Global Action Research Center (Global ARC). Together this group is designing a half dozen shovel-ready projects for which funding will be sought once the design phase is completed.

The DAC project addresses core challenges for bringing water resource resilience to California's DACs, which are faced with water scarcity, urban heat island effects, a lack of access to healthy food, rising potable water prices, and periodic flooding from intense storms. Alternative nonpotable water reuse systems (for example, laundry-to-landscape graywater use, rainwater harvesting) can strengthen urban resilience by supporting urban agriculture. The project's plans for drought- and flood-resilient green spaces are also good for environmental public health. One of the more difficult aspects of work like this is the need to translate current research, science, and policy around alternative nonpotable water reuse into designs that can be permitted, effectively managed, and useful to residents in DACs and publicly supported housing. In order to maximize potential benefits, significant effort has to go into joining bottom-up grassroots efforts that reach into the resident base of communities with "treetop" efforts within the government and other institutions. One treetop effort that has the potential to join local and global objectives, by embracing green infrastructure, is climate action planning. Municipalities, counties, port districts, and other subnational as well as national agencies are creating and implementing climate action plans.

C40 and climate action plans

C40 is a network of the world's megacities. It has rapidly grown since its birth in 2005. C40 facilitates collaboration among 94 of the world's largest cities with the intent to accelerate meaningful and measurable climate change solutions. C40 represents 700+ million citizens and one-quarter of the global economy. The mayors of C40 cities are committed to delivering on the most ambitious goals of the Paris Agreement at the local level. As outlined in Box 19.2.1, C40 defines a climate action plan as a strategic document (or series of plans and documents) that demonstrates how a city will deliver on its commitment to address climate change.

The C40 mayors have joined forces with 9,000 others committed to taking action called for in the Paris Agreement. The C40 mayors estimate that the combined collective impact of these commitments could achieve annual reductions from "business as usual" of 1.4 gigatons of CO_2 equivalent (CO_2e) in 2030 and 2.8 gigatons CO_2e in 2050.

Box 19.2.1 Climate Action Plan Objectives and Strategies

A climate action plan will:

- Develop a pathway to deliver an emissions neutral city by 2050 at the latest and set an ambitious interim target and/or carbon budget.
- Demonstrate how the city will adapt and improve its resilience to the climate hazards that may impact the city now and in future climate change scenarios.
- Detail the wider social, environmental, and economic benefits expected from implementing the plan, and improve the equitable distribution of these benefits to the city's population.
- Outline the city's governance, powers, and the partners who need to be engaged in order to accelerate the delivery of the city's mitigation targets and resilience goals.

A city will do this by:

- Considering adaptation and mitigation in an integrated way, identifying interdependencies to maximize efficiencies and minimize investment risk.
- Setting an evidence-based, inclusive, and deliverable plan for achieving transformational mitigation and adaptation, centered on an understanding of the city's powers and wider context.
- Establishing a transparent process to monitor delivery, communicate progress, and update climate action planning in line with governance and reporting systems.

C40 Cities Climate Planning Framework. 2018. Chapter 1, page 4. Retrieved from https://resourcecentre.c40.org/climate-action-planning-framework-home.

Unfortunately, while real progress is being made, many cities have not yet been able to address climate change. Several deficits and obstacles stand in the way. Relevant city policies and action plans are not yet in place; urban and environmental planning regulations are out of step with the complexities posed by climate change; misinformation and a lack of public awareness make communication about climate change risks and vulnerabilities difficult.

FIGURE 19.2.2 OVGG Community Garden and Chollas Creek in the Pueblo watershed, San Diego, CA. Adapted from Google Earth; inset photograph by Keith Pezzoli.

Green infrastructure at a watershed scale

Connecting climate action planning with strategies to green a bioregion's infrastructure is a good way to advance climate change mitigation and adaptation. An example of this can be seen in a vacant land asset mapping project that took place in San Diego, California. Figure 19.2.2 shows the Pueblo watershed (the polygon area layered as blue) in San Diego County. The dark blue line depicts one of the most polluted creeks in the United States, Chollas Creek. Chollas Creek drains into San Diego Bay, one of the most polluted bays in the US. Contamination of Chollas Creek and the San Diego Bay are in part due to the way urban development paves over the earth. Streets, parking lots, buildings cover the land with impervious surfaces, reducing the porosity necessary for rainwater to seep into the earth. Consequently, rain events pick up surface pollution that gets dumped directly into the bioregion's creeks, bays, and ocean.

During storm events, flooding is a major problem, a problem likely

FIGURE 19.2.3 Bioswale at the Ocean View Growing Grounds, San Diego, CA. Photograph by Keith Pezzoli.

to get worse in Southern California with climate change. Thus, significant effort is going into figuring out how to reclaim the Earth's capacity to absorb storm water. This is where green infrastructure comes into play. The tiny yellow polygons shown in Figure 19.2.2 are 810 vacant lots distributed throughout Southeast San Diego. UC San Diego's Bioregional Center did a survey of these vacant lots as part of a research grant. Many of the 810 vacant lots would be very good sites for urban agriculture and installations of green infrastructure. The inset photo in Figure 19.2.2 shows a work group planting a food forest on what was one of the 810 vacant lots. The site now includes a community garden and food forest; it is called the Ocean View Growing Grounds (OVGG). Over the period from 2014 to 2019, local residents, community leaders, civically engaged academics, various professionals, students, and volunteers transformed the vacant lot. Members of OVGG installed a bioswale on-site to retain water for the food forest. The bioswale in this case is a simple carved-out depression in the land, spanning 30 by 20 feet and surrounded by the planted trees, shrubs, and plants (Figure 19.2.3). A bioswale is a hydromodification of a landscape to slow, collect, infiltrate, and filter storm water.

