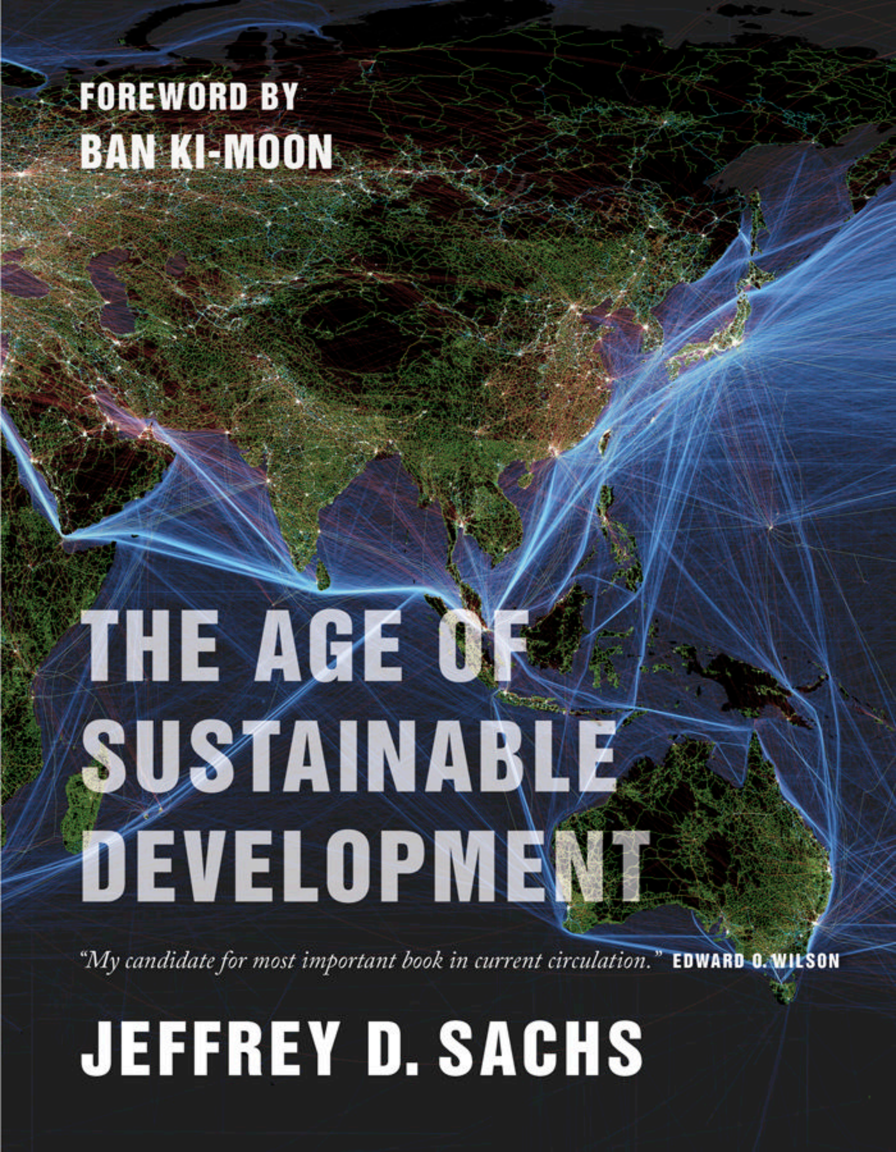


FOREWORD BY
BAN KI-MOON

THE AGE OF SUSTAINABLE DEVELOPMENT

"My candidate for most important book in current circulation." **EDWARD O. WILSON**

JEFFREY D. SACHS

12

CLIMATE CHANGE

I. The Basic Science of Climate Change

Roughly forty years ago, a small group of scientists and policy makers began to realize that humanity was on a dramatic collision course, as the rapidly growing world economy and population threatened to collide with the planet's finite resources and fragile ecosystems. The danger was first highlighted globally at the 1972 UN Conference on the Human Environment (UNCHE) in Stockholm. A famous and influential book that same year, *Limits to Growth*, warned that business as usual could lead to an economic collapse in the twenty-first century.

Back in 1972, as the core idea of planetary boundaries was first being understood, the kinds of boundaries that would turn out to be the most important were not yet very clear to the scientific community. The big concern in 1972 was that humanity would run out of certain key minerals or ores and that the resulting scarcity would make it difficult to maintain the level of economic activity, much less to continue to achieve economic growth.

What was not so clearly appreciated back in 1972 was that the real limits were not the minerals, but rather the functioning of the Earth's ecosystems, the biodiversity, and the ability of the atmosphere to absorb greenhouse gases (GHGs) emitted by humanity from fossil fuels and other agricultural and industrial processes. It is only now that we are beginning to see that the real planetary boundaries are mainly ecological rather than limits of mineral ores. There is no doubt that the greatest of all of these threats is human-induced climate change, coming from the buildup of GHGs including carbon dioxide, methane, nitrous oxide, and some other industrial chemicals.

There has never been a global economic problem as complicated as climate change. It is simply the toughest public policy problem that humanity has ever faced. First, it is an absolutely *global crisis*. Climate change affects every part of the planet, and there is no escaping from its severity and threat. Humanity in the modern period has faced some pretty terrible threats, including nuclear annihilation along with mass pandemic diseases. Climate change ranks right up there on the scale of risks, especially for future generations.

Every part of the world is contributing to the problem, though on a per capita basis, some places like the United States are causing far more damage and risk than other parts of the world. Roughly speaking, emissions are in proportion to income levels. High-income countries tend to have the largest GHG emissions per capita, while poor countries are often great victims of human-induced climate change without themselves having contributed much to the crisis.

Second, when crises are global, as this one is, there are huge challenges in getting the world mobilized to take corrective actions. The UN Framework Convention on Climate Change (UNFCCC), signed at the Rio Earth Summit in 1992, has 195 signatory governments plus one regional organization, the European Union (EU). The 195 nations in the UNFCCC have vastly different perspectives. Some are exporters of fossil fuels; others are importers. Some use massive amounts of renewable energy (such as hydroelectric power); others use very little. Some are rich; others are poor. Some are highly vulnerable to climate change (such as small island economies or tropical countries); others believe themselves to be less vulnerable (such as countries in cold climates in high latitudes). Some countries are democracies; others are not. All of these differences give rise to sharp differences of opinion and interests on the proper way forward.

Third, the problem crosses not only countries but also generations. The people who are going to be most profoundly affected by human-induced climate change have not yet been born. They are not voting, writing op-eds, publishing papers, or giving speeches right now. They are not even on the planet yet. Humanity is surely not very good at considering, much less solving, such a multigenerational crisis. Who represents the future generations? Is it the politicians facing election next year? Is it the business people worrying about the next quarterly report? Is it any of us as we focus on today, tomorrow, or the next day? It is no doubt very difficult for a political system, or any of us, to keep in mind and fairly represent the interests of generations yet to come.

Fourth, the challenge is also complicated because the problem of GHG emissions goes to the core of a modern economy. The success of modern economic growth arose from the ability to tap into fossil fuel energy. First came the steam engine and its ability to harness coal; then the internal combustion engine and its ability to use petroleum; and then the invention of the gas turbine with its ability to use natural gas. The entire world economy has grown up as a fossil fuel–based economy, and yet fossil fuels are at the core of the climate change crisis. The number one human contributor to climate change is the burning of fossil fuels that emit carbon dioxide into the atmosphere and thereby change the planet. We must undertake a kind of "heart transplant," replacing the beating heart of fossil fuel energy with an alternative based on low-carbon energy!

Fifth, climate change is a slow-moving crisis. To be more precise, it is a very fast-moving crisis from the perspective of geological epochs, but very slow from the point of view of daily events and the political calendar. If the climate change crisis were going to culminate in a single event in a year's time, there could be little doubt that humanity would get itself organized to prevent or adapt to the crisis. Yet the climate changes underway will play out over decades, not months.

Our situation is a bit like the proverbial frog that is put in water that is very slowly heated. The story has it that a frog in gradually warming water will never jump out and will eventually be boiled alive. Perhaps humanity will be the same. The changes year to year may be too gradual to provoke large-scale political actions, yet the cumulative effects could prove devastating; or, we may wake up to reality when it is simply too late to change course decisively.

Sixth, the solutions to climate change are inherently complex. If there were one action, one magic bullet, one new technology that would do the trick, the problem would be solved by now. The kinds of changes that are needed in response to human-induced climate change involve every sector of the economy, including buildings, transportation, food production, power generation, urban design, and industrial processes. With such operational complexity on the pathway to deep decarbonization, it is no surprise that very few governments have been able to establish workable plans or pathways.

Seventh, the energy sector is home to the world's most powerful companies. The large oil and gas companies are generally among the world's largest companies by revenues. A remarkable seven of the ten largest companies in the world in 2013, as ranked by Global Fortune 500 (with the rank shown in parentheses), are in the energy sector:

Royal Dutch Shell (1)
Exxon Mobil (3)
Sinopec Group (4)
China National Petroleum (5)
BP (6)
China State Grid (7)
Total (10)

Incidentally, companies ranked 8 and 9 are Toyota and Volkswagen, which both produce petroleum-based vehicles. The lobbying clout of the oil, gas, and automobile industries is therefore staggering.

In short, we are dealing with the heaviest of heavyweights of the world economy and of global politics. By and large these companies hope, plan, and lobby for the world to remain heavily dependent on oil and gas, despite the risks to ourselves and to future generations. These companies are able to win political support to stall the conversion to low-carbon energy through many tools: campaign financing, lobbying, and other means of persuasion. Some companies have gone so far as to promote antiscientific propaganda and to sow doubt in the public mind regarding well-known and mainstream science. With enough money, any big lie can be defended, at least for a while. In the United States, the wealthy Koch brothers, who own a major U.S. oil company among other interests, have financed an aggressive campaign against climate science and against measures to convert to low-carbon energy.

Altogether, climate change is therefore one very tough issue, and time is running out! The emissions of the main GHGs that lead to human-induced climate change are increasing each year, and the threats to the planet are growing as well. We are losing time even though the stakes for the planet are incredibly high.

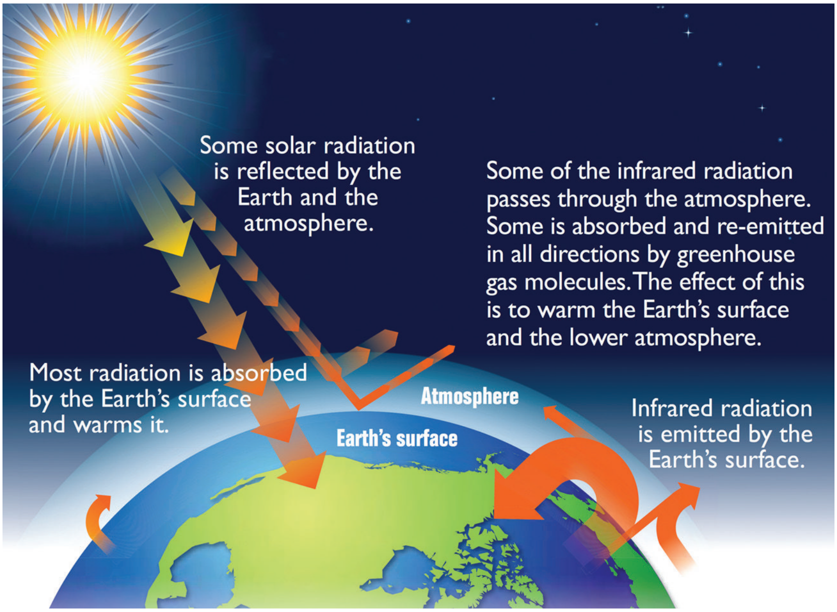
The Basics of Climate Science

When seeking a true solution to the problem, the best place to start is with the science itself. The science is not new. The basics of human-induced climate change were already worked out by scientists in the nineteenth century. One great scientific genius, Svante Arrhenius, a Swedish Nobel laureate in chemistry, calculated accurately by hand, without a computer, the effects of doubling the atmospheric concentration of carbon dioxide (CO2) (Arrhenius 1896). And he did so back in 1896! He correctly calculated that a doubling of the CO_2 in the atmosphere would cause a rise in the mean temperature of the planet of around 5° Celsius, an estimate that is within the likely range today based on advanced computer models and vastly more extensive data than Arrhenius had at his disposal.

Yet Arrhenius was a better scientist than an economic forecaster. He was not accurate in his guess about the timescale in which the CO_2 concentration would double. Arrhenius expected that human use of coal and oil and other fossil fuels would cause the atmospheric CO_2 to double in around 750 years. In fact, because of the remarkable geometric growth and energy use of the world economy since Arrhenius's time, the doubling of CO_2 is likely to occur roughly 150 years after Arrhenius's study, that is, around 2050.

The basic reason the likely doubling of CO_2 is so frightening can be understood with the schematic diagram of the GHG effect in figure 12.1. As the diagram explains, the sun's radiation reaches the Earth as ultraviolet radiation. A large part of the ultraviolet radiation passes through the atmosphere and arrives on the planet. A small part of the incoming solar radiation is reflected by clouds and goes back into space; and some of the solar radiation that lands on the surface of the Earth, for instance on the ice, is also reflected directly back into space.

The Earth warms as a result of the solar radiation that reaches the surface and is not immediately reflected back to space. By how much does the Earth warm?



12.1 The greenhouse effect

Source: U.S. Environmental Protection Agency, 2012.

By just enough that it reaches a temperature at which the Earth radiates energy to space at the same rate that the sun transmits energy to Earth. The key to understanding this energy balance is a concept known as "black-body radiation." Any warm body, including the Earth itself, radiates electromagnetic energy. The warmer the body, the greater the radiation. When the sun radiates energy to Earth, the Earth warms to just the temperature at which the Earth radiates energy to the sun equal to the sun's radiation reaching the Earth. An energy balance is thereby struck. (This basic concept of how the Earth's temperature is determined was discovered by the great French scientist Joseph Fourier in 1824.)

