# 8 Climate Change Mitigation Options

## OVERVIEW

Throughout the world, countries are adopting policies in an attempt to make progress against climate change. Common approaches include increasing renewable energy generation and encouraging energy efficiency. The positive effects of these are reducing dependence on petroleum, reducing our vulnerability to energy price spikes, promoting development of local economies, and improving air quality. Another major approach is addressing the $CO_2$ we have already generated and doing something about managing that. One answer currently available is carbon sequestration—the actual storing of $CO_2$ in designated repositories so that it can no longer add to the climate change problem. This chapter examines several other mitigation and management options being utilized today including cap and trade as a policy tool, how the carbon trading market works in an international arena, the need for global action, and possible economic implications. It also examines the carbon pricing rationale and compares it with the cap and trade approach. Next it looks at both direct and indirect carbon sequestration and storage and then examines both geologic formation and deep ocean sequestration. Following that, this chapter reviews the economic benefits of carbon storage and concludes by exploring the value and necessity of various global adaptation strategies.

## INTRODUCTION

As the earth's atmosphere continues to warm and more people become aware and educated about climate change—including its effects and ramifications for the future—efforts worldwide are being made to reduce its impacts, find ways to mitigate the situation, and adapt to the present environment, as well as prepare for the future. Every person on this earth will have to, in some way, adapt to the effects of climate change, focusing on ways to help solve the problem, reduce what impacts are possible, find ways to be environmentally responsible, and learn to cope in a positive way to permanent change. On a community, national, and international level, there are also adaptation and mitigation options available—some already successfully in operation, others just beginning, and still others on the horizon. The important thing is that we keep progressing and moving ahead; taking the action possible to minimize what impacts we can, prevent what we can, and adapt to the rest. In order to make that possible, our forward actions cannot pause.

## DEVELOPMENT

Climate change mitigation refers to efforts taken to reduce or prevent the emission of GHGs. Mitigation can mean several things. It can mean using new technologies and renewable energies, making older equipment more energy efficient, or changing the management practices or consumer behavior. It can be as complex as a plan for a new city, or as simple as an improvement to an air conditioner design—it is whatever enables less GHGs to be emitted. Worldwide, there are efforts being made to achieve these goals; from high-tech transportation systems, construction of urban and inner-city bicycle paths, to convenient recycling centers that serve communities and everything in between. Mitigation also includes protecting existing natural carbon sinks, such as oceans and forests, or creating new sinks through the development of green agriculture or silviculture. Any method of mitigation that is a good fit for a community and helps lower harmful GHG emissions into the atmosphere is a success.

### Climate Change Mitigation Options

Mitigation can apply to several general categories: agriculture, forest, energy, manufacturing, transportation, tourism, buildings, cities, and waste. We will discuss each one of these sectors in this section.

#### The Agricultural Sector

One of the biggest challenges to be faced with climate change is the adequate production of food. As the climate changes—temperatures warm, droughts occur, and land becomes degraded—areas that we have typically been able to rely on for food production are going to become stressed to the point that it will become difficult, if not impossible, to continue food production at our present level.

Current farming methods are depleting the earth's resources and producing huge quantities of GHGs. Agricultural operations currently produce 13 percent of human-based global GHG emissions (UNEP, 2016). This means that while current agricultural practices are engaging in unsustainable practices such as deforestation and promoting biodiversity loss in much of the world, the environment is paying a huge price there, as well as in contributing to the GHG problem. Conventional agriculture also has other harmful side effects, such as erosion, leeching chemicals into water sources, and lowering soil fertility, while the global economy pumps billions of U.S.

dollars into the effort. Turning toward sustainable agricultural methods makes sense from several angles. It will ease pressure on the environment, help cope with climate change, create opportunities to diversify economies, increase yields, reduce costs, generate jobs, reduce poverty, and increase food security. In fact, increasing farm yields and improving ecosystems services will greatly help the 2.6 billion people who make their livelihood from the agricultural industry—especially in developing nations where most farmers live on small parcels in rural areas.

One form of mitigation that would make a notable difference would be to simply reduce agricultural waste and inefficiency. Almost 50 percent of food produced is lost through crop loss or waste during storage, distribution, marketing, and household use. Some of these inefficiencies—most notable crop and storage losses—could be solved with an investment in simple storage technology, and buying locally.

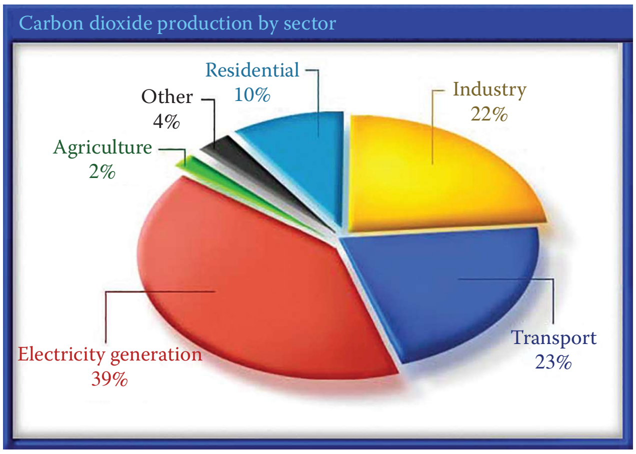


**FIGURE 8.1** $CO_2$ production by sector. (Courtesy of U.S. Energy Information Administration [EIA], Washington, DC.)

## The Forestry Sector

Forestry is an enormous industry—it supports the livelihoods of over 1 billion people. Most of these are in the developing countries of the world. Forestry is also species rich. More than half of all the earth's species live in forests. They play a valuable part in our lives for many reasons: they help regulate our climate through the carbon cycle (they are a $CO_2$ sink) and protect some of our purest watersheds. Unfortunately, approximately 13 million hectares is destroyed, deforested, or degraded every year. It is estimated that if $40 billion per year from 2010 to 2050 was invested in reforestation and payment to landholders for conservation, it could raise the value of the forest industry by 20 percent, and at the same time increase forest carbon storage by 28 percent. Creating a stable global market that would attract investment in forest-derived goods and assure their equitable and sustainable production could possibly offer one of the best possibilities for establishing a workable plan. In order for this to work, it would be necessary to create financial value for forest carbon storage. Adding value for conservation measures, forest management, and enhancing forest stocks would make it even more attractive (UNEP, 2016).