Part of the OVGG narrative speaks to how a plot of contaminated

vacant land (what the EPA designated as a brownfield site because of concerns about toxicants in the soil, discussed below) got transformed into a neighborhood garden resource as well as a watershed asset. The neighborhood garden part is easy to understand; the site now produces fresh fruits and vegetables in a food desert (that is, a geographical area that suffers from a deficit of markets providing healthy food). The watershed part of the story is less obvious but merits attention for ecological reasons. OVGG sits within the Pueblo watershed with a great deal of impervious services (streets, parking lots, driveways, alleyways). Paving over the land with concrete has created an urban runoff problem that ends up degrading Chollas Creek. Chollas Creek drains the Pueblo watershed, which empties into the heavily contaminated San Diego Bay.

The bioswale at OVGG is a hydromodification of the land surface that improves on-site water retention and flow. This also provides a benefit to the health of the Pueblo watershed. It does so by reclaiming some of the watershed's capacity to be more spongelike as opposed to impermeably hardscaped. At least 100 of the 810 vacant lots surveyed in the Chollas Creek watershed appear to be well positioned with respect to their location in the watershed's urban runoff flow paths. If a concerted effort were made to hydromodify some of the vacant lots, as was done at the OVGG site, then, it is reasonable to assume, less pollution would end up in the waterways. Herein lies an opportunity to think about creating green infrastructure improvement districts.

Imagine incentivizing owners of vacant land to allow community groups to use their land for urban agriculture, at least for some defined period until said landowners decide to develop their land. Now imagine 20 or 30 landowners taking advantage of the incentive as part of a green infrastructure improvement district. As a result, 20 or 30 vacant lots get transformed by local groups of residents, school or faith-based organizations, neighborhood associations, and the like, into community gardens and/or food forests. The locals working on these lots could get support through the green infrastructure improvement district. For instance, there could be small grants to install low-cost but effective bioswales and/or rain gardens. Rain gardens are smaller-scaled versions of bioswales. Both bioswales and rain gardens are landscape elements designed to slow and filter storm water, and both are, in effect,

small-scale natural climate solutions. This scenario is not farfetched. In 2018 the State of California passed the Urban Agriculture Incentive Zones Act (Assembly Bill 551). This bill allows landowners in metropolitan areas to receive tax incentives for putting land into agricultural use. Cities and counties must first create urban agriculture incentive zones to set the stage. With the intent to scale up efforts like this, UC San Diego's Bioregional Center—supported in part by a grant (P42ES010337) from the National Institute of Environmental Health Sciences, Superfund Research Program—enlisted hundreds of students to do site suitability analysis of the 810 vacant lots in the Pueblo watershed shown in Figure 19.2.2. *Site suitability analysis* in this context refers to a method of assessment that gauges the qualities of the land and its surroundings as a potential growing space (for example, the lot's soil condition, access to water, adjacent land uses, slope, shading, plant cover, trees, upkeep). This effort helps to embed small micro interventions (a community garden on one lot) in a larger watershed context.

The Bioregional Center contributed the image shown in Figure 19.2.3 to the sixteenth report of the Good Neighbor Environmental Board. Said report, which focused on ecological conservation in the US-Mexico border region, was submitted in 2014 to President Obama and the Congress of the United States. The image as included in the report has the caption "Vacant lot in San Diego being converted into a food forest and site for urban ecological restoration." This line of thinking adds value to and helps justify/advance efforts like California's Assembly Bill 551. But this effort, as good as it sounds, is not without its risks. Some of the vacant lots are contaminated with lead and other toxicants. Contaminated storm water and urban runoff might negatively affect the soil that people are using to grow food in the community garden and/or food forest. The Community Engagement and Research Translation teams of UC San Diego's Superfund Research Center are providing soil testing and risk assessment communication to deal with this concern.

Many obstacles, not just pollution, stand in the way of meeting the high demand in Southeast San Diego and other urban food deserts for places to grow fresh fruits and vegetables. Much work needs to be done to change legislation and regulations. Climate action plans are helpful insofar as they elevate systems thinking that values the greening

FIGURE 19.2.4 **San Diego–Tijuana US-Mexico border.** Adapted from Google Earth.

of infrastructure and effort to work with nature not against it. Urban forestry is now included as an important part of the City of San Diego's climate action plan. The City of San Diego and the City of Tijuana plan to use geographic information systems (GIS) as a way of locating the best sites for green infrastructure, including the use of vegetated bioswales for storm water management and the strategic use of trees, including food forests, for carbon sequestration and other benefits.

The Good Neighbor Environmental Board report mentioned above argues that a vigorous and engaged urban forestry program (a natural climate solution) is critical to meeting San Diego's integrated commitments to ecological restoration, climate change, carbon sequestration, storm water reduction, and water conservation. With these goals in mind, the City of San Diego developed a long-range urban forest management plan to guide the city's urban forest into the future.

Understanding natural climate solutions and urban-rural linkages is especially important in a transborder metropolis like San Diego–Tijuana.

The two cities share a watershed, so collaborative binational land management is crucial to any hope of realizing climate-friendly sustainable development. The San Diego–Tijuana shared bioregion located along the US-Mexico border has a south-to-north slope to the land. Storm water flows from Tijuana across the border into the US, picking up along the way tons of soil washed loose from Tijuana's rapidly urbanizing canyons. The erosion is a major problem. Tijuana's thinly vegetated steep canyon slopes are easily disturbed by poorly planned urbanization lacking adequate infrastructure. The eroded soil, trash, and contaminants that flow from Tijuana's canyons into the US clog the wetland on the US side. This puts farmland at risk of contamination and causes frequent beach closures to protect public health. The soil loss and land degradation release carbon to the atmosphere.