While the sun radiates ultraviolet radiation to the Earth's surface, the Earth radiates infrared (long-wave) radiation back to space. In energy balance, the incoming ultraviolet radiation must equal the outgoing infrared radiation. But here is the kicker at the heart of the entire climate change problem. The Earth's atmosphere contains some special molecules, like CO_2, that trap part of the infrared radiation heading out to space. These gases, called GHGs, thereby change the energy balance: more ultraviolet hits the Earth than infrared radiation reaches space. On net, the Earth absorbs net radiation, and the planet begins to warm. (Note that the GHGs do not absorb the incoming ultraviolet radiation, only the outgoing infrared radiation.)

Yet by how much does the Earth warm as a result of the GHGs? The Earth warms by just enough so that at the higher temperature the Earth radiates *extra infrared radiation*, by just enough that even after some is trapped by the GHGs, the remainder that leaves the Earth and goes into space just balances the amount of solar radiation that reaches the Earth's surface from the sun. Now indeed we can see by how much the GHGs will warm the planet. If we know by how much the CO_2 traps infrared radiation, we also know by how much the Earth must rise in temperature to restore a net energy balance with the sun.

There are several major GHGs: CO_2, methane (CH_4), nitrous oxide (N_2o), and some industrial chemicals called hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6). Another major GHG is water vapor (H_2O), which, like CO_2, traps infrared radiation and thereby warms the planet. The first kind of GHGs (CO_2, CH4, N_2O, and HFCs) are all directly emitted by human activity. Water is only indirectly affected by human activity. As the planet warms, the water vapor in the atmosphere tends to increase, and this increase causes an additional greenhouse effect, meaning an additional rise in temperature.

The basic greenhouse effect is a lifesaver for us. If the Earth, like the moon, had no GHGs, then the Earth would be a much colder place and would not support life as we know it. Without the greenhouse effect, the average Earth temperature would be around –14°C (about 6.8°F), well below the freezing point of water. With the greenhouse effect, the average temperature on Earth is around 18°C (around 64°F). For this much we must be grateful!

Yet as we put more GHGs into the atmosphere, we warm the planet from the range we have known throughout human history to a much warmer and essentially unfamiliar planet Earth. Our food crops and farm systems, the locations of plants and animals, the location of cities, key infrastructure (roads, bridges, ports, buildings), and public health have all been shaped by a planet with a fairly stable temperature range during the period of civilization, roughly the past 10,000 years. This modern period, known as the Holocene (preceded by the epoch known as the Pleistocene, which was characterized by periodic ice ages), is the period of civilization. It has been remarkably stable in temperature and benign in overall average climate. It is that period of stability that we are now threatening to overturn by our massive production of GHGs.

There are a number of points about the various GHGs. Perhaps most important, CO_2 stays up in the atmosphere for a long time. We speak of a long "residence time," in the case of CO_2, lasting for centuries. When it comes to CO_2, what goes up does not come down, at least not anytime soon. The CO_2 is not washed back to Earth by rainfall, for example. Other GHGs differ from CO_2 in their heat-trapping capacity (what is called their "radiative forcing") and in their residence time. Methane, for example, traps roughly 23 times more heat than CO_2, counting each molecule of CH_4 compared with each molecule of CO_2. Yet the residence time of methane is much shorter, around ten years rather than hundreds of years in the case of CO_2.

The total warming effect of all of the anthropogenic (human-caused) GHGs is determined by adding up the separate radiative forcings of each of the six GHGs. For each GHG, we measure its radiative forcing in units of CO_2 equivalent (CO_2E). For example, since CH_4 has a radiative forcing equal to 23 times that of CO_2, we say that each single molecule of CH_4 in the atmosphere should be counted as equivalent in warming potential to 23 molecules of CO_2. Similarly, each molecule of N_2O counts as equivalent to 296 molecules of CO_2. In this way, we are able to take any combination of CO_2, CH_4, N_2O, HFC, PFC, and SF6 and express the total radiative forcing in units of CO_2 equivalents, as if there were only one GHG, CO_2, with a radiative forcing equivalent to the actual forcing caused by the presence of six distinct GHGs.

We can then ask the share of each of the GHGs in the total warming effect. Carbon dioxide takes the prize. As we see in the final column of table 12.1, CO_2 accounted for fully 77 percent of the total greenhouse effect of the six molecules. Taken together, the top three GHGs (CO_2, CH_4, and N_2O) account for the lion's share of the total warming effect, around 99 percent of the total greenhouse effect.

Table 12.1 Greenhouse gas characteristics

	Lifetime in the atmosphere (years)	100-year global warming potential (GWP)	Percentage of 2000 emissions in CO_2E
Carbon dioxide (CO_2)	5–200	1	77%
Methane (CH_4)	10	23	14%
Nitrous oxide (N_2O)	115	296	8%
Hydrofluorocarbons (HFCs)	1–250	10,000–12,000	0.50%
Perfluorocarbons (PFCs)	> 2,500	> 5,500	0.20%
Sulfur hexafluoride (SF6)	3,200	22,200	1%

Source: The Stern Review Report © Crown copyright 2006.

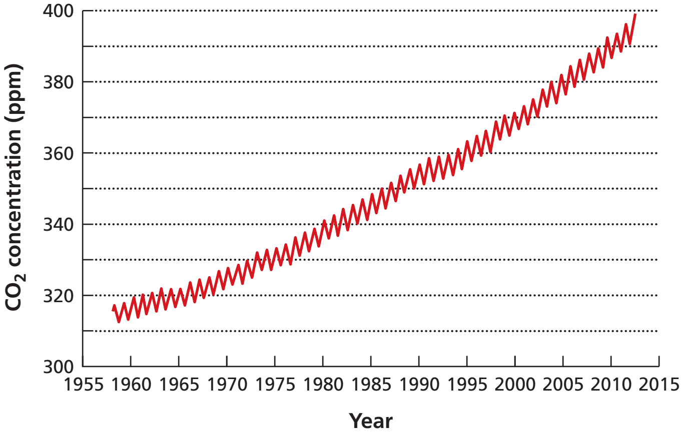
We don't actually count the number of CO_2 molecules that we add to the atmosphere. Instead, we measure the total number of tons of CO_2 that humans emit into the atmosphere (mainly by burning coal, oil, and gas). From there, we are able to convert the tons emitted into the atmosphere into a change in the CO_2 concentration in the atmosphere, measured not in tons but in molecules of CO_2 per million molecules in the atmosphere. Here is the rough calculation. Each 1 billion tons of CO_2 added to the atmosphere amounts to an additional 127 molecules of CO_2 for each 1 billion molecules of the atmosphere. Thus, an extra 16 billion tons of CO_2 in the atmosphere equals 2 extra molecules of CO_2 per million overall molecules. When the world burns around 35 billion tons of CO_2 each year in energy use, around 46 percent of that, equal to 16 billion tons, stays in the atmosphere. The other 54 percent of the CO_2 is absorbed into the forests, soils, and oceans. The part that stays in the atmosphere results in a rise in CO_2 concentration by roughly 2 parts of CO_2 per million atmospheric molecules.

In total, the world is emitting around 55 billion tons of CO_2E (meaning the CO_2 equivalent tons, counting all six GHGs). The CO_2 part of that total is about 35 billion tons, which comes from burning coal, oil, and gas. An additional amount, perhaps 3.5 billion tons of CO_2 per year, results from cutting down trees and clearing land for farms and pasturelands. There is more uncertainty about the net CO_2 emissions due to land-use changes than due to energy changes, since the land is both a source of emissions (e.g., through deforestation) and also a CO_2 "sink," meaning that increases in soil carbon and aboveground plant matter capture some of the CO_2 in the atmosphere. The net effect year to year is hard to measure with precision.

How big is an annual CO_2 emission of 35 billion tons due to fossil fuel use and other industrial processes? It is certainly big enough to cause huge planetary-scale dangers. About 50 years ago a very far-sighted scientist, Charles Keeling, put monitors on a mountaintop in Hawaii and started to measure the amount of CO_2 in the atmosphere. Thanks to those measurements from 1958 till now, we have the annual and even seasonal levels of CO_2 (Scripps 2014). The resulting instrument record is known as the Keeling Curve (figure 12.2), showing that the amount of CO_2 in the atmosphere has been rising significantly over the years. As usual, the CO_2 is measured as parts per million (ppm) of CO_2, or the number of CO_2 molecules per million of total molecules in the air.

Starting back in 1958 when that machine first went up on the top of Mauna Loa in Hawaii, the CO_2 was 320 molecules for every 1 million molecules in the air (320 ppm). By now, CO_2 has reached 400 ppm. Before James Watt came along with his brilliant steam engine, the atmosphere contained about 280 ppm. In the geologic history of the last 3 million years, the CO_2 varied roughly between 150 and 300 ppm. Then came humanity and the Industrial Revolution, and we have since been burning so much oil, gas, and coal, and deforesting so many regions, that we have sent the CO_2 levels soaring, reaching 400 ppm in the spring of 2013. This is a concentration of CO_2 not seen on the planet for 3 million years. In other words, human activity is pushing the planet into a climate zone completely unknown in both human history and Earth's recent history.

Notice the within-year ups and downs of the CO_2 in the Keeling Curve. Atmospheric CO_2 is high in the winter and spring months, reaching a maximum in May, and is low in summer and fall, reaching a minimum in October. We are watching the planet breathe. During the winter months in the Northern Hemisphere (where most land and vegetation is located), the trees reduce their photosynthesis and shed their leaves, thereby releasing CO_2 into the atmosphere. During the



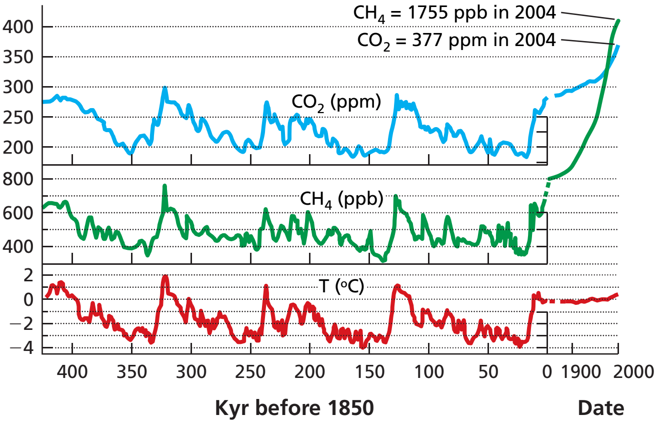
12.2 Keeling curve of atmospheric CO2 concentration (1958–2013)

Source: Scripps 2014.

summer months in the Northern Hemisphere, the trees build up their carbon content, thereby withdrawing atmospheric CO_2 and building up the terrestrial plant mass.

Some great scientists, like James Hansen of Columbia University, are able to use various techniques, such as measuring the isotopic properties of CO_2 in ice cores, to look at the long history of CO_2 and temperatures on the planet. Figure 12.3 is a kind of open manuscript of the Earth's climate history, showing a long reconstruction of CO_2 and temperatures over the past 450,000 years. We see that atmospheric CO_2 fluctuated in natural cycles not caused by humanity. These were natural fluctuations of CO_2 driven by natural processes of volcanoes, the fluxes of CO_2 between the ocean and the atmosphere, and changes in the Earth's orbital cycle with a periodicity of tens of thousands of years.

This paleoclimate (ancient climate) record shows that when CO_2 concentrations were high as a result of natural processes, the Earth's temperature was also high. This is the basic greenhouse effect at work: *raise the CO_2 in the atmosphere (by natural or human means), and the result is a warmer planet.* This relationship has been true throughout history, and it is true now.

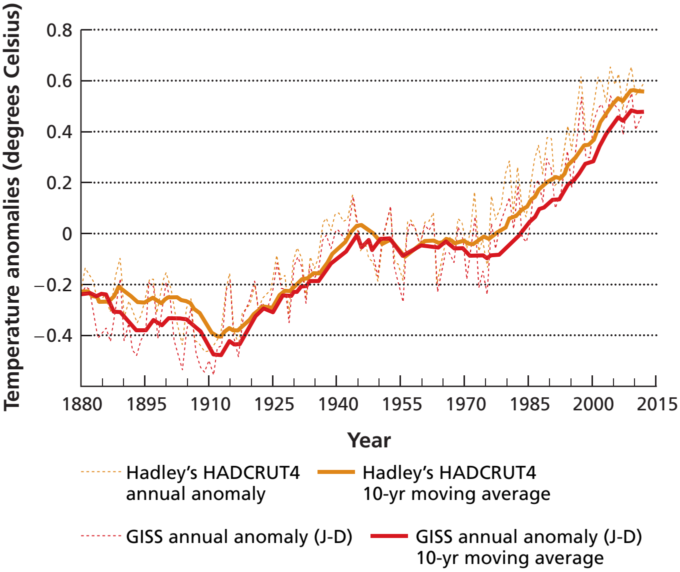


12.3 CO2, CH4, and temperature, 450,000 years ago–present

Source: Hansen, James E. 2005. "A Slippery Slope: How Much Global Warming Constitutes 'Dangerous Anthropogenic Interference'?" Climatic Change *68(3): 269–279.*

If we look at the temperature from the start of the Industrial Revolution until now (figure 12.4), the Earth has warmed by about 0.9 of 1°C, and it has not finished its warming in response to the GHG increases that have already taken place. Even if we were to put no further GHGs into the atmosphere, Earth would continue to warm by perhaps another 0.6 of 1°C, because the oceans take a long time to warm up in response to the GHGs that have already risen in the atmosphere. (There is some evidence that the year-to-year warming slowed a bit after 1998, with growing evidence suggesting that changes in Pacific Ocean patterns, with more La Niña conditions, contributed to this slowing; a swing back to El Niño conditions would, in that case, lead to a return to higher year-to-year warming.)

