CHAPTER 4

Overview of the Ten Solutions for Bending the Curve

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CHAPTER CONTENTS

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).

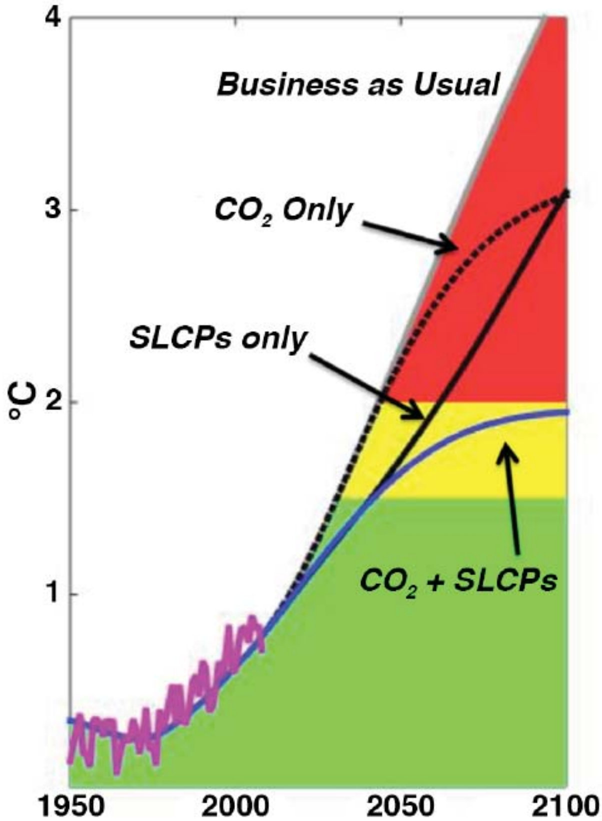


FIGURE 4.1.1 **Projections of future warming, showing business-as-usual and pathways for CO_2 mitigation only, SLCP mitigation only, and mitigation of both CO_2 and SLCPs. The purple line represents the historical temperature record.** From Ramanathan et al. 2017.

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.

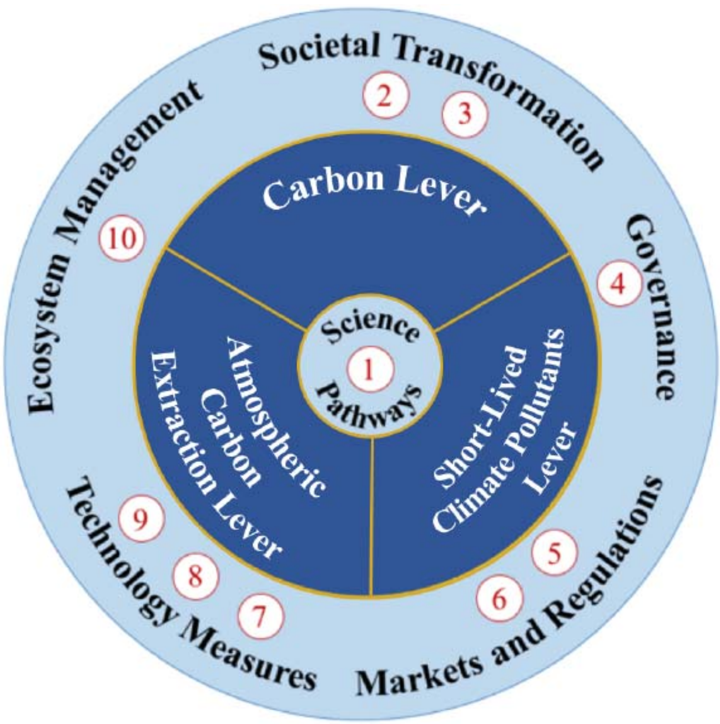


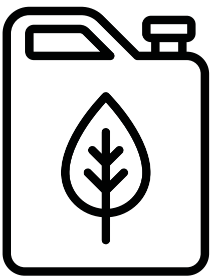
FIGURE 4.3.1 The six clusters, three levers, and ten solutions. From Ramanathan et al. 2017.

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.