Research universities, and local partners, on both sides of the US-Mexico border have formed an alliance to try to help solve some of the border region's complex problems. A recent grant from the National Science Foundation (NSF, 2018 award number 1833482) provided support for several workshops in the US and Mexico geared to scoping out an actionable research agenda for a binational Border Solutions Alliance. One of the work groups for these workshops is named Measuring, Understanding and Improving Natural Climate Solutions: Enabling Carbon Neutral Development through Transborder Urban-Rural Linkages and a Green Infrastructure Nexus, clearly indicating its focus.

19.3 Natural Climate Solutions and Hybrid Approaches

Significant global and national efforts are underway to accelerate climate change mitigation and adaptation. But there is a rising level of concern that these efforts may be too little too late. The IPCC, among many other reputable science-based organizations, is sounding the alarm: much more needs to be done, and quickly, if we are to avert devastating climate disruption. The fact that Earth's land, water, and ecosystems are subject to mounting cumulative stresses from unsustainable development practices complicates matters.

Carbon budgets and CO_2 removal

Researchers are keen to understand and improve methods to *remove* carbon from the atmosphere. The concept of a "carbon budget" has drawn attention to the notion that the atmosphere can absorb just so much carbon if we hope to avoid global warming beyond a certain level—a level that if surpassed could be catastrophic. There is a fair amount of debate concerning the assumptions and methods used to specify the upper limit for this carbon budget. Likewise, there is debate and a wide range of estimates concerning how much carbon humans have already dumped into the atmosphere. The IPCC's Fifth Assessment Report says the upper limit is 1 trillion metric tons of carbon. The same report estimates that a little more than half of the 1 trillion metric tons (that is, 515 billion metric tons) is already saturating the atmosphere. By those figures, roughly half our carbon budget (buffer) is already used up, spent.

Getting fixated on carbon budget numbers misses the point. The main thing to keep in mind is that we are not yet reducing emissions fast enough. This makes it clear that we need to get busy removing carbon from the atmosphere. Of course we still need to get all hands on deck to aggressively reduce carbon emissions. Carbon removal methods provide another pathway, simultaneously with emissions reduction, to avert going beyond critical global warming thresholds.

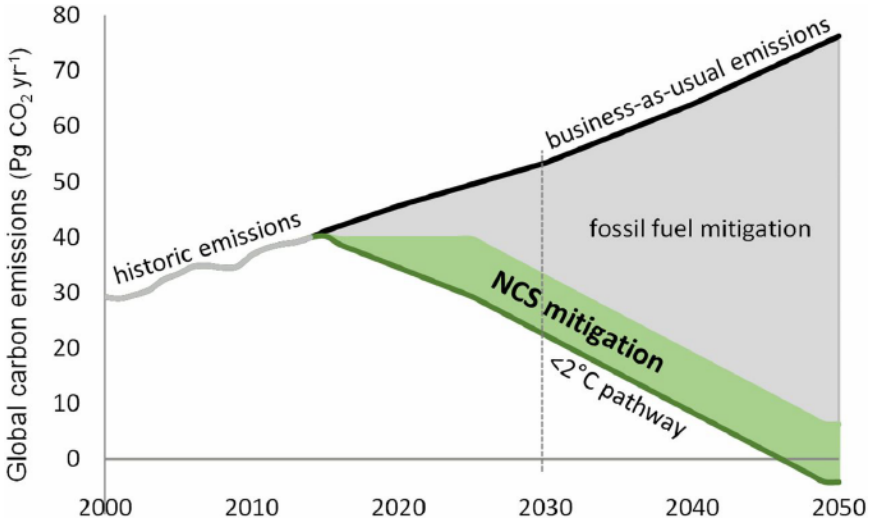

FIGURE 19.3.1 Contribution of natural climate solutions (NCSs) to stabilization of warming to below 2°C. From Griscom et al. 2017.

Climate change solutions focused on removal are often referred to as negative emissions technologies—wherein the *negative* is intended to convey a drawing down of emissions via sequestration, as contrasted with preventing or reducing upward flows. Some are now arguing that *natural climate solutions* (*NCSs*) provides a more sensible term for labeling removal technologies. That is what we are using in this chapter.

NCSs can remove significant amounts of carbon from the atmosphere through better stewardship of natural and working lands. This includes land management practices that increase carbon storage and/or avoid GHG emissions through ecological restoration, wetland protection, regenerative agriculture, community composting, carbon farming, and reforestation. All of these NCSs are possible in rural as well as urban environments.

One global study published by Griscom and colleagues in the *Proceedings of the National Academy of Sciences* estimates that NCSs can provide over one-third of the climate mitigation needed between now and 2030 to keep global warming under 2°C. Figure 19.3.1 illustrates two curves. One curve, following from the historic record (gray line), projects CO_2 business-as-usual emissions out to the year 2050 (black

line). The green area shows the amount that NCSs can offer to the total mitigation needed between 2016 and 2050. It is significant.

Another study published in *Science Advances* by Fargione and colleagues focused on NCSs solely in the United States. Their study quantified the potential of 21 NCSs, including conservation, restoration, and improved land management interventions on natural and agricultural lands. The authors estimate that NCSs could annually sequester and avoid the emissions of 1.2 petagrams CO_2e per year, which is equivalent to 21% of current net annual US emissions. NCSs also provide many other co-benefits (air and water filtration, flood control, soil health, wildlife habitat, and climate resilience benefits).