Yet we are certainly not done emitting GHGs. As the world economy has grown in recent years, the total emissions per year have also increased significantly. Even though the world's governments promised to curb emissions of CO_2 when they signed the UNFCCC at the Earth Summit in Rio de Janeiro in 1992, the actual emissions per year have continued to soar, not least because of China's

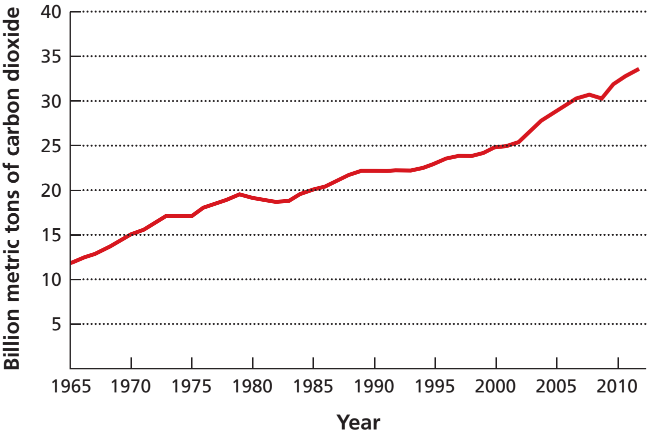


12.4 Global temperature deviation since 1850

Source: GISS/NASA.

remarkable economic growth combined with China's dependence on coal as its major energy source. As emissions rise, the CO_2 concentration in the atmosphere continues to rise (remember that the CO_2 residence time is a matter of centuries, not years), so that we can expect the Keeling Curve to continue to increase for decades to come.

It has been more than twenty years since the Rio Earth Summit where the world's governments agreed that we have an urgent challenge in heading off the human-induced GHGs; but we have still not reduced emissions. In fact, the rate of emissions has been increasing year to year as the world economy increases in scale, as figure 12.5 shows. With the growth of China, there has been an enormous increase of GHG emissions in recent years. China, by virtue of its huge size and use of coal as its primary energy source, has become the world's largest emitter of CO_2.



12.5 Annual global emissions of CO2, 1965–2012

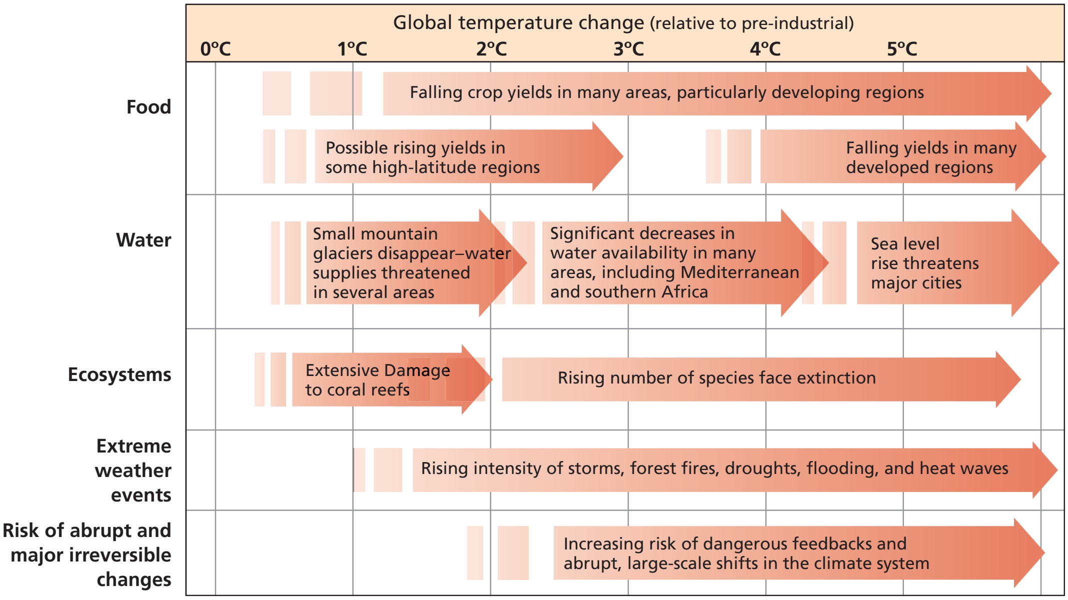
Source: BP Statistical Review of World Energy June 2014.

II. The Consequences of Human-Induced Climate Change

Why should we care about human-induced climate change? The fact is that we should be truly scared, and not just scared, but scared into action—both to mitigate climate change by reducing GHG emissions and to adapt to climate change by raising the preparedness and resilience of our economies and societies. The consequences of a business as usual (BAU) trajectory for this planet could be absolutely dire. The temperature increase by the end of the century compared with the preindustrial average temperature could be as much as 4–7°C. Such an increase in temperature would be very likely to have devastating effects in many ways.

There is no absolute precision on how big the average temperature increase might be. It is very difficult to determine how much GHGs humanity will emit on the BAU path with a growing world economy. There are also uncertainties about the Earth's physical processes and the precise feedbacks from CO_2 to temperature increases. Climate models cannot precisely get the exact decimal points of the likely increases of temperature. Yet there is overwhelming evidence coming from many different directions—the instrument record, the paleoclimate, the statistical models used by climate scientists, the direct measurements of energy fluxes in space and the oceans, and the overwhelming evidence of changes already underway in physical and human systems—to tell us that we are on a dangerous path of rising temperatures with dangerous potential consequences.

An important report on climate change produced by Lord Nicholas Stern, known as the Stern Review of Climate Change, offered a graphical representation of the potential dangers (Stern 2006). In figure 12.6, the top of the chart shows the various possible concentrations of CO_2 depending on the policies we follow. The higher the CO_2 concentrations, the higher the temperature increases will be. Then, along the left-hand side of the chart are the various sectors that will be impacted by the temperature increases. These include: food, water, ecosystems, extreme weather events, and major irreversible changes to the Earth's physical



12.6 Temperature increases and potential risks

Source: Stern, Nicholas. 2006. The Stern Review Report: The Economics of Climate Change. © *Crown copyright 2006.*

systems (such as the melting of the great ice sheets on Greenland and Antarctica, which would raise the ocean level by tens of meters).

The graph makes clear that the danger in each of these areas (shown by the intensity of the color red in the diagram) rises markedly as the mean global temperature increases. By the time the world average temperature is raised by around 3°C, the danger in every area—food supply, water supply, hazards, and so forth—is already in the bright-red danger zone. By a 4°C increase, we are contemplating truly catastrophic potential changes. And yet that is the trajectory of BAU. We simply need to change course.

Consider food, for example. At just 1°C above the preindustrial temperature (basically what has already occurred), one of the consequences is likely to be severe impacts on food production in the Sahel region. The Sahel is the part of West Africa just below the Sahara Desert. It is a very dry region already (caught graphically in the photo in figure 12.7), so the consequences for the Sahel of even a 1°C increase in temperature are quite serious. What would happen at a 4°C

12.7 A dry region of the Sahel Desert

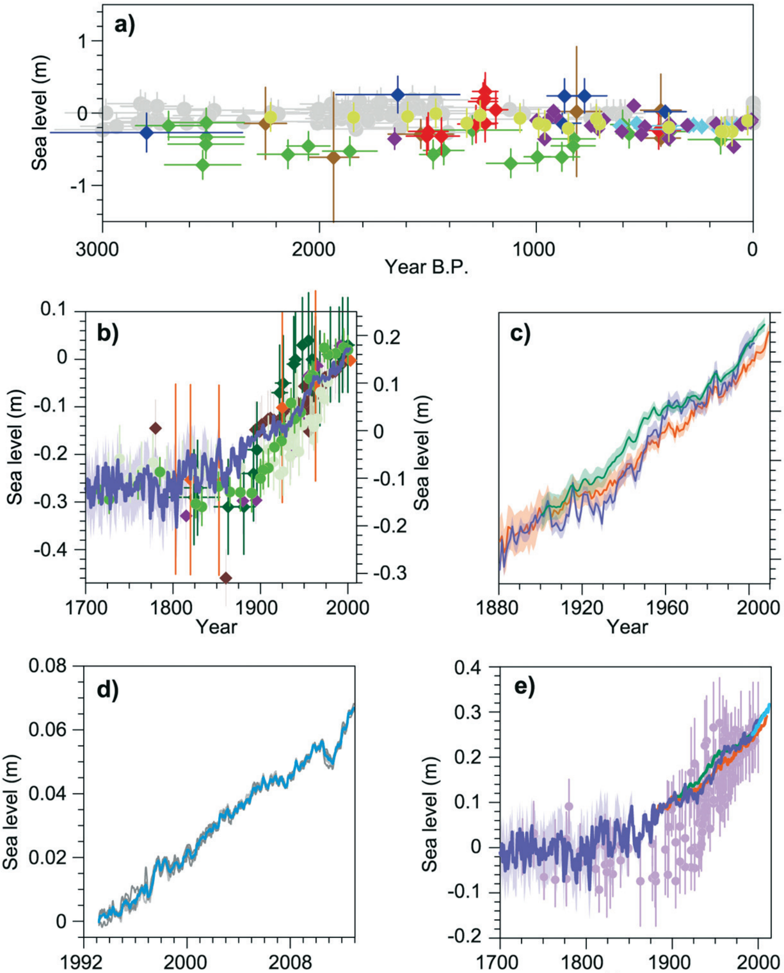
EC/ECHO/Anouk Delafortrie, Flickr, CC BY-ND 4.0.

increase? According to the evidence, entire regions of the world would experience major declines in crop yields, with up to a 50 percent decline of crop yields in Africa. Such a catastrophic decline in food production would likely result in mass hunger. If temperatures rise by more than 4°C, the consequences are absolutely terrifying. Glaciers will disappear, soil moisture will be lost (as water evaporates at a much higher rate), rainfall will decline in many regions (notably, today's subhumid and arid regions in the subtropics, like the Mediterranean basin countries), and extreme events such as massive heat waves, droughts, floods, and extreme tropical cyclones, will all become far more frequent.

With temperature increases of 5°C or more, the ensuing sea level rise would likely threaten major world cities, including London, Shanghai, New York, Tokyo, and Hong Kong. Calamitous events are possible with a mega-rise in sea levels. If the big ice sheets in west Antarctica and Greenland melt sufficiently or even partially break up into the ocean, the sea level will rise by many meters (in addition to the sea level increase directly resulting from the expansion of ocean water at higher temperatures). Whenever the Earth was a few degrees Celsius warmer than now, the ice sheets and glaciers retreated, and sea levels were indeed several meters higher than today. Yet in those episodes tens of thousands and hundreds of thousands of years ago, we didn't have mega-cities of millions of people dotting the Earth's coastline!

On the northeast coast of the United States, the sea level has already risen by around one foot or roughly one-third of a meter. Worldwide, the average sea level has increased by roughly one-quarter of a meter since the late nineteenth century, as shown in figure 12.8. (One might have thought that the sea level rise around the world would be fairly uniform, as in a bathtub filling with water, yet in fact differences in the Earth's topography and other geologic features of Earth mean that the sea level will rise at somewhat different rates across the planet.) More storm surges and coastal erosion are already occurring as sea levels are rising. New evidence suggests that by the end of this century, on a BAU path, sea levels could be a meter higher than now; in the worst case, the rise could be several meters.

There is no precise estimate of how and when the great ice sheets of Greenland and Antarctica might melt or break apart, but the human impact is large enough to cause a massive loss of those ice sheets and a massive rise in sea level. The ice



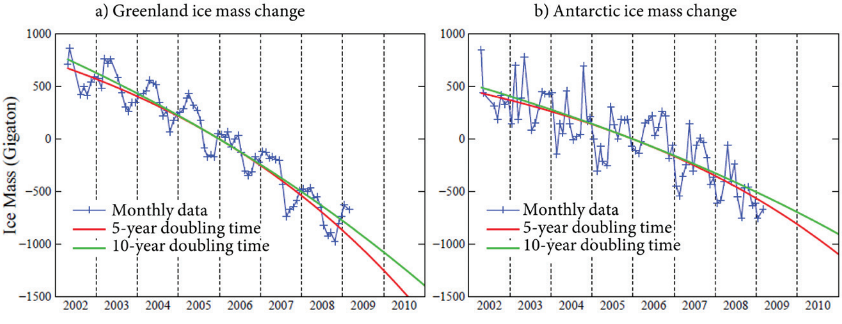
12.8 Sea level rises over time

Church, J.A., P.U. Clark, A. Cazenave, J.M. Gregory, S. Jevrejeva, A. Levermann, M.A. Merrifield, G.A. Milne, R.S. Nerem, P.D. Nunn, A.J. Payne, W.T. Pfeffer, D. Stammer, and A.S. Unnikrishnan, 2013: Sea Level Change. 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., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York.*

sheets are already under stress, as figure 12.9 shows (Hansen and Sato 2012, 41). Together, the consequences for the urban areas hugging the oceans and for our food supplies around the world are extraordinary.

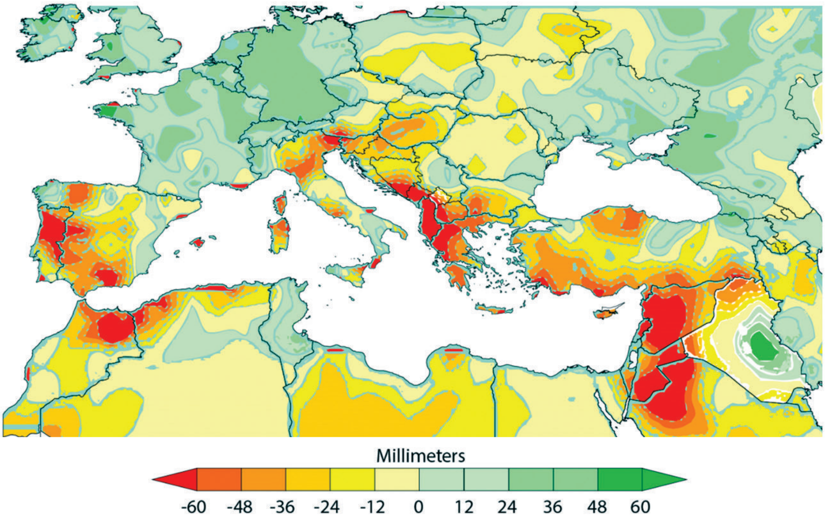
Certain regions of the world are extraordinarily vulnerable to higher temperatures and the loss of soil moisture needed for agriculture. I have already noted the vulnerability of the Sahel. Yet the problems are not just in the poor, dry parts of the developing world. The U.S. Southwest (Texas, New Mexico, Arizona, and southern California) is also extraordinarily vulnerable to drying. The Mediterranean basin, including the countries of southern Europe (Spain, Italy, and Greece), North Africa (Morocco, Algeria, Libya, Tunisia, and Egypt), and the eastern Mediterranean (Turkey, Syria, Israel, and Jordan), could also be devastated by drying.