## The Energy Sector

One of the most rapidly expanding sectors is energy. As populations continue to grow and societies continue to develop, there is an ever-increasing demand for energy. Unfortunately, this sector is the most difficult to curtail because it is such a fundamental part of our lives. Energy is needed in everything we do, as shown in Figure 8.1. As we continue to indulge in the use of fossil fuels, we not only have to take responsibility for the GHGs we are adding to the atmosphere at a furious rate but we also have to deal with other significant issues as well, such as energy security, air pollution, and environmental degradation. The current fossil fuel-heavy energy system we use is not only environmentally unsustainable but also highly inequitable, leaving approximately 1.4 billion people without access to electricity (UNEP, 2016). Added to this, much of the growing energy demand is occurring in developing countries, where rising fossil fuel prices and resource constraints are adding further pressure on both the environment and the economy.

Because of these downfalls, mitigation is becoming critical. Investing in renewable energy sources is where the future of energy must go. The good news is that technology is rapidly advancing and it is becoming affordable for both businesses and private consumers to invest in it as a primary energy source. In 2015, renewable energy sources accounted for about 10 percent of total U.S. energy consumption and about 13 percent of electricity generation (U.S. Energy Information Administration, 2016). The changes and growth of renewable energy sources and use from 2001 to 2013 are shown in Figure 8.2.

With the government rebates being offered for solar panels, many homeowners are investing in solar power. It is projected that by the end of 2016, more than 1 million American homes will have solar panels. In 2006, only about 30,000 homes had solar panels. At that time, the cost was $9 per watt of power generated by solar panels. Today, the cost has been reduced to $3.79 per watt (Harrington, 2015). Solar panels have also increased in efficiency. American homes are now able to meet more than 85 percent of their electricity demand (EnergySage Solar Research, 2015). Chief Executive and Founder of EnergySage Solar Marketplace says "People love solar; there's very little not to like about it. No noise, no emissions, out of sight, produces electricity, it's beautiful, and it makes financial sense. I think as more people find out about it and more people become comfortable shopping for solar, and they don't feel like they're being sold but they have control, I think the sky's the limit."

As more people become aware of the climate change issue and realize the negative effects happening right now, as we saw in the previous chapter, the incentive to invest in renewable energy will continue to grow, at all levels: government, business, and in the private sectors. This is the best mitigation option available.

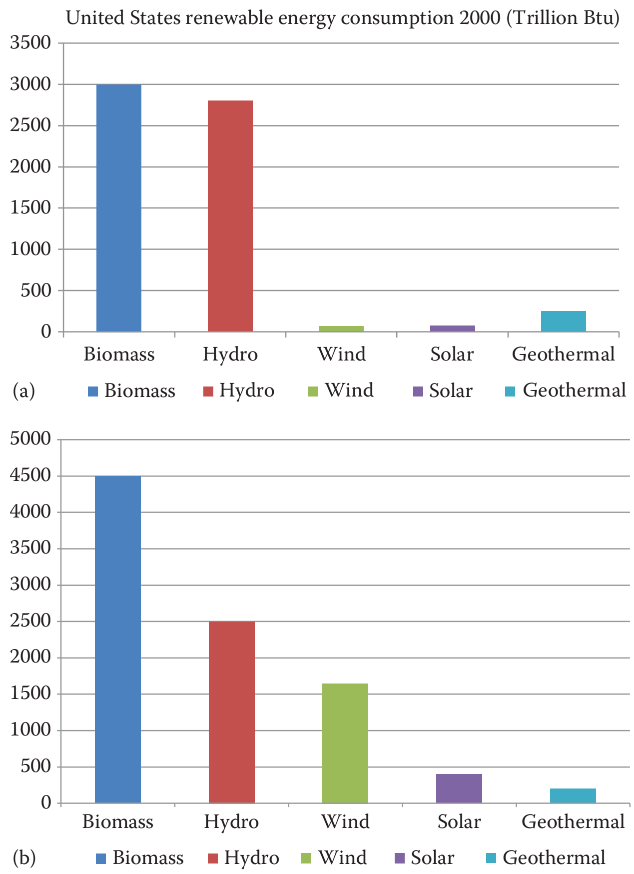


**FIGURE 8.2** (a) U.S. renewable energy use by sector in 2001. (b) U.S. renewable energy use by sector in 2013. (Created by author.)

## The Manufacturing Sector

Manufacturing is responsible for 35 percent of global electricity use, 20 percent of $CO_2$ emissions, and one-fourth of primary resource extraction. It has a major impact on the environment and plays a significant role in climate change. Simultaneously, manufacturing accounts for 23 percent of worldwide employment makes it a crucial sector of the worldwide economy. Therefore, its importance cannot be ignored; instead, a healthy and workable solution must be found to mitigate the climate change problem. The best way to approach this is to change the manufacturing process. In some cases, it may be possible to re-design a product, which may improve not only the product's life span but also lead to a more efficient use of resources, easier recycling, and the generation of less pollution during the manufacturing process and life of the product. As an example, two innovations that can