The National Academies of Sciences, Engineering, and Medicine notes in a 2018 report that climate change researchers and policymakers have historically focused most of their attention on mitigation technologies aimed at reducing or preventing greenhouse gas emissions. NCS efforts get less than 3% of public and private climate financing globally. This figure is low despite findings, reported in the journal *Science Advances*, that NCSs can provide 37% of the mitigation deemed necessary on a global scale from 2016 to 2030. The IPCC finds that it may be impossible to hold the increase in global average temperature to 1.5°C if we don't pursue carbon removal, reduction, and prevention at the same time.

NCSs that are especially promising for widespread adoption at local and bioregional scales are biological processes to increase carbon stocks in soils, forests, and wetlands. The two cases we will concentrate on here include (1) urban agriculture and food forests and (2) a neighborhood-scale food-waste-to-soil-and-energy system operating on the UC San Diego campus. Both cases are examples of civically engaged research and action helping drive localization and the bioregional transition.

Urban agriculture and food forests

In the journal *Renewable Agriculture and Food Systems*, University of California researcher Rachel Surls and colleagues define **urban agriculture** as "the production, distribution and marketing of food and other products within the cores of metropolitan areas (comprising community

FIGURE 19.3.2 Food forest planting, Ocean View Growing Grounds, Southeast San Diego. Photograph by Keith Pezzoli.

and school gardens; backyard and rooftop horticulture; and innovative food-production methods that maximize production in a small area) and at their edges (including farms supplying urban farmers markets, community supported agriculture and family farms located in metropolitan green belts)." The installation of community gardens and food forests in places where people live in poverty and lack access to fresh fruits and vegetables (that is, **food deserts**) creates opportunities to foster food justice by driving socio-ecological change that is civically engaged and climate friendly.

Figure 19.3.2 shows a community work group planting a food forest in southeast San Diego in the Ocean View Growing Grounds discussed above. An urban food forest is a land management system that replicates a woodland or forest ecosystem using edible plants, trees, shrubs, annuals, and perennials. Fruit and nut trees provide the forest canopy layer; lower-growing trees and shrubs create an understory layer; and combinations of berry-producing shrubs, herbs, and edible perennials and annuals make up the shrub and herbaceous layers. Other companions or beneficial plants, along with soil amendments, provide nitrogen and mulch, hold water in the soil, attract pollinators, and prevent erosion.

By re-creating the functions of a forest ecosystem, a food forest can improve air, water, and soil and can create habitat, harvestable food, and green space in the densest urban areas or campus environments.

Properly managed trees, plants, and soil have the potential to stabilize nitrogen, reduce soil erosion and storm water runoff, sequester carbon, and remove harmful pollutants. As urban green spaces, food forests can reduce urban heat island effects and give residents a visual and physical respite from the impacts of urban living. Clean amended and replanted soils have the capacity to produce a healthy soil microbiome, which can support more nutrient-dense foods and sequester carbon. Pollinators, beneficial insects, and birds can also find habitat in a food forest.

Neighborhood-scale microgrid, food-waste-to-soil-and-energy systems

Students from five different student organizations at UC San Diego have come together to collaborate across the boundaries of their academic disciplines. They work in teams to co-invent, innovate, and evolve local solutions to climate change and food insecurity. The students created Rogers Community Garden and Urban FarmLab (abbreviated here as Urban FarmLab). The Urban FarmLab is a one-quarter-acre site located on land designated by UC San Diego as an urban forest. As a whole, the interconnected student projects constitute a functioning neighborhood-scale (in this case a campus) renewable energy **microgrid**. The microgrid runs mainly on power from the sun and biogas. The system combines regenerative ecological approaches (food forestry, traditional community gardens, composting, and green/hoop houses) with engineered, technological approaches (an aquaponics system powered with photovoltaic energy, hydro- and aeroponics systems, and a prototype anaerobic digester). Together engineering students and environmental chemists are making the coupled human and natural systems more efficient and user friendly, biochemists are evaluating and maintaining the anaerobic digestate, chemical engineers are developing processes to convert digester output into hydroponic fertilizer, computer scientists are building sensors and monitoring the streaming data, and visual artists/designers are incorporating an aesthetic component.

The Urban FarmLab is designated as an outdoor research space inside UC San Diego's urban forest on campus. It functions as a plug-and-play microgrid designed to encourage transdisciplinary knowledge exchange and experiential learning among the student researchers. Figure 19.3.3

shows student leaders at Rogers Urban FarmLab explaining to campus planners and researchers how the anaerobic digester system works. The site is laid out in such a way that individual components/sections of the microgrid can be researched and funded by grants and outside businesses. A goal of the students and faculty running the research site is to find ways to affordably replicate components of the system that could function sustainably in community gardens and neighborhoods.

Integrated system design like this requires new forms of cyberinfrastructure for assessment, monitoring, and evaluation based on data. An important aim of the Urban FarmLab has been designing a robust, automated, real-time data collection pipeline. This cyberinfrastructure enables data collection, integration, and sharing for research and teaching purposes across diverse metrics of interest (for example, volume, composition, and energy density of biogas from the anaerobic digester; energy generated from the photovoltaic system; pounds of student-collected food waste; sequestered CO_2 from edible plants and fruit trees grown from treated digestate; pounds of compost-enriched soil). The challenge is to enable measurement of such metrics in real time using identical core hardware and software. This common core affords a degree of flexibility: only slight modifications are necessary to capture/measure each distinct metric of interest. The common core framework of the Urban FarmLab's microgrid hardware/software has a plug-and-play feature, making data collection and analysis by student researchers very doable. This product, referred to as the omnibox, enables the students to quickly learn and explore fundamental and applied research questions, encouraging more collaboration across disciplinary silos.