Note the changes of rainfall in the Mediterranean basin over the last century in figure 12.10. The Mediterranean basin has experienced a significant trend of drying. The record clearly indicates that if we continue with BAU, this region could experience further dramatic drying with quite devastating consequences to economies, nature, ecosystems, and food security. This is a region of potentially great instability, because higher food prices combined with politics have already created a tremendous amount of unrest in places like North Africa and the eastern Mediterranean (Syria and Palestine) in recent years.



12.9 Ice mass changes in Greenland and the Antarctic (2002–2010)

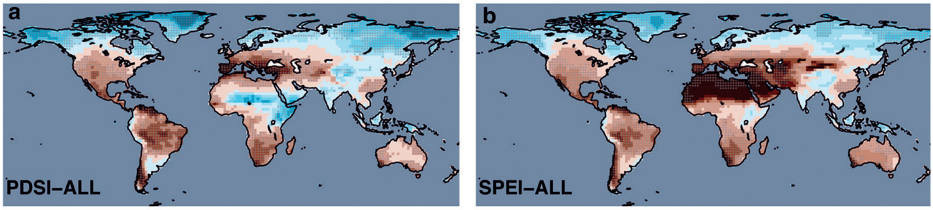
Source: Hansen, James, and Makiko Sato. 2012. "Paleoclimate Implications for Human-Made Climate Change." In Climate Change: Inferences from Paleoclimate and Regional Aspects*, ed. André Berger, Fedor Mesinger, and Djordjie Šijački, 21–48. Heidelberg: Springer.*



12.10 Winter rainfall during 1970–2010 compared to 1900–2010 average (millimeters)

Source: NOAA.

Recent studies show that many populous parts of the world are likely to experience significant declines of soil moisture needed to grow food. One recent study, summarized in figure 12.11, estimates the increase of drought risk (using two technical indicators, called PDSI and SPEI) around the world for the period 2080–2099 using a series of climate models that incorporate the

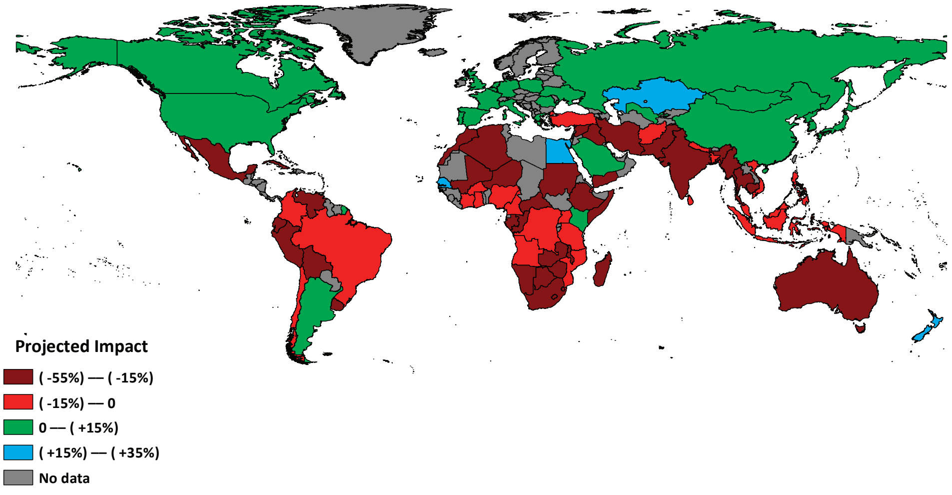


12.11 Prospects for drought 2080–2099

Cook et al. 2014. With kind permission from Springer Science and Business Media.

implications of temperature and precipitation on soil moisture. Most of the world near the equator to the midlatitudes is shaded brown, meaning a tendency toward drought! Only the higher latitudes are found to have more, rather than less, soil moisture.

The map in figure 12.12 comes from a study asking what might happen to food production if the combination of warmer temperatures and more drying were to take place. While the net effects of food production are rather uncertain, the evidence suggests the possibility of massive losses of food productivity in many parts of the world, especially in the tropics and subtropics (i.e., the equatorial region to the midlatitudes). In South Asia and tropical Africa, the map is filled with red zones, meaning the likelihood of major loss of agricultural production. This is the same in the southern part of the United States and much of Latin America and Australia. The only areas of consistent increase in food productivity are likely to



12.12 Projected changes in agricultural productivity (2080)

Source: Hugo Ahlenius, UNEP/GRID-Arendal. Source: Cline, W. R. 2007. Global Warming and Agriculture: Impact Estimates by Country. Washington D.C., USA: Peterson Institute. http://www.grida.no/graphicslib/detail/projected-agriculture-in-2080-due-to-climate-change_141b be the high latitudes. In short, the world's food supply will be in increasing peril on the BAU path.

Even if one put aside all of the climate-induced changes from the rise of CO_2 concentrations—such as all of the major storm events, the rising sea levels, the rising temperatures, the increased floods and droughts, and the loss of soil moisture needed to grow food—the basic physical fact is that a higher CO_2 concentration in the atmosphere will also lead to more CO_2 dissolving into the oceans, which in turn will raise the acidity of the oceans (as shown by the already-occurring decline in ocean pH depicted in figure 6.2). As the ocean becomes more acidic, major classes of animal life, including shellfish, animals with exoskeletons like lobsters and crabs, certain microscopic plankton (a vital part of the major food chains), and the coral reefs that are so vital for marine ecosystems, are all likely to experience a massive dying-off.

These multiple threats are beyond our easy imagination; and unfortunately there is another kind of climate denial that has been promoted by systematic propaganda from major vested interest groups, including some of the big oil companies. There is every reason to change the game, every reason to mitigate the human-induced climate change for our own safety and for the safety of the planet and future generations. Yet how can human-induced climate change best be brought under control? How can we mitigate human-induced climate change?

III. Mitigation of Greenhouse Gas Emissions to Limit Global Warming to Two Degrees Celsius

There needs to be a strong global response to the climate change challenge. There are two terms to reflect the two different ways of responding, both of which are important. One term, *mitigation*, means to reduce the GHGs causing human-induced climate change. The world has agreed on several occasions to try to limit the increase in average global temperature to no more than 2°C above the pre-industrial mean temperature. The other term used is *adaptation*, which means preparing to live more safely and effectively with the consequences of climate change. Adaptation includes steps like safeguarding cities against storm surges; protecting crops from high temperatures and droughts; and redesigning agricultural technologies to promote more drought resistance, heat tolerance, and flood tolerance in our crops and production systems.

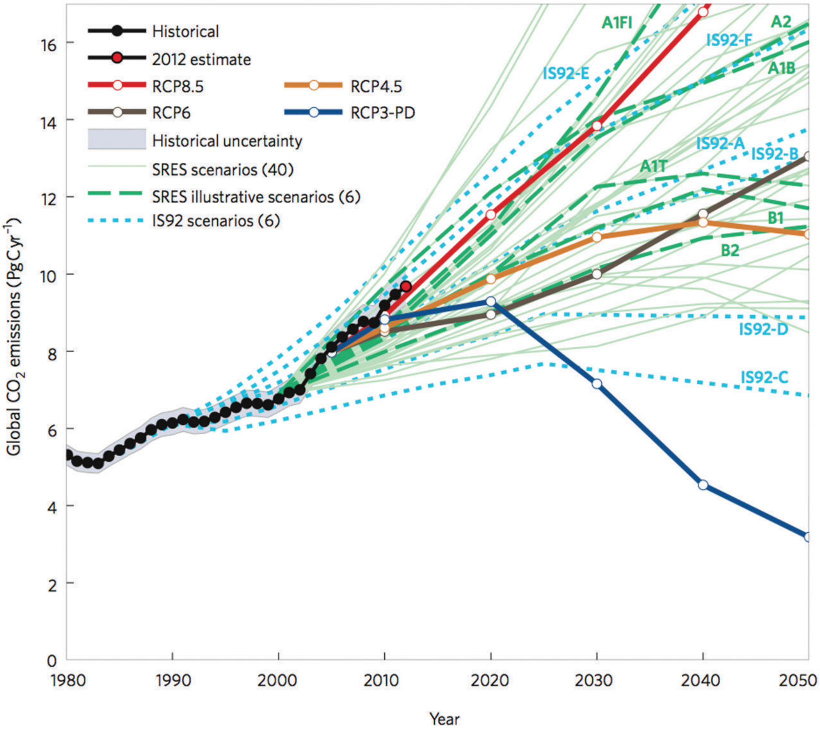
There is a limit to how much we can adapt, because if the changes are so dramatic that sea levels rise several meters or the global food supply is profoundly threatened by higher temperatures and drier conditions, then we are unlikely to be able to control the consequences of massive and worldwide crises. Mitigation is essential. At the same time, it is important to adapt, because climate change is happening and will continue to happen, even if mitigation is highly successful. There is inertia in the warming, as already noted, and it will take us some considerable time at the global scale to bring GHG emissions under control.

In short, mitigation is therefore an enormous priority and requires a careful diagnosis and prescription. Measures must be taken to head off further increases of GHG concentrations. Since about three-fourths of the increased radiative forcing of anthropogenic GHGs is due to CO_2, our highest mitigation priority should be to reduce the emissions of CO_2. Since most of the CO_2 emissions come from the burning of fossil fuels, the reduction of energy-related CO_2 emissions is the number one item on the mitigation agenda. The second way that CO_2 concentrations are increasing is land-use change, so next on the list (actually to be pursued simultaneously with energy-sector reform) is to head off the deforestation that is causing the emissions of CO_2 from land-use change. The third priority is to reduce the emission of CH_4, which results from several processes, both agricultural and nonagricultural. Our fourth priority is the reduction of emissions of N_2O.

For each of these human-induced emissions of GHGs, feasible and economical reductions in emissions must be sought. How long will it take to shift to a low-carbon energy system? What are the technological alternatives available for low-carbon energy? What are the most cost-effective ways to substantially reduce GHG emissions?

The right place to start is with CO_2. Scientists have usefully posed the mitigation question as follows: What would it take to reduce CO_2 emissions (mainly from fossil fuels, but also from land use) to keep the total increase of the Earth's temperature below the limit of 2°C? The basic answer is that since temperature has already increased by almost 1°C, we would need to dramatically reduce CO_2 emissions in the coming decades.

One recent scientific study of what this would require is shown in figure 12.13. Note that the measure of emissions is PgC yr^{-1}. PgC is petagrams (10^{15} grams) of carbon (C) per year, which translates to billions (= 10^9) of tons (= 10^6 grams) of carbon per year. To translate into billions of tons of CO_2 per year, we must multiply by a factor 3.667 (= 44/12), which is the atomic weight of CO_2 relative to the



12.13 Pathways of CO2 emissions: estimated CO2 emissions over the past three decades compared with the IS92, SRES, and the RCPs.

Reprinted by permission from Macmillan Publishers Ltd: Nature, *Peters, Glen P., Robbie M. Andrew, Tom Boden, Josep G. Canadell, Philippe Ciais, Corinne Le Quéré, Gregg Marland et al. "The Challenge to Keep Global Warming Below 2 °C." Copyright 2014.*

atomic weight of carbon. Thus, the current emissions level in 2014 of around 9.5 petagrams of carbon is equivalent to around 35 billion tons of CO_2.

There are many possible trajectories for future CO_2 emissions. On the horizontal axis are the years to 2050. In the various pathways in the figure, two are most important. The red path is the BAU trajectory, which assumes continued rapid growth of the world economy and few gains in energy efficiency. Global emissions reach around 17 billion tons of carbon by 2040, or as much as 60 billion tons of CO_2. In this scenario, the world economy is growing rapidly, and it uses more and more fossil fuels as it grows. Such a trajectory would take us to massive increases in global temperatures by 2100, probably to between 4°C and 7°C above the preindustrial level.

What trajectory of CO_2 is needed to avoid a 2°C increase? One trajectory that would most likely succeed is shown by the blue curve that bends down sharply after 2020. The blue trajectory holds CO_2 levels to around 450 ppm, and would be likely (but not certain) to contain the rise in temperature below the 2°C limit.

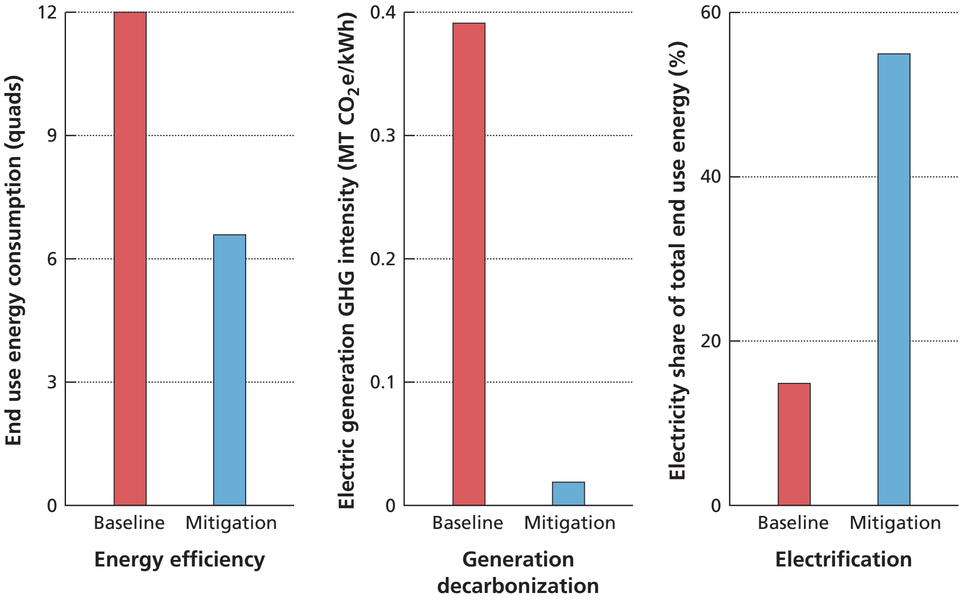
Yet such a trajectory will be very tricky to accomplish, especially with a growing world economy. We basically need a trajectory in which the world economy grows by a factor of perhaps 3 times by 2050 (reaching $250–300 trillion in today's prices), yet emissions fall by half or more as of 2050 compared with today. A frequent assumption for a 2°C limit is that 2050 emissions should be somewhere between 10 and 15 billion tons of CO_2 (2.7 and 4.1 billion tons of carbon) compared with 35 billion tons in 2014. That would mean that emissions per dollar of gross world product (GWP) would need to decline by a factor of 6 or even more!