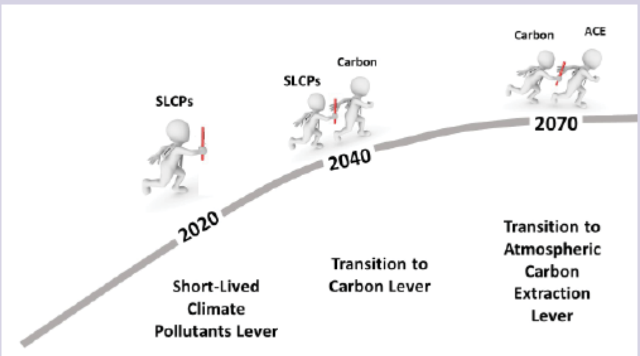
The "CO_2 + SLCPs" pathway in Figure 4.1.1 represents the combined effects of the carbon and SLCP levers. The SLCP lever should reduce projected warming of the planet by approximately 50% by 2050, compared with business-as-usual projections.

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.

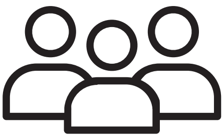
Figure adapted from images in shutterstock.com.

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.

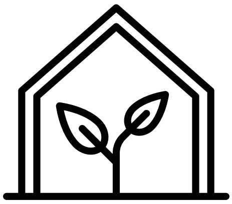
For a global culture of support to really take root, we will need to engage in dialogue at all levels: international, national, city, and neighborhood. This dialogue will involve a wide range of stakeholders—decisionmakers; community members; researchers and academics; and business, community, and religious 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.

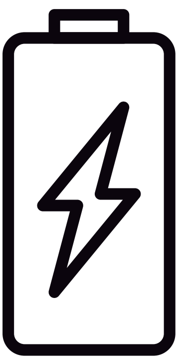
Regulatory measures are given lower priority than market-based incentives on our solutions list because they are generally less cost-effective. However, direct regulations provide an alternative instrument for emissions reduction, particularly where economic measures may not be technically or politically 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.

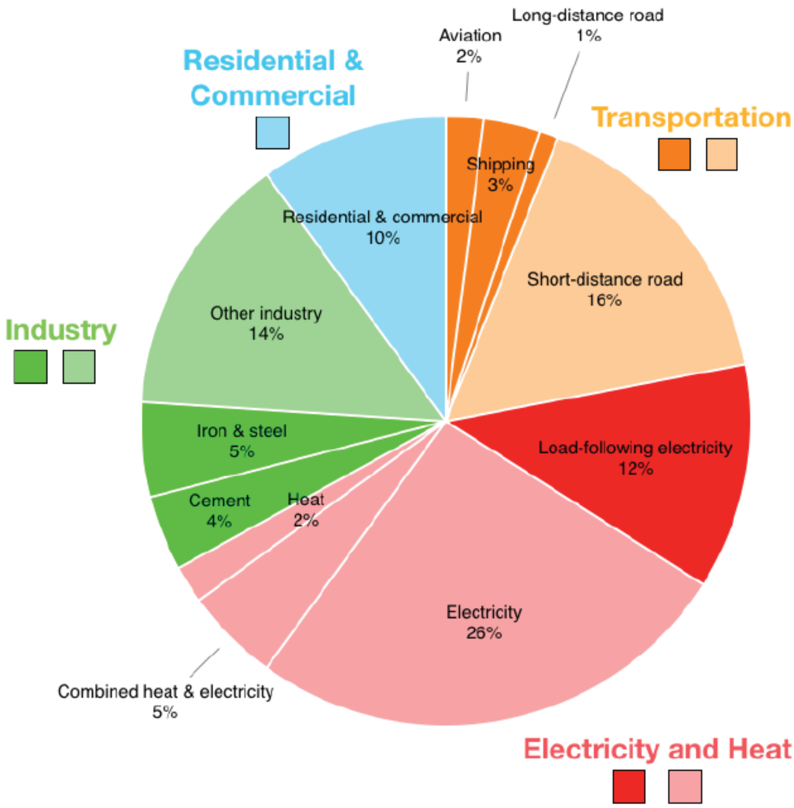
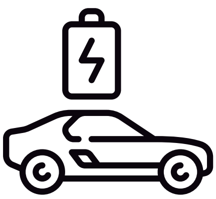


FIGURE 4.3.2 Global CO_2 emissions from fossil fuels and industry, 2014. The darker colors indicate the emissions that are most difficult to eliminate; they account for just over a quarter of the global total. Data from Davis et al. 2018.