The Urban FarmLab microgrid accomplishes carbon removal and sequestration through a diverse ensemble of anaerobic/composted food-waste-to-soil infrastructure, hydroponics, and food forestry. This generates a range of methane and carbon-based environmental and economic benefits. These benefits, if proven substantial enough, can be funded as viable carbon offsets—in this case helping the UC San Diego campus meet its climate action goals to be zero-waste and carbon neutral. The anaerobic digester project recently conducted a GHG emissions analysis of the digester's inputs and outputs using the EPA's Waste Reduction Model (WARM) version 14. An analysis of the 41,500 pounds of food

FIGURE 19.3.3 Tour of anaerobic digester at UC San Diego, Rogers Urban FarmLab. Photograph by Keith Pezzoli.

waste students collected and fed into the digester over a one-year period demonstrated an overall reduction of 6,637 metric tons CO_2e. This means that 6,637 metric tons of CO_2 were sequestered and prevented from being emitted into the atmosphere. This initiative, dubbed the BioEnergy Project—Repurposing Food Waste, won the nationally prestigious 2019 Lemelson-MIT Student Prize undergraduate-team award.

The Urban FarmLab's BioEnergy Project has four main components: the anaerobic digester, digestate processing system, biogas purification and storage, and composting. The Lemelson-MIT award recognized the BioEnergy Project's commercialization potential. The project's food-waste-to-food-and-fuel system produces four marketable products, including organic produce, organic soil and fertilizer, biogas for electricity and heating, and food waste collection. This is a good example of economic localization with ecological and climate benefits. The UC San Diego campus has already bought into this system, relying upon it to partially meet it's zero-waste and carbon neutrality goals. The BioEnegy system can be scaled and modified for use in other public and private establishments such as commercial shopping malls or airports, K–12 schools, grocery stores, and other locations that demand food waste collection services and fresh produce.

19.4 Rooted Universities and the Green Infrastructure Nexus

Research universities have an increasingly important role to play in discovering, implementing, and sharing local and bioregional solutions to climate change. The example given above of the plug-and-play research space at the Rogers Community Garden and Urban FarmLab at UC San Diego is one way for students to embrace this challenge by assuming leadership roles at the frontiers of sustainability research and action.

The rooted university and community development

The **rooted university** transition creates opportunities for faculty and students to work together with community groups in tackling root causes of socio-ecological problems and climate change. Three place-based challenges are especially important for the imagination, ethics, and practice of rootedness: (1) rebuilding urban and rural communities—on a human scale—to nurture a healthy sense of place, secure attachments, and rootedness among community inhabitants; (2) coupling human and natural systems in ways that holistically and equitably instill eco-efficiency, resilience, and green cultural values into just systems of production, consumption, and daily life; and (3) making known (and valuing) how wildlands, water bodies, working landscapes, ecological services, and rural livelihoods enable cities to exist. Figure 19.4.1 illustrates the efforts of an academic center focused on enabling the bioregional and rooted university transition by linking sustainability science, planning, and design.

Place-based efforts are key to rallying the public around climate change solutions. The bioregional approach advances place-based concepts such as foodshed, watershed, and rooted community development. Rooted community development creates opportunities for coupling ecological design and democracy in how we humans build, work, and dwell together. Rooted universities have a role to play in this, on many levels. The rooted university is a university that invests

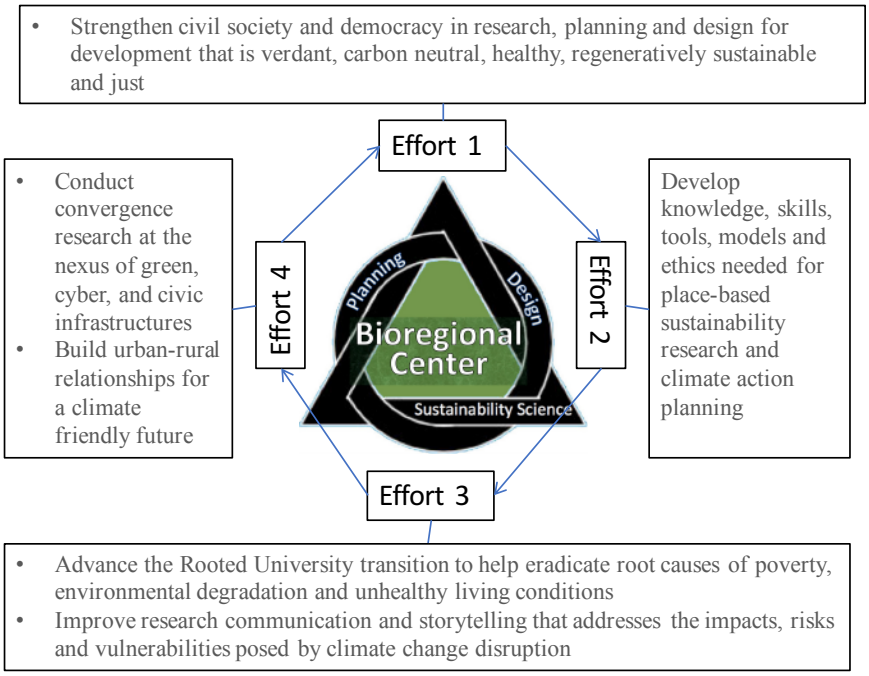

FIGURE 19.4.1 Bioregional Center for Sustainability Science, Planning and Design. Reproduced with permission.

a significant amount of its attention and resources in place-based education, research, and community engagement. The rooted university's place-based approach is geared to understanding and improving how local-global forces interact and shape the coupled human-natural environments we inhabit.