The term *decarbonization* is used to mean a sharp reduction of CO_2 per dollar of GWP. A deep decarbonization of the world economy is necessary to remain within the 2°C limit. Since most of the CO_2 comes from burning fossil fuels, we therefore need a sharp reduction in the use of fossil fuels or a large-scale system to capture and sequester the CO_2 that is used.

One major economy, the state of California, is committed by law to reducing its emissions by 80 percent per by the year 2050. This is no small step, given California's importance in the U.S. economy and in the world economy. Indeed, if California were an independent country, its gross domestic product (GDP) would rank twelfth in the world (as of 2012).

A fascinating recent study has examined California's pathway to this goal (Williams et al. 2012). The pathway found in the study is quite important, because it sets certain general principles of deep decarbonization that will be widely applicable. There are three key steps of deep decarbonization, shown in figure 12.14. The first is *energy efficiency*, to achieve much greater output per unit of energy input. Much can be saved in heating, cooling, and ventilation of buildings; electricity use by appliances; and energy directed toward transportation.

The second necessary step is to *reduce the emissions of* CO_2 *per megawatt-hours of electricity*. This involves, first and foremost, dramatically increasing the amount of electricity generated by zero-emission energy such as wind, solar, geothermal, hydroelectric, and nuclear power while cutting the production of power based



12.14 Three energy transformations to reduce GHGs in California by 2050

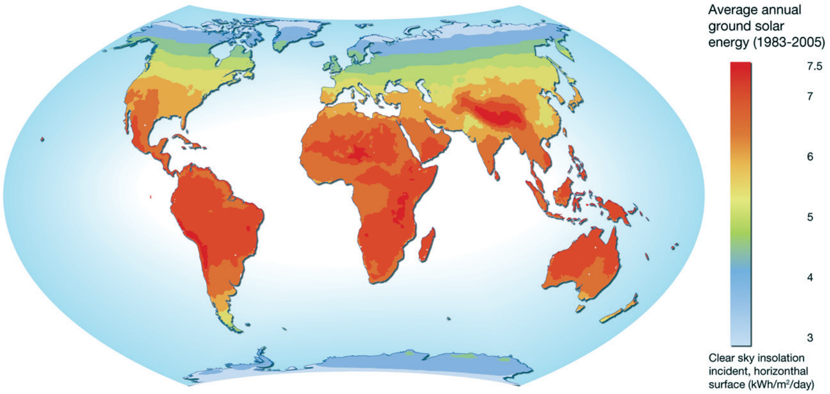
Source: Williams, James H., Andrew DeBenedictis, Rebecca Ghanadan, Amber Mahone, Jack Moore, William R. Morrow III, Snuller Price et al. 2012. "The Technology Path to Deep Greenhouse Gas Emissions Cuts by 2050: The Pivotal Role of Electricity." Science *335(6064): 53–59. Reprinted with permission from AAAS.*

on fossil fuels. It may also utilize carbon capture and sequestration as an adjunct or fallback technology, depending on the eventual costs of capturing and storing CO_2 from fossil fuels.

The third step is a *fuel shift,* from direct use of fossil fuels to electricity based on clean primary-energy sources. This kind of substitution of fossil fuel by clean energy can happen in many sectors. Internal combustion engines in automobiles can be replaced by electric motors. Furnaces and boilers to heat buildings can be replaced by heat pumps run on electricity. Open furnaces in industry can be replaced by fuel cells run on hydrogen, with the hydrogen produced by electricity. And so on. There are innumerable ways in every sector to shift from direct burning of fossil fuels to reliance on electricity. The trick then is to generate the electricity with low or zero carbon.

Regarding energy efficiency, one policy that has been quite successful is to put appliance standards into effect through regulation. Some economists do not like this approach, but markets are often not very effective in spurring transformations in energy efficiency at the necessary speed. Basic standards can be placed on automobile mileage per gallon or energy use in refrigerators and air conditioners. Building codes, which are part of the normal policy framework of any well-run city, can make a big difference. Building material quality, the insulation and ventilation properties, the choice of heating and cooling systems, and, of course, the types of power sources, all make a huge difference in the energy efficiency of buildings.

There are also several scalable approaches to low-carbon energy. One key option is photovoltaic (PV) cells. Photovoltaic cells have the ability to convert the energy in light rays (photons) into electrical energy. Albert Einstein first explained the underlying physical phenomenon, the photoelectric effect, in 1905. Photovoltaic systems can be the basis for large-scale power generation in much of the world. Figure 12.15 is a map of the solar energy potential across the planet, determined mainly by latitude and by average cloud cover. Note, for example, that solar potential is very high over the midlatitude deserts (such as the Mojave in California and the Sahara in Africa), but actually a bit lower at the equator, where the solar rays are more direct (i.e., overhead) but cloud cover is high.



12.15 World solar energy potential

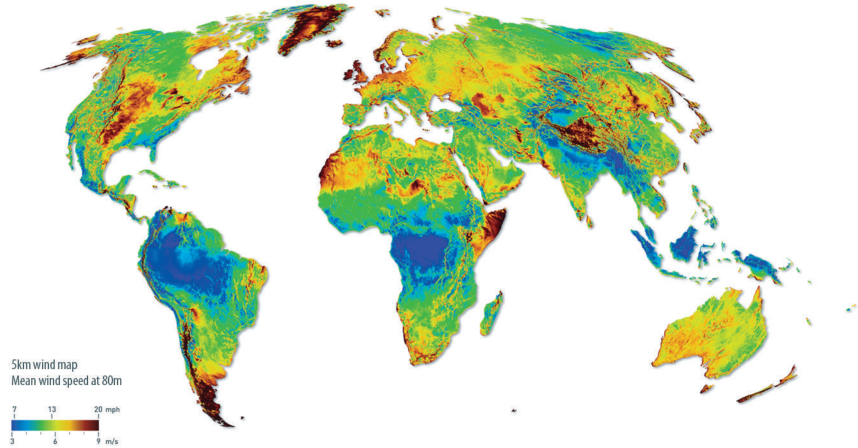
Credit: Hugo Ahlenius, UNEP/GRID-Arendal; Source NASA. 2008. "NASA Surface Meteorology and Solar Energy (SSE) Release 6.0 Data Set, Clear Sky Insolation Incident On A Horizontal Surface." http://www.grida.no/graphicslib/detail/natural-resource-solar-power-potential_b1d5#.

Figure 12.16 shows another potentially scalable approach to zero-carbon electricity: wind power. The wind turbine uses electromagnetic induction (rotating a coil of conducting material such as copper through a magnetic field) to generate electricity. Wind power is already cost competitive with fossil fuels in many windy places. Figure 12.17 is a map of average wind speeds around the world measured at 80 meters above the surface, showing land regions of high wind potential in orange and red areas. We can see many high-potential areas, including the U.S. Midwest and Northeast, the southern tip of South America, several desert regions of Africa (including Morocco, Sudan, Ethiopia, and Somalia), northern Europe along the North Sea, and parts of central and western China, among others.

Another zero-carbon alternative is geothermal energy. In favorable locations, for example, along the boundaries of tectonic plates, it is possible to tap large-scale heat energy in the Earth's mantle. The geothermal energy is used to boil water to turn steam turbines for electricity generation. Geothermal energy already powers much of Iceland (which uses the energy both to produce electricity and to heat water that is then piped to homes and offices) and is being deployed at an

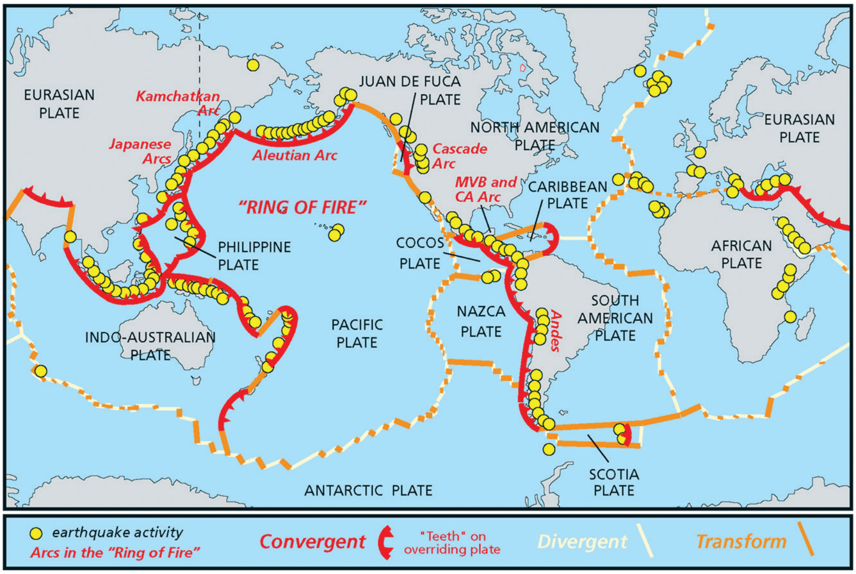
12.16 Wind turbines

"Wind Turbine," Chrishna, Flickr, CC BY 2.0.



12.17 Average global wind speeds

3TIER by Vaisala.



12.18 World geothermal provinces

"What Is Geothermal Energy?" by Mary H. Dickson and Mario Fanelli. Pisa: Istituto di Geoscienze e Georisorse, CNR, 2004. International Geothermal Association http://www.geothermal-energy.org.

increasing scale in the Rift Valley of East Africa and other geothermal sites. Figure 12.18 offers an estimate of geothermal potential in different parts of the world. Notice for example the geothermal zone along the Rift Valley of East Africa.

Nuclear power, such as the British nuclear plant shown in figure 12.19, also offers zero-carbon energy at a relatively low cost, and currently accounts for around 12 percent of global electricity generation. Yet nuclear plants are controversial because of non-climate risks, such as the secret diversion of nuclear fuel and waste for nuclear weapons use, and accidents that cause the release of nuclear radiation into the surroundings, as occurred in the 2011 Fukushima disaster in Japan (when the power plant was hit by a tsunami) and the 1986 Chernobyl disaster in the Ukraine (when nuclear fuel rods were accidentally allowed to overheat as the result of inappropriate procedures). Another challenge is the long-term disposal of nuclear waste materials. Nuclear power is set

12.19 Nuclear power plant in England

"Nuclear power thriving in England," Jared and Corin, Flickr, CC BY-SA 2.0.

to grow markedly in East Asia, notably in China and Korea, while other countries, including Germany, have decided to abandon nuclear power. Still others, such as the United States, are on the policy fence, with society deeply divided between supporters and opponents.

When electricity is produced with low-carbon or zero-carbon technologies, electricity offers an indirect means to reduce carbon emissions from other sectors of the economy that now directly burn fossil fuels. Rather than running vehicles on internal combustion engines, vehicles can be powered by electric motors run on low-carbon electricity (figure 12.20). There are many ways to do this, including battery-powered vehicles that are recharged on the power grid or fuel-cell vehicles in which the fuel cell uses an energy source such as hydrogen that is produced with low-carbon electricity. (The electricity can be used to split water molecules, H_2O, into hydrogen and oxygen.) Synthetic liquid biofuels such as methanol can also be produced through industrial processes using low-carbon energy.

12.20 Electric vehicle at a charging point, London

"Electric car charging," Alan Trotter, Flickr, CC BY 2.0.

Similarly, buildings that are now heated by burning coal, oil, or natural gas on the premises can instead be heated with an electric-powered heat pump, in which the electricity is generated with a low-carbon source. In this way, the direct emissions of CO_2 from the building are eliminated. A heat pump is like a refrigerator run in reverse, pumping heat from a relatively cold to a relatively warm reservoir. In this case, the pump takes heat from outside the building (e.g., heat from underground in the wintertime), and pumps it inside the building. Since the heat is transferred from a relatively cold exterior reservoir (in the ground) to a relatively warm reservoir (the building interior), it must be "pumped" against the natural flow (like pumping water uphill).

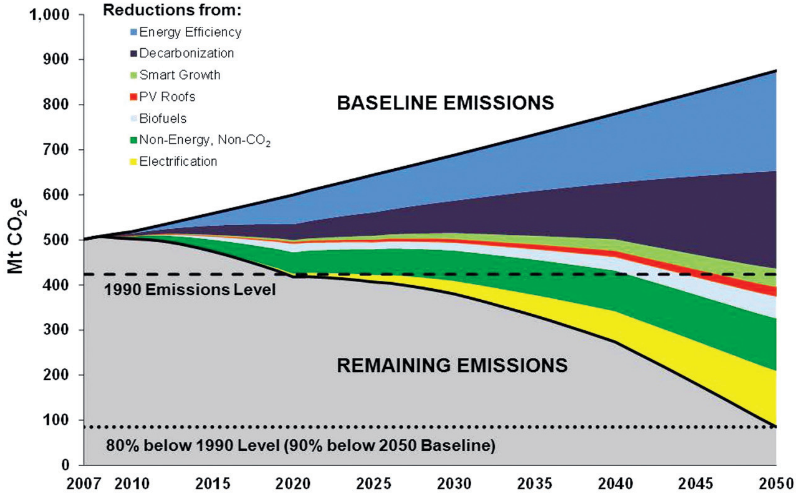
There are also many industrial processes that can be converted from the direct burning of fuels (e.g., in furnaces) to heat provided by hydrogen fuel cells and other sources produced by electricity. As with vehicles and buildings, low-carbon electricity offers a way to eliminate the reliance on fossil fuels and thereby to reduce CO_2 emissions from industry. Some of the highest-emitting industrial processes today, such as steel production, can be reengineered to be part of a low-carbon economy.