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.

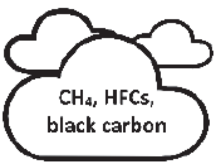
In the transportation sector, cars and light-duty trucks with electric motors powered by lithium ion batteries or hydrogen fuel cells could drastically reduce emissions if low-carbon sources were used for battery charging and hydrogen production. Emissions from homes and commercial buildings could be 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

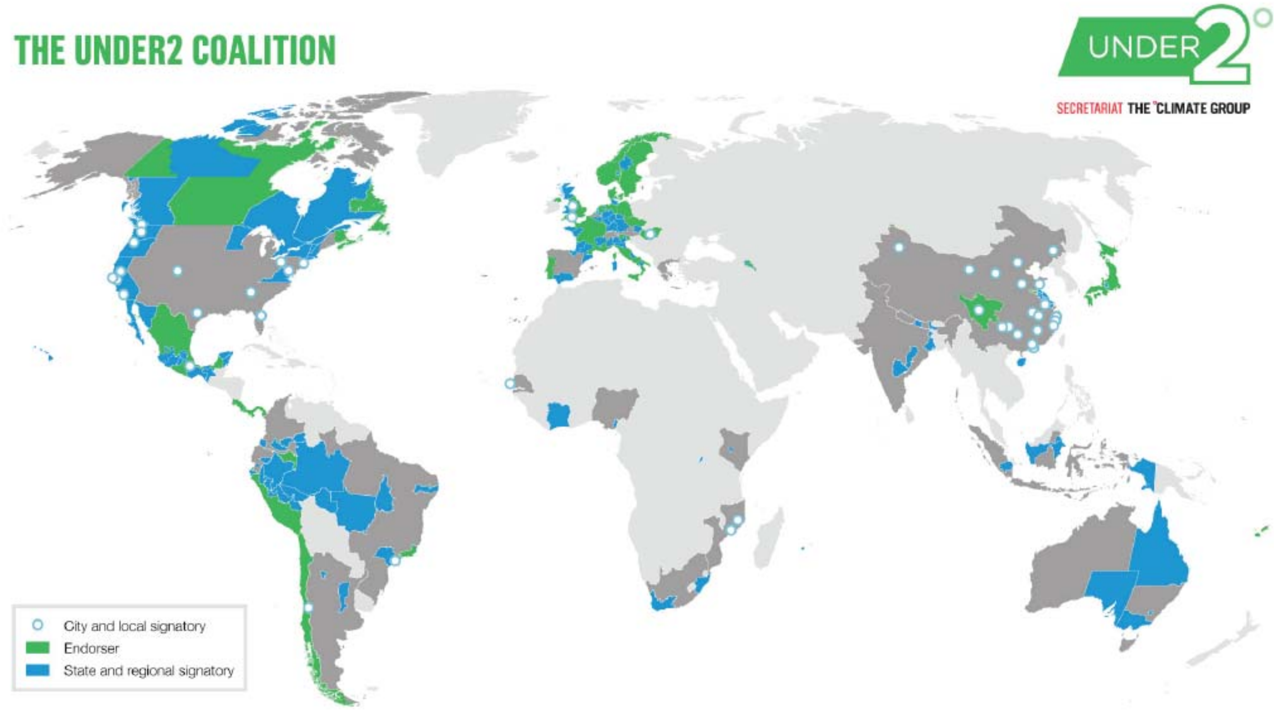


FIGURE 4.4.2 Map of Under2 Coalition members as of late 2017. Reproduced with permission from Under2 Coalition.

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**

Year	*Targets* *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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Figure 4.2.1: Mumbai photograph by Johnny Miller/mediadrumimages.com. https://www.bbc.com/news/in-pictures-45257901.

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4.1 Setting the Stage for Mitigation

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