A culminating idea: the green infrastructure nexus

A green infrastructure nexus can support the coupling of ecological design and democracy in efforts to advance local and bioregional solutions to climate change. This kind of nexus exists where *green-cyber-civic infrastructures converge* in support of sustainable development. The Urban FarmLab's bioenergy microgrid on the UC San Diego campus is a good example. The bioenergy microgrid integrates three infrastructures: (1) *green*—including urban agriculture and food forestry that benefits from the output of food-waste-to-soil-and-energy systems and solar power generation; (2) *civic*—including institutional channels for student, faculty,

staff, and community input, plus citizen science; and (3) *cyber*—including hardware and software for data integration and visualization, spatial analytics, monitoring, integrated modeling and assessment, scenario planning, and so on.

One of the initiatives briefly mentioned above (Measuring, Understanding and Improving Natural Climate Solutions: Enabling Carbon Neutral Development through Transborder Urban-Rural Linkages and a Green Infrastructure Nexus) got a good kick start during a series of NSF workshops. The strategic planning workshops brought together researchers from eight US and Mexican universities during June 2019 to scope out the prospect of creating a binational Border Solutions Alliance. The NSF's Smart and Connected Communities (S&CC) program supported this effort with a grant (award number 1833482).

The S&CC program notes how rapidly changing intelligent technologies are transforming our world. And while this transformation may improve well-being and prosperity, it also poses significant challenges. The NSF thus seeks to support research aimed at understanding and improving how intelligent technologies can bring about economic opportunity, safety, security, health, and overall quality of life. The NSF wants this research to be place based, that is, focused on communities defined as having geographically delineated boundaries (for example, towns, cities, counties, neighborhoods, community districts, rural areas, and tribal regions). The research design must engage the community as participants, while generating new knowledge that can be used to "synergistically integrate intelligent technologies with the natural and built environments, including infrastructure, to improve the social, economic, and environmental well-being of those who live, work, or travel within it." The key dimensions of the NSF's S&CC program—its place-based emphasis on territorial units, community engagement, inclusion of urban and rural, coupling of natural and built systems—all lean toward the kind of localization and bioregional approach we've been examining in this chapter. The fact that one of the USA's premier science agencies is dialing into these dimensions is promising. Integrated approaches like this can help democratize science and technology and drum up enthusiasm for civically engaged scholarship urgently needed to bend the curve.

19.5 What We Have Learned So Far

1. Global problems arising from escalating human demands and stresses on Earth's natural systems are spurring interest in local solutions to climate change. Local solutions at the level of neighborhoods, cities, towns, and districts are necessary complements to solutions focused on higher levels of organization, such as nation-states and global institutions/networks.
2. The UN's New Urban Agenda is stimulating the rise of local approaches to climate change.
3. Roughly 45% of the world's population is rural. Rural communities need to be part of climate solutions. Rural inclusion in climate action planning can be improved through agrarian policy. It can also be improved by addressing urban-rural linkages that can join the fate of cities and their rural neighbors.
4. Localized climate change solutions that can strengthen urban-rural linkages include composting systems, carbon farming, agroforestry, farmers' markets, and community-supported agriculture.
5. Localization is a narrative framework useful for elevating the value of integrated, territorially specific (place-based) interventions seeking climate-friendly development, food-energy-water security, equity, and justice.
6. Localization is a key component in bioregional theory and practice. The bioregional transition provides opportunities to value rural places and natural and working lands in relationship to urban and metropolitan areas and needs.
7. Localization is visible where place-based investments are made, for instance, in renewable energy microgrids, storm water management and water-harvesting systems, carbon-neutral and zero-waste local industry, urban agriculture, and farmers' markets.

8. Climate action plans are comprehensive road maps that outline specific activities an agency should undertake to reduce greenhouse gas emissions.
9. Green infrastructure has become a significant element in localizing climate action planning focused on mitigation and adaptation. Green infrastructure couples natural and human systems in efforts to make life and living in cities, towns, and working lands regeneratively sustainable, resilient, and healthy.
10. Green infrastructure is made up of undergirding support structures, systems, and linkages needed to meet needs for food, water, energy, and healthy space for living, working, and recreating. Green infrastructure thus interacts with, and can be used to improve, other forms of infrastructure such as the electric grid, water provisioning, and transportation.
11. Green infrastructure can restore and enhance ecosystems, providing carbon sequestration and other benefits. Green infrastructure and biotic approaches have not yet gotten the attention they warrant. But this is slowly changing. Green infrastructure using biotic approaches includes regenerating damaged natural ecosystems, improving natural sinks for carbon through afforestation, reducing deforestation, and restoring soil organic carbon.
12. Urban forests, including food forests, are a form of green infrastructure. Forests in urban and rural areas alike have significant potential for biomass production and carbon sequestration. Improved management of forest and tree landscapes of all types is among the speediest solutions for bending the curve. The global annual potential for carbon mitigation from afforestation, reduced deforestation, and restoration of soil organic carbon is about 8 to 12 gigatons per year.
13. Turning food waste into energy and soil is a good way to sequester carbon. Implementing food waste reduction programs and energy recovery systems can maximize the utilization of food produced and recover energy from food that is not consumed. Globally, one-third of food produced is not eaten. In the United States, 40% is not eaten. The carbon and other greenhouse gasses emitted in

producing this wasted food contribute 3.3 gigatons annually to carbon emissions.