When the California study added up the numbers, the engineers found a pathway to reach California's bold target of an 80 percent reduction of CO_2 by 2050. That path is illustrated in figure 12.21 (Williams et al. 2012, 54). The baseline emissions are the line at the top, which shows that CO_2 emissions with BAU are on the rise in California because of long-term economic growth. The preferred mitigation trajectory is the downward-sloping line at the bottom of the curve. The gap is explained in the list of the ways of reducing CO_2 emissions. The light blue zone, for example, shows the reduction of emissions coming from energy efficiency. The purple zone shows the reduction of emissions coming from decarbonizing electricity generation. The yellow zone shows the reduction from fuel shifting (electrification), such as the transition from vehicles with internal combustion engines to electric vehicles.

There are also other smaller categories of low-carbon energy, such as the deployment of biofuels. Biofuels use biomass to produce a liquid fuel that is a substitute for fossil fuel. Figure 12.22 shows one example of an advanced biofuel. These panels look like PV solar cells, but they are in fact filled with genetically modified bacteria engineered to use solar energy to synthesize liquid hydrocarbons. There are many biological pathways by which biomass can be grown and converted into fuels. The problem with biofuels, however, is that in many cases the production of the biomass feedstock competes with food production. This is very much the problem with the large U.S. program to convert corn (maize) to ethanol through the anaerobic respiration of yeast. The diversion of maize production for this program has driven up food prices (by shifting maize out of the supplies of food and feed) while doing little to reduce net CO_2 emissions.

Regional Solutions for Renewable Energy

There are two further crucial aspects to tapping renewable energy sources like wind and solar power. First, the greatest potential for renewable energy is often located far from population centers. Solar energy, for example, is highest in the



Wedge Category:	Emissions Reduction Mt CO$_2$e (% of Total) 2030	2050	Types (and Numbers) of Measures Used	Key Attributes in 2050
Energy Efficiency	102 (33%)	223 (28%)	Building EE (18); Vehicle EE (9); Other EE (6)	Improve energy efficiency 1.3% per year on average for 40 years
Electricity Decarbonization	72 (23%)	217 (27%)	High renewables, high nuclear, high CCS, and mixture of the three	Meet 90% of generation requirement with CO$_2$-free sources. Equivalent decarbonization in each scenario.
Smart Growth	13 (4%)	41 (5%)	Reductions in vehicle miles traveled (VMT) (6)	VMT reduced in light duty vehicles (LDV) by 10%; freight trucks 20%; other transportation 20%
Rooftop PV	8 (3%)	21 (3%)	Residential and commercial PV roofs (2)	Rooftop PV displaces 10% of electricity demand by 2050.
Biofuels	18 (6%)	49 (6%)	Transportation biofuels: ethanol, biodiesel, biojet fuel (9); Residential, commercial, industrial biomethane (3)	By 2050, biomethane displaces 2% of natural gas use in buildings, and biofuels displace 10-20% of petroleum-based fuels for vehicles
Non-Energy, Non-CO$_2$	67 (22%)	116 (15%)	Cement, agriculture, and other (3)	Non-fuel, non-CO$_2$ GHG emissions reduced 80% below baseline
Electrification	29 (9%)	124 (16%)	Transportation electrification (9); Other end-use electrification (5)	75% of LDV gasoline use displaced by PHEVs & electric vehicles; 30% of fuel use in other transport sectors electrified; 65% electrification of non-heating/cooling fuel use in buildings; 50% electrification of industrial fuel uses
Baseline Case Emissions	**688**	**875**		
Mitigation Case Emissions	**380**	**85**		
Total Reduction	**308**	**791**		

12.21 Emission reduction wedges for California in 2050

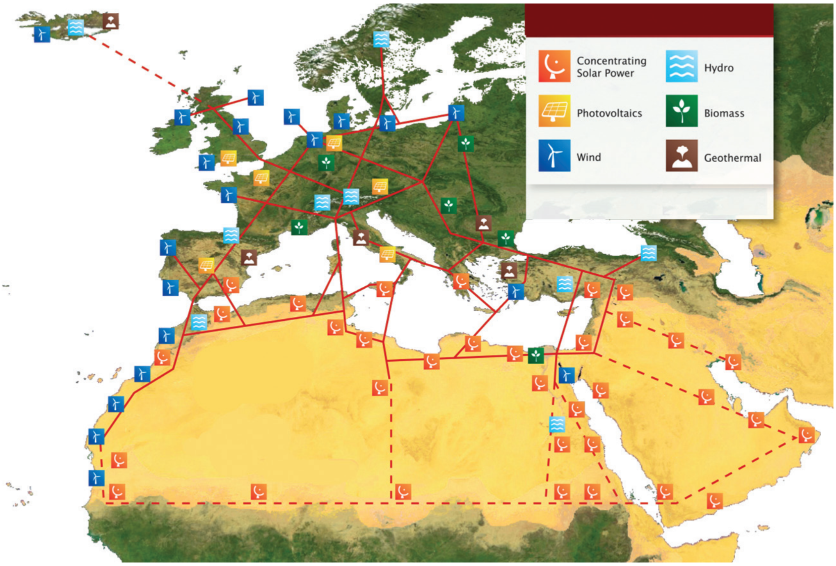
Source: From Williams, James H., Andrew DeBenedictis, Rebecca Ghanadan, Amber Mahone, Jack Moore, William R. Morrow III, Snuller Price et al. 2012. "The Technology Path to Deep Greenhouse Gas Emissions Cuts by 2050: The Pivotal Role of Electricity." Science *335(6064): 53–59. Reprinted with permission from AAAS.*

12.22 Biofuel plant: making ethanol from sunlight and CO_2

Credit: Joule.

desert regions. Second, both wind and solar power are intermittent energy. Solar power obviously varies predictably by time of day, but it also depends on the random fluctuations of cloud cover. Winds also fluctuate unpredictably. Even very windy locations occasionally experience hours or days of becalmed conditions with little power generation, and in many places winds are highly seasonal.

There are three main implications. First, tapping renewable energy on a large scale will generally require building new transmission lines to carry the power from remote locations to the major population centers. Second, the storage of renewable energy—for hours, days, or longer—makes them far more attractive as energy sources. There are many proven and emerging technologies for storing intermittent power sources. Third, there is a strong case for joining disparate renewable energy sources into a shared transmission grid. When it is cloudy in some part of the network, it is likely to be sunny in other parts of the network, thereby helping to smooth out the fluctuations in any single location.

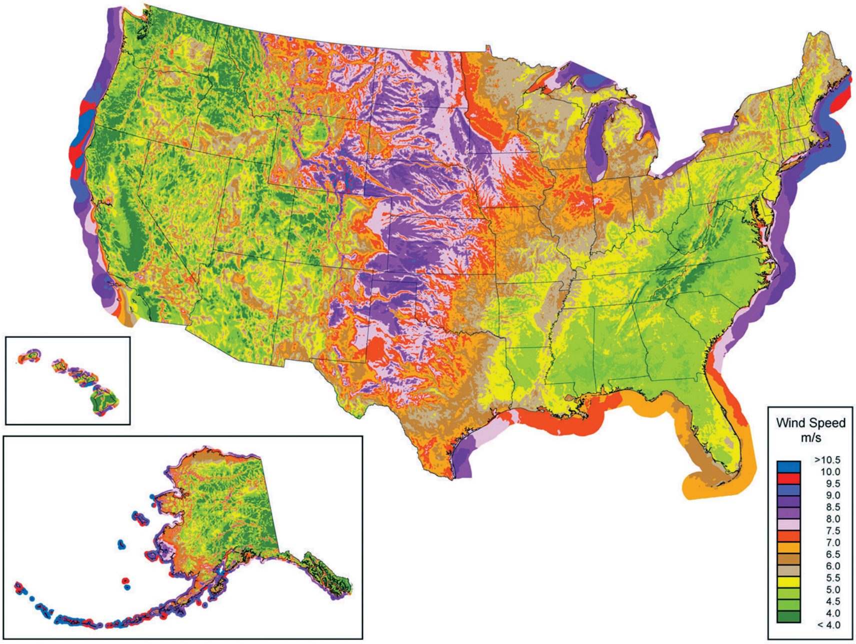


12.23 DESERTEC energy plan

Source: DESERTEC.

Consider three examples of potential large-scale power generation and distribution based on renewable energy. None has yet been developed, yet each is under consideration by governments and private investors. The first project is known as DESERTEC, and is designed to link North Africa, the Middle East, and Europe into a single grid (shown in figure 12.23). This system would tap the strong solar and wind potential of North Africa and the Arabian Peninsula, both to supply energy for these economies and to export the surplus to Europe. The challenges to realizing this concept are enormous, beginning with an estimated price tag of several hundred billion dollars and technical challenges of managing a far-flung grid based heavily on renewable, intermittent energy. Yet the concept is potentially a key solution to Europe's unsolved challenge of deep decarbonization and an enormous boost to the economies of North Africa and the Middle East.

A second major concept is to tap the enormous offshore wind potential of the United States, illustrated in figure 12.24. Proponents of wind power have argued

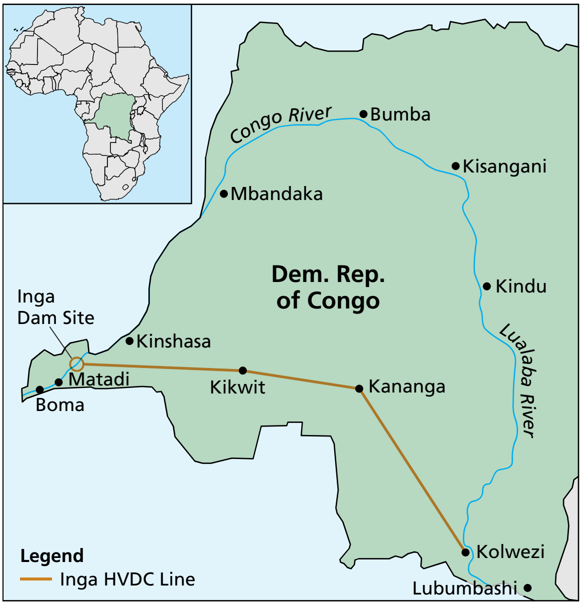


12.24 U.S. offshore wind resources

Wind resource map developed by NREL with data from AWS Truepower.

persuasively that the wind off the shore of the Eastern Seaboard could potentially meet most of the electricity needs of the U.S. Northeast, from Virginia to Maine. Yet despite many proposals and business plans, there is still no offshore wind power tapped in the United States, due to regulatory, political, and environmental challenges and debates. There are also unsolved technological challenges that seem to be within reach of solution yet have not been explored with adequate public or private research and development (R&D) funding. Of course, the United States has vast untapped large-scale renewable energy potential, including solar energy in the Mojave, onshore wind in the Dakotas, and the offshore wind shown in figure 12.24.

A third renewable energy project with the potential to transform its region with zero-carbon energy is the vast hydropower potential of Inga Falls in the Congo River



12.25 Map of Inga Falls dam site

Source: International Rivers, Congo's Energy Divide (2013).

basin. The Grand Inga Dam Project, discussed for half a century, could produce up to 40 gigawatts of hydroelectric power, more than one-third of the total electricity currently produced in Africa. However Inga Falls is in one the least bankable places in the world, the Democratic Republic of Congo. Yet many close observers now feel that an arrangement is now within reach in which the nations of the region, including the Democratic Republic of Congo, the Congo (Brazzaville), Burundi, Rwanda, and perhaps South Africa, join together to back a multilateral project. Potential funders of the project, which is estimated to cost around $50 billion in total, might include the African Development Bank, the Chinese Development Bank, and the World Bank Group (including the International Finance Corporation).

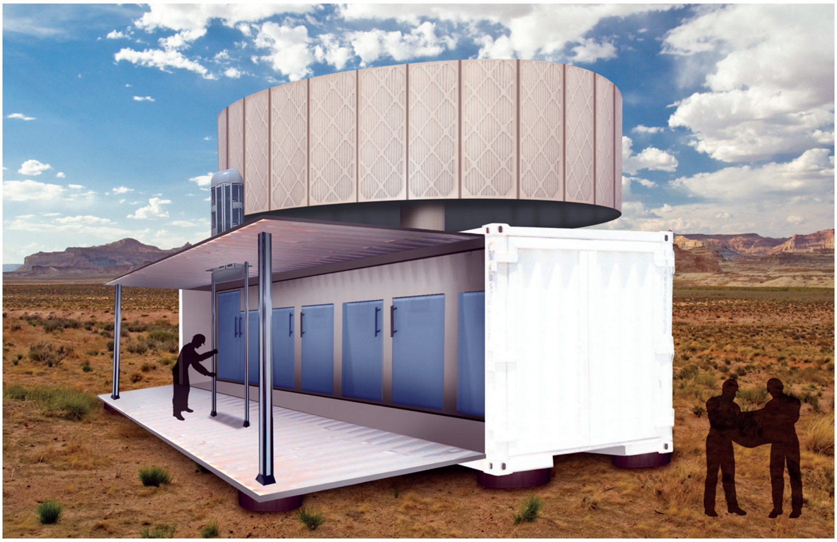
All three of these projects illustrate a basic reality of deep decarbonization. Large-scale, zero-carbon projects are within reach. Yet they are politically complex, require massive upfront investments, and need further R&D to bring them to fruition. In short, massive renewable energy is possible but far from assured. A serious global commitment to low-carbon energy will be required.

Carbon Capture and Sequestration

In addition to energy efficiency, low-carbon electricity, and fuel switching, there is one more potential way to reduce the CO_2 emissions from fossil fuel use. Currently, when fossil fuels are burned, the CO_2 enters the atmosphere, where it may reside for decades or centuries. A potential solution is to capture the CO_2 instead of allowing it to accumulate in the atmosphere. Two main ways to do this have been proposed. The first is to capture the CO_2 at the site where it is produced (e.g., the power plant), and then to store it underground in a geologic deposit (e.g., an abandoned oil reservoir). The second is to allow the CO_2 to enter the atmosphere but then to remove the CO_2 directly from the atmosphere using specially designed removal processes (e.g., collecting the CO_2 with special chemical sorbents that attract the CO_2). This latter approach is called "direct air capture" of CO_2. Figure 12.26 is a mock-up of a direct-air-capture facility as proposed by Professor Klaus Lackner, one of the world leaders in the engineering of direct air capture of CO_2 (Lackner et al. 2012).

If carbon capture and sequestration (abbreviated as CCS) proves to be successful, then there is a wonderful way to reduce CO_2 emissions without having to change our current technologies or energy mix! Rather than shifting to new sources of noncarbon energy, we could continue to use fossil fuels but then remove the CO_2 that is produced, either at the power plant or via direct air capture. Some oil companies, for example, have presented climate change scenarios in which CO_2 mitigation is achieved largely through the scaling up of CCS.

There are vigorous technical and policy debates about the feasibility and cost-effectiveness of large-scale CCS technologies. There are, indeed, many questions. First, how costly will it be to capture CO_2 on a large scale (through either method)? Second, how costly will it be to ship the CO_2 by a new pipeline network and then store the CO_2 in some safe, underground geologic deposit? And third, if the CO_2 is put underground (e.g., in an abandoned oil reservoir or perhaps a saline aquifer that can hold the CO_2), how sure are we that the CO_2 will stay where it is put, rather than



12.26 An illustration of an air capture unit on a standard shipping container (by Prof. Klaus Lackner)

Credit: GRT, 2009.

returning to the surface and then into the atmosphere? Leakage rates of CO_2 would have to be very low to make this technology feasible on a large scale.

Governments, including the United States, European Union, Australia, and China, have been talking about the large-scale use of CCS for at least a decade, but there is still far too little R&D underway to test the economic and geologic potential for large-scale CCS. Remember that tens of billions of tons of CO_2 would have to be captured and stored each year for CCS to play the leading role in addressing CO_2 emissions. Perhaps it will prove feasible and economical at a smaller scale, where the location of power plants and suitable geological storage sites make CCS an especially low-cost option.

Geoengineering as a Final (Desperate?) Option

There is one more idea around, called geoengineering. The basic idea is that if carbon emissions cannot be stopped at a reasonable cost or on a reasonable timeline, then there may be other ways to compensate for or counteract the effects of the rising CO_2. For example, if CO_2 continues to rise and dangerously warm the planet, some scientists have suggested that we should deliberately add sulfate aerosol particles into the air to dim the incoming sunlight and thereby cool the planet in order to offset the warming effects of the CO_2. Another idea is to place giant mirrors in space in order to deflect some amount of incoming solar radiation. These are, evidently, very radical, and perhaps completely unworkable ideas.

Another huge problem with such suggestions is that the compensatory action (in this case, the deliberate emission of sulfate aerosols) may have hugely deleterious effects (e.g., air pollution or dimmer sunlight), so that they "solve" the CO_2 problem only by introducing an even greater or more unpredictable problem. Remember that if we actually try to offset the CO_2 warming by adding sulfate aerosols, the CO_2 concentrations in the atmosphere would continue to rise. This continued increase would have two huge implications. First, it would mean that if we ever stop adding sulfate aerosols into the atmosphere, the warming effect of the CO_2 would quickly be exposed. Temperatures would surge as the sulfate aerosols are washed back to Earth (e.g., in rainfall). Second, the high concentrations of atmospheric CO_2 would continue to acidify the oceans, even though the aerosols temporarily offset the warming effect of the CO_2.

For these reasons it seems unlikely that offsetting geoengineering could ever make it safe for humanity to continue to increase the atmospheric concentration of CO_2. Humanity most likely has no good alternative other than to keep the carbon emissions below the trajectory associated with a 2°C increase in temperature.

IV. Adaptation

It is possible to reduce human emissions of GHGs substantially. The technologies are within reach. Energy efficiency, low-carbon electricity, and fuel switching (e.g., electrification of buildings and vehicles) are all needed. Carbon capture and sequestration may play some role. Yet even hugely successful efforts in these directions are bound to involve an ongoing buildup of atmospheric

CO_2 for years to come, and with it, continued climate change and global warming. In other words, it is too late to prevent at least some further increase of climate damage.

In fact, the situation is even grimmer than that. Suppose (unrealistically!) we could immediately stop all new net emissions entirely, and thereby maintain the atmospheric levels of CO_2 and other GHGs as they are in 2014. This would not be enough to stop global warming. The Earth's average temperature has so far increased by 0.9°C compared with the preindustrial temperature, yet the oceans have not yet warmed as much as the land (given that oceans have an enormous capacity to absorb heat). When the oceans finally warm in line with the GHG concentrations, the Earth's average temperature is likely to be an additional 0.6°C warmer than now (or a total warming of 1.5°C). Thus, further warming is in store for two reasons: (1) "thermal inertia" (the delay in ocean warming); and (2) the inevitability of a further buildup of greenhouses gases in the short term.

For these reasons, we will need not only to prevent future climate changes by decarbonizing the energy system (and taking actions vis-à-vis the other GHGs), but also learn to live with at least some climate change as well. With great diligence and global cooperation it may be possible to keep the global average temperature from rising by 2°C above the preindustrial level, yet even so, a 2°C rise will imply massive changes to the climate system, including more droughts, floods, heat waves, and extreme storms. We need to get ready for such eventualities.

Adaptation will require adjustments in many sectors. In agriculture, crop varieties must be made more resilient to higher temperatures and more frequent floods and droughts (depending on location). Cities need to be protected against rising ocean levels and greater likelihood of storm surges and flooding. The geographic range of some diseases, such as malaria, will spread as temperatures rise. Biodiversity will suffer as some animals and plants are unable to adjust to the changing climate conditions; special efforts will be needed to ensure that particular species are not thereby driven toward extinction. The list, in short, is very long and location-specific.

Policy Instruments for Deep Decarbonization

Economists rightly emphasize the need for corrective pricing to provide proper incentives for producers and consumers to reduce CO_2 emissions and avoid the "externalities" associated with CO_2-induced climate change. Carbon dioxide imposes high costs on society (including future generations), but those who emit the CO_2 do not pay for the social costs that they impose. The result is the lack of a market incentive to shift from fossil fuels to the alternatives. Ideally, producers and consumers would choose among alternative energy technologies in order to minimize the true social costs of energy use, including the costs of climate change and the costs of adverse health consequences of polluting energy sources. On both counts—climate and health—users of fossil fuels should be required to pay a higher price than users of clean energy, in order to shift the incentives to a low-carbon economy.

There are several ways to overcome part or all of the current incorrect pricing of fossil fuel use. The most straightforward is that all users of fossil fuel should bear an extra "carbon tax" equal to the social cost of the CO_2 emitted by the fuel. This would raise the costs of coal, oil, and gas compared with wind, solar, nuclear, and other low-carbon energy sources, shifting the energy use toward the low-carbon options. (Of course if these alternatives also impose social costs, such as the risks of nuclear accidents, those alternatives should also bear the true social costs inclusive of those risks.) Economists have proposed a carbon tax on the order of $25–100 per ton, on the grounds that the social cost of an extra 1 ton emission of CO_2 is estimated to be in the range of $25–100 per ton. Over time, as climate change intensifies, the social cost of CO_2 emissions, and hence the carbon tax, would most likely increase.

A related alternative approach, in use in Europe and in some U.S. states, is a permit system, in which emitters of CO_2 must buy a permit to do so. This is closely akin to the carbon tax, except that emitters buy a permit on the open market (or receive it from government) instead of paying a tax. If an emitter would like to increase emissions of CO_2 (perhaps because the business is expanding so that energy use is rising), the emitter can buy an extra emissions permit on the market from another firm that is successfully reducing its carbon emissions.

There have been heated debates for two decades about whether carbon taxes or emissions permits are the appropriate policies. Carbon taxes are likely to give more predictability as to the future price of carbon. Emissions permits may (or may not) give more predictability to the future quantities of emissions. They would seem to give more predictability about the total emissions (since emissions are limited in theory by the availability of the permits), but in fact permit systems are often not very credible, since an expected scarcity of permits (driving up their price) frequently leads governments to increase the allotment of permits. Taxes in general are much easier to administer, while permit systems are in principle easier to configure to meet special interests (e.g., specific favored industries can be given permits for free in order to delay their adjustment to alternative energy sources). In practice, both types of systems are likely to be used in future years, though the tax-based systems are likely to be significantly more robust, predictable, and easier to administer.

A third way to adjust market prices is through "feed-in tariffs." The government tells a utility company or a power generator, "We will buy electricity from you, and will pay an extra high price if the electricity that you are bringing into this system is from a low-carbon source such as solar power." Rather than taxing the CO_2, the government instead gives an added boost to the alternative sources. These positive incentives can be quite powerful in inducing companies to shift to low-carbon energy generation. The main problem of feed-in tariffs compared with a carbon tax is that the government may not have the budget revenues available to pay the subsidy for low-carbon energy. Indeed, several countries that promised such feed-in tariffs pulled back their commitments after the 2008 financial crisis.

The Double-Edged Sword of Technological Advance

It is heartening to realize that advances in technological know-how can enable humanity to find a safe, efficient, and relatively low-cost transition from fossil fuels to a low-carbon economy based on greater energy efficiency, low-carbon electricity, and fuel switching. Recent technological advances include sharp reductions in the cost of wind and solar energy; improved geothermal energy; improved batteries for electric vehicles; smarter power grids; improved building materials; better waste management; new building design requiring less energy for heating, cooling, and ventilation; and much more. And there are significant advances ahead, such as the potential for direct air capture of CO_2, storage of intermittent renewable energy, highly efficient long-distance power transmission, advanced biofuels, and new nanotechnologies for strong, lightweight construction materials, among others. Technological advances can save the day.

Yet we should not be overly simplistic about the saving grace of technological advances. Ironically, in a world of externalities (such as CO_2 emissions), technological advances can worsen rather than improve the situation, since they can exacerbate the tendencies toward the exploitation of high-carbon energy sources. The simple fact is that the oil and gas sector has been quite technologically sophisticated in recent years, dramatically improving the capacity to find, develop, produce, and transport fossil fuel–based energy! Here are a few pertinent examples.

The first advance, shown in figure 12.27, is a true technological marvel: a floating liquefied natural gas (LNG) plant, designed and built by Royal Dutch Shell, and soon to be introduced into service (Shell 2014). This facility, described as the largest structure ever sent to sea, will cool offshore natural gas into LNG for onward ocean transport. Before the advent of this new facility, offshore gas must be transferred by pipeline to a land-based LNG plant. Ocean deposits of methane too far from the land are not economical when they must be transferred by pipeline, but now will be economical to produce. Moreover, pipelines are not only expensive but are also vulnerable to storms, leaks, ruptures, and other accidents in the open seas. A technological marvel, yes—and one that will accelerate the production and use of natural gas.

A second example of a technological breakthrough is the capacity to develop Canada's vast reserves of oil sands, which are sand and rock deposits that contain bitumen, a highly viscous form of petroleum. One of the development sites is shown in figure 12.28. Canada's oil sands (and also the oil sands of Venezuela) are vast deposits that would substantially raise the quantity of petroleum available to world markets. They have been too expensive to produce until recently, when the combination of improved mining and processing technologies and higher world oil prices have made these deposits profitable. The proposed Keystone XL

12.27 Model of floating liquefied natural gas factory (Shell Prelude)

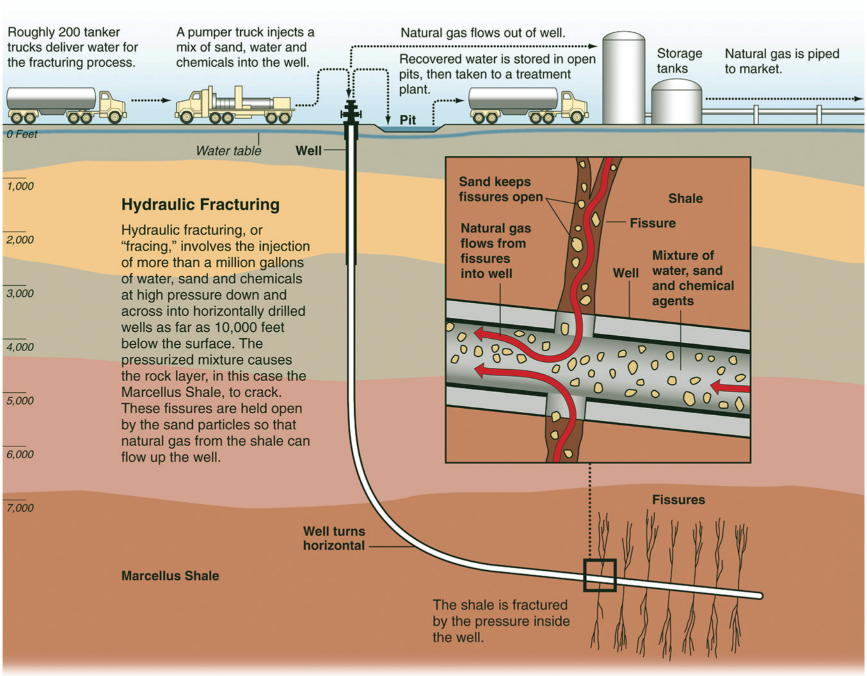
Photographic Services, Shell International Ltd.

12.28 Canadian oil sands, Alberta

“Tar sands, Alberta,” Dru Oja Jay, Howl Arts Collective, Flickr, CC BY 2.0.