14. Civically engaged, well-informed community leaders and residents are necessary to democratically bolster climate action planning. Universities can facilitate collective efforts to democratize climate change mitigation and adaptation.

15. Place-based (rooted) university-community partnerships can help establish the kind of green, civic, and cyberinfrastructure linkages necessary to support globally minded localization and the bioregional transition to a post-carbon world.

Sources for the Figures

All figures and images courtesy of the author unless otherwise noted.

Figure 19.1.1: NASA. Earth's City Lights, from Visible Earth: A Catalog of NASA Images and Animations of Our Home Planet. https://visibleearth.nasa.gov/view.php?id=55167.

Figure 19.1.2: https://www.epa.gov/file/green-infrastructure-climate-resiliency-infographic

Figure 19.2.1: Environmental Protection Agency (EPA). 2019. Green Infrastructure for Climate Resiliency Infographic. https://www.epa.gov/file/green-infrastructure-climate-resiliency-infographic.

Figure 19.2.2: Adapted from Google Earth; inset photograph by Keith Pezzoli.

Figure 19.2.4: Base map adapted from Google Earth imagery and Google DigitalGlobe.

Figure 19.3.1: Griscom, B. W., et al. 2017. Natural climate solutions. *Proceedings of the National Academy of Sciences USA* 114(44), 11645–11650.

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Keith Pezzoli's research, teaching, and community engagement concentrate on trying to understand and improve ways humans can live together sustainably in healthy, just, and rooted communities guided by a regenerative land ethic. Pezzoli's efforts focus on three interlinked challenges: (1) improving urban-rural linkages through bioregionalism and natural climate solutions: coupling human and natural systems in the planning, design, and development of cities, towns, and working and natural lands; (2) democratizing science and technology: establishing university-community relationships and joint projects that enable students, researchers, and diverse community participants to work together in transformative and equitable ways; and (3) enabling connectivity: bridging the digital divide between researchers and underserved communities through cyberinfrastructure and knowledge networking that can foster democratic participatory planning, decision-making, and justice in matters of public concern.

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V. Ramanathan discovered the greenhouse effect of halocarbons (in particular CFCs) in 1975. Along with Dr. Roland Madden, he predicted in 1980 that global warming would be detected by 2000. In 1985, he led the first international assessment of the climate effects of non-CO_2 greenhouse gases and concluded that they are as important as CO_2 to climate change, and in 1995 he led the Indian Ocean experiment and

discovered the Atmospheric Brown Clouds over most of South Asia. In 2015, he led 50 faculty from the University of California and produced the *Bending the Curve* report, which came up with ten solutions to mitigate climate change and led the effort to create the Climate Solutions course. He was the Science Advisor to Pope Francis's Holy See delegation to the Paris climate summit and also advises former Governor Jerry Brown of California on climate change. Dr. Ramanathan was the United Nations' Champion of Earth for 2013 and was awarded the Tang Prize in 2018 for his seminal contributions to climate science.

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Scott Samuelsen is a Distinguished Professor of Mechanical, Aerospace, and Environmental Engineering at the University of California, Irvine; Director of the Advanced Power and Energy Program; and the founding Director of both the UCI Combustion Laboratory and the National Fuel Cell Research Center. His research is focused on energy systems and their impacts on the environment, gas turbine combustion, fuel cells and fuel cell systems, microgrid/smart grid technology, the hydrogen and electricity infrastructure for the evolving generation of zero-emission alternative vehicles, and the merging of the electric grid with transportation in an era of high penetration of intermittent wind and solar. He received BS, MS, and PhD degrees in mechanical engineering from the University of California, Berkeley and is the founding Chair of UCI Mechanical Engineering. Professor Samuelsen pioneered the

development of octane posting with the Federal Trade Commission and is responsible for the popular (R+M)/2 posting methodology that anchors today's engine design and fuel formulation. He has published over 300 peer-reviewed archival publications and conference proceedings, was recognized by President Obama in 2011 as a Champion of Change, and received the UCI Medal in 2010 for his contributions to energy and the environment.

Whendee L. Silver

Rudy Grah Endowed Chair in Forestry and Sustainability, Department of Environmental Science, Policy, and Management
UC Berkeley

Whendee Silver's work seeks to determine the biogeochemical effects of climate change and human impacts on the environment and the potential for mitigating these effects. Professor Silver and her lab are determining the potential for land-based climate change mitigation by exploring the potential for soil carbon sequestration through improved land management. The group is also studying ways to repurpose high-emitting organic waste streams into soil amendments to lower emissions and sequester atmospheric carbon dioxide. The Silver Lab was awarded the Innovation Prize by the American Carbon Registry in 2015. Professor Silver is a fellow of the Ecological Society of America and was named a University of California Climate Champion for 2016 for outstanding teaching, research, and public service in the areas of climate change solutions, action, and broad engagement.

Gina Solomon

Clinical Professor
UC San Francisco, Department of Medicine

Gina Solomon, MD, MPH, is a Clinical Professor in the Division of Occupational and Environmental Medicine at the University of California, San Francisco (UCSF), where she has taught since 1997. She is also a Principal Investigator at the Public Health Institute in Oakland. Dr. Solomon was appointed by Governor Edmund G. Brown Jr. in April 2012 to serve as the Deputy Secretary for Science and Health at the California Environmental Protection Agency. Prior to joining CalEPA, Dr. Solomon was a senior scientist at the Natural Resources Defense Council (NRDC). During her time at NRDC, she led the group's response to Hurricane

Katrina, performing rapid environmental assessments in New Orleans to document the environmental health impacts of the flooding. She also published a rapid response investigation of the 2006 California heat wave, documenting significant spikes in emergency department visits and hospitalizations. Since that time, Dr. Solomon has spoken and written extensively about the health effects of fossil fuel production and combustion and of climate change.

Richard C. J. Somerville
Distinguished Professor Emeritus
UC San Diego

Richard C. J. Somerville is an internationally recognized climate scientist and an expert on communicating clearly to the public what scientists have learned about climate change. Somerville's research has been focused on critical physical processes in the climate system. This work has led to many innovations and important improvements in computer models of the climate. He is an author, co-author, or editor of more than 200 scientific publications. Among many honors, Somerville has been named a fellow of three major scientific societies: the American Association for the Advancement of Science, the American Geophysical Union, and the American Meteorological Society. The American Geophysical Union has awarded him its Ambassador Award (2017) and its Climate Communication Prize (2015). He has been a professor at Scripps Institution of Oceanography, University of California, San Diego, since 1979.

Daniel Sperling
Professor
UC Davis

Dr. Daniel Sperling is Distinguished Professor of Civil Engineering and Environmental Science and Policy and the founding Director of the Institute of Transportation Studies at the University of California, Davis. He has held the transportation seat on the California Air Resources Board since being appointed by Governor Arnold Schwarzenegger in 2007 and served as Chair of the Transportation Research Board (TRB) of the National Academies in 2015–2016. Among his many prizes are the 2018 Roy W. Crum Award from TRB, its highest research award, and the 2013 Blue Planet Prize from the Asahi Glass Foundation for being "a pioneer in opening up new fields of study to create more efficient, low-carbon, and

environmentally beneficial transportation systems." He served twice as lead author for the Intergovernmental Panel on Climate Change (IPCC) (sharing the 2007 Nobel Peace Prize), testified eight times to the US Congress, and has authored or co-authored over 250 technical papers and 13 books, including *Three Revolutions: Steering Automated, Shared, and Electric Vehicles to a Better Future* (Island Press, 2018). He is a regular contributor to *Forbes* and an Energy Expert contributor to *The Wall Street Journal*.

Mary Evelyn Tucker
Senior Lecturer and Senior Research Scholar
Forum on Religion and Ecology
Yale University

Mary Evelyn Tucker teaches at Yale in the MA program in religion and ecology and directs the Yale Forum on Religion and Ecology with her husband, John Grim. Together they founded this new field of religion and ecology with ten conferences held at Harvard and ten books published by Harvard. With evolutionary philosopher Brian Thomas Swimme, Tucker created a multimedia project called *Journey of the Universe* that includes a book and an Emmy-award-winning film that was broadcast on PBS and is now available on Amazon Prime. Tucker served on the international Earth Charter Drafting Committee and was a member of the Earth Charter International Council. She received an Inspiring Yale Teaching Award in April 2015. In June 2019, she and John Grim received a Lifetime Achievement Award from the International Society for the Study of Religion, Nature and Culture.

David G. Victor
Professor, International Relations
UC San Diego

David G. Victor is Director of the Laboratory on International Law and Regulation and a professor at the School of Global Policy and Strategy at the University of California, San Diego, where he also co-leads the university's Deep Decarbonization Initiative. A political scientist, his research focuses on how regulatory law affects the environment, technology choices, industrial structure, and the operation of major energy markets. Prior to joining the University of California, San Diego, Professor Victor served as Director of the Program on Energy and Sustainable

Development at Stanford University, where he was also a professor at the law school. He has been a member of the Board of Directors of the Electric Power Research Institute (EPRI), on the advisory council for the Institute of Nuclear Power Plant Operations (INPO), and Chairman of the Community Engagement Panel that is helping to guide the decommissioning of Units 2 and 3 at the San Onofre Nuclear Generating Station. He also co-leads the Initiative on Energy and Climate at the Brookings Institution.

Durwood Zaelke

President, Institute for Governance & Sustainable Development
UC Santa Barbara

Durwood Zaelke is President of the Institute for Governance & Sustainable Development in Washington, DC, and Paris, which focuses on fast mitigation strategies to protect the climate, including reducing short-lived climate pollutants (HFCs, black carbon, tropospheric ozone, methane), in the context of the need for speed to limit anthropogenic warming to 1.5°C. IGSD also supports climate litigation through its Center for Climate Integrity. Mr. Zaelke is co-author of the standard textbook on *International Environmental Law & Policy* (with Hunter & Salzman) (5th ed., 2015) and *Well Under 2 Celsius: Fast Action Policies to Protect People and the Planet from Extreme Climate Change* (with V. Ramanathan and M. Molina, 2017), as well as numerous journal articles, including the following: M. Molina, et al. (2009), Reducing abrupt climate change risk using the Montreal Protocol and other regulatory actions to complement cuts in CO_2 emissions, in *Proceedings of the National Academy of Sciences*; M. Molina & D. Zaelke (2013), A comprehensive approach for reducing anthropogenic climate impacts including risk of abrupt climate changes, in *Pontifical Academy of Sciences*; Yangyang Xu, et al. (2013), The role of HFCs in mitigating 21st century climate change, in *Atmospheric Chemistry and Physics*; D. Victor, D. Zaelke, & V. Ramanathan (2015), Soot and short-lived pollutants provide political opportunity, in *Nature Climate Change*; M. Molina, V. Ramanathan, & D. Zaelke (2018), Climate report understates threat, in *Bulletin of the Atomic Scientists*; and V. Ramanathan & D. Zaelke (2018), Unexpected, unreported, and so far unexplained emissions of CFC-11, in *Bulletin of the Atomic Scientists*.

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V. Ramanathan