Pipeline, a highly controversial new pipeline development, would carry the Canadian oil to refineries in the Gulf of Mexico, and (mainly) on to global markets. A technological breakthrough: yes, but one associated with massive pollution on site (as evident in the figure) and a vast increase of fossil fuel resources that will tend to push the world even faster over the 2°C carbon budget.

A third remarkable technological breakthrough is shown in the illustration in figure 12.29. The figure illustrates the breakthroughs of horizontal drilling and hydraulic fracturing (hydrofracking) of natural gas caught in shale rock. In this process, the drilling is first down and then horizontal (as shown) into shale rock containing methane in the rock pores. To release the methane, a high-pressure mix of fluids and drilling materials are blasted into the rock, thereby fracturing



Roughly 200 tanker trucks deliver water for the fracturing process.

A pumper truck injects a mix of sand, water and chemicals into the well.

Natural gas flows out of well.

Recovered water is stored in open pits, then taken to a treatment plant.

Natural gas is piped to market.

Hydraulic Fracturing

Hydraulic fracturing, or "fracing," involves the injection of more than a million gallons of water, sand and chemicals at high pressure down and across into horizontally drilled wells as far as 10,000 feet below the surface. The pressurized mixture causes the rock layer, in this case the Marcellus Shale, to crack. These fissures are held open by the sand particles so that natural gas from the shale can flow up the well.

The shale is fractured by the pressure inside the well.

12.29 Hydrofracking diagram

Al Granberg/ProPublica.

the rock and freeing the methane, which rises to the surface, where it is collected. The shale gas boom (and a similar shale oil boom) has been transforming the U.S. energy landscape and rural landscape in recent years. The process is highly contentious. On the one hand it is leading to an oil and gas boom in the United States. On the other hand, it is leading to massive local pollution and a boom in fossil fuels that is at least delaying, if not blocking, an eventual shift to low-carbon energy.

All three advances have greatly expanded the world's capacity to tap fossil fuel reserves, but we must pause to ask ourselves if we are really doing ourselves a favor by slowing down the transition to urgently needed low-carbon energy. These advances are making it harder, not easier, to live within the carbon budget. They have made the politics around climate change even more difficult, since the fossil fuel lobby has something important to show for itself: real resources earning real profits (and large profits at that). Yet none of this changes the basic truth: we are on a path of grave long-term planetary danger at the price of short-term market returns.

V. The Politics of Carbon Dioxide Mitigation

There are many obstacles to a low-carbon world: technological, economic, engineering, and organizational. Getting to a low-carbon economy will not be easy. Indeed, it will require serious planning alongside market forces. It will require global cooperation to invest in the improvement of low-carbon technologies. It will require a commitment to much deeper decarbonization than most governments are now considering. The right approach is to recognize that by 2050 we must have cut emissions by more than 50% of today's levels, and then to "back-cast" (that is, work backwards from 2050) to the present period in order to chart out the timing of deep changes in the energy system. None of this is easy—far from it.

Yet perhaps no obstacle is as important as politics, at least in countries with large domestic supplies of coal, oil, and gas. The fossil fuel industry is probably the most powerful lobby in the United States and in most other major fossil fuel countries. The biggest obstacle to a strong global agreement on climate change remains the bargaining positions of the major fossil fuel countries: the United

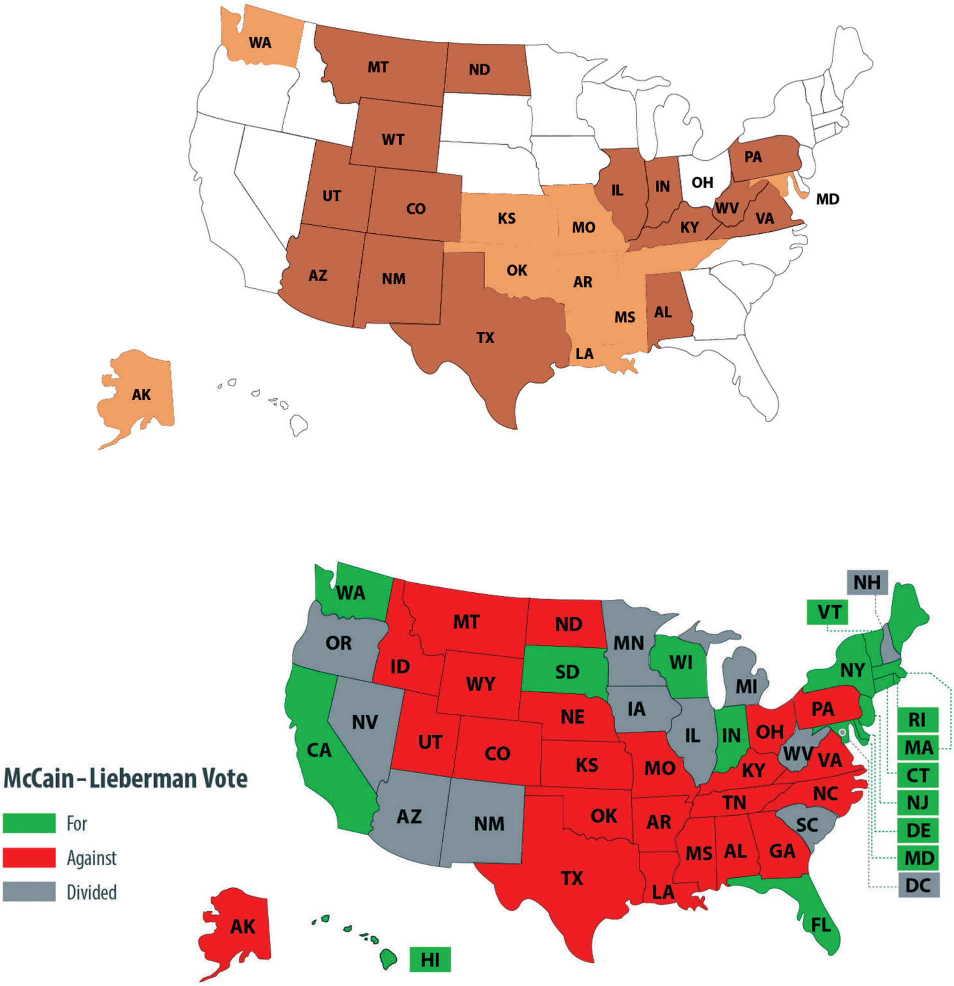
States, Canada, China, Russia, and the Persian Gulf economies. These positions, in turn, reflect mainly domestic political considerations.

Figure 12.30 shows two maps. The shaded areas in brown on the top map are states that produce coal, about half of the U.S. states. The bottom map shows in red the states where the senators voted against the Climate Stewardship Acts (also known as the McCain-Lieberman Acts), which would have introduced a cap-and-trade system for GHGs. It is an almost-perfect fit. Coal, oil, and gas interests finance the politicians in the "brown states" and have so far been able to maintain a veto on federal climate control legislation. This is the case all over the world, which makes it extremely difficult to make progress. Interestingly, many of the "green states" in the voting map have implemented state-level mitigation programs, such as California's decision to reduce CO_2 emissions by 80 percent by 2050.

The global politics of climate change have been largely stuck since 1992, when the world's governments adopted the UNFCCC at the Rio Earth Summit. It is a well-reasoned, well-balanced document that points the way forward on global mitigation. The main objective of the treaty is described clearly in article 2, which states that:

> the ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, *stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system* [emphasis added]. (UN 1992b)

This objective makes perfect sense and has been made more precise and operational in recent years by associating "dangerous anthropogenic interference" with a rise in the mean global temperature of 2°C. Yet since the UNFCCC went into effect in 1994 (upon ratification by enough countries), the world has failed to implement it properly. The treaty parties have met year after year, and have just finished the COP20 (Conference of the Parties, 20th session) in Lima in 2014. Yet the treaty has not even succeeded in slowing the year-to-year of increase of GHG emissions, much less forced the emissions curve to turn downward.



12.30 Coal producing states vs. Climate Stewardship Acts voting patterns

Source: U.S. Department of Energy & U.S. Senate.

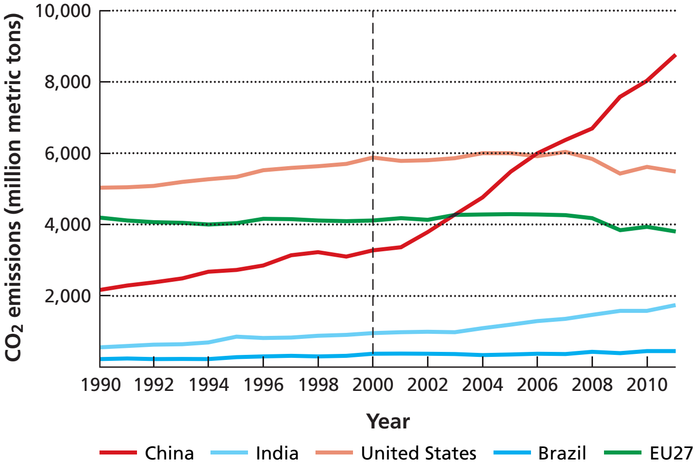
The first major attempt to implement the treaty came with the Kyoto Protocol, signed in 1997 (UN 1998). This was an agreement by the high-income countries to reduce their emissions by an average of 20 percent by 2012 compared with 1990. The developing countries, including the fast-growing emerging economies such as China, were not obligated to meet specific emissions targets. The treaty did not work. On the one hand, the United States never signed and Australia and Canada did not implement the treaty despite having signed it. (Notice the pattern of major fossil fuel–producing countries!) On the other hand, the emissions by China and other emerging economies soared, thereby keeping the global emissions levels on a steeply rising course.

Since 1992, the U.S. Senate (which must ratify all treaties) has been in the grips not only of the coal, oil, and gas lobbies but also of a perception that the United States should do nothing if China will not do as much or more. The U.S. rationale has held that it is "unfair" to expect the U.S. to act in advance of China, as that would leave China in an advantaged competitive position in world trade. This is an odd sense of "fairness," because the U.S. for decades has been changing the climate of the entire world without any sense of fairness about the huge costs it has imposed on the rest of the world. Though President Clinton's administration actually signed the Kyoto Protocol in 1997, the president never sent it to the Senate for ratification, as its defeat in the Senate was assured.

The UNFCCC actually assigns the initial mitigation responsibilities to the high-income countries (known as Annex I countries under the treaty). The high-income countries are assigned this responsibility for a few reasons: (1) they are better able to bear the extra costs of low-carbon energy; (2) they are disproportionately responsible for the rise in CO_2 in the past; and (3) the poorer countries need time and help to catch up with the richer countries. China has long insisted that the United States and Europe should lead the way and that it would follow some years later as its economy gained strength.

Since 1992, however, much has changed. China has now become the world's second-largest economy and has actually become by far the world's largest GHG emitter. Even though the Chinese economy is not as large as the United States, it emits far more CO_2 for three reasons: (1) it is less energy efficient (higher energy input per unit of GDP); (2) it relies more on coal, the most CO_2-intensive of all fossil fuels (higher CO_2 per unit of energy); and (3) it is more industrial, so that the economy has several large, energy-intensive sectors such as steel production. Indeed, one of the reasons that the United States and Europe emit less CO_2 than China is that they are net importers of energy-intensive products in their trade with China.

Still, twenty-two years after the UNFCCC was agreed upon, the global politics are shifting, and China is now being called upon by countries around the world to take up more global leadership on climate mitigation. China today is a far richer country than it was in 1992. It has had another two decades of very rapid economic growth. As just noted and shown in figure 12.31, China is now the world's largest GHG emitter, having overtaken the United States around 2007. China notes in its own "defense," however, that in per capita terms it still emits much less CO_2 than does the United States. The United States emits 17.6 tons of CO_2 per person, while China emits about 6.2 tons of CO_2 per person. Still, the Chinese leadership clearly acknowledges that China must do far more in order for the world to achieve the 2°C target.



12.31 Top absolute fossil fuel emitters: China becomes world's largest emitter

Source: The Policy Climate. 2013. San Francisco: Climate Policy Initiative.

There are internal pressures as well. For one thing, China itself is highly vulnerable to climate change. A significant part of China is already very dry and is likely to get drier as a result of climate change. China is highly vulnerable to extreme storms, extreme events, and massive flooding. China is deeply vulnerable to climate change and so has a real reason to participate in a global mitigation effort.

Heavy smog pollution is becoming more frequent in major Chinese cities. This smog arises from a mix of industrial pollution, heavy coal burning, and automobile congestion. Recent estimates suggest that some regions of northern China are losing as many as 5.5 years of life expectancy due to the heavy air pollution! Switching from coal to low-carbon or zero-carbon energy would therefore have two huge benefits for China: climate change mitigation and improved public health.

At the COP17 in 2011 in Durban, South Africa, the Parties to the UNFCCC agreed that they would reach a more definitive agreement on climate control by 2015, at which time all countries would take binding commitments to mitigate their GHG emissions. Unlike the Framework Convention, which put the responsibility for action on the rich countries as a start, the new agreement in principle is to put responsibility everywhere. This is, at least, conceptually a breakthrough, because there is now the potential for the United States, China, and other major emitters to agree on a new approach. This was understandably hailed as a breakthrough, though it of course must be put into perspective: the decision in Durban in 2011 was taken nineteen years after the UNFCCC was signed in 1992; to be negotiated twenty-three years later in 2015; ratified twenty-six years later in 2018; and enter into force twenty-eight years later in 2020. This is not exactly a world standing on the precipice and acting with due urgency!

In practical, problem-solving terms, each region of the world needs to implement a sensible, economically efficient, deep decarbonization program built on the three pillars of energy efficiency, low-carbon electricity, and fuel switching. It can be done, if the will is there. The world should also agree to joint programs of R&D on key low-carbon challenges, such as the effective storage of renewable intermittent energy and CCS. The world should also agree to help the poorest countries take on this challenge, for example, by helping central Africa build the Grand Inga Dam. In short, the world has climate solutions. What it lacks is the time for further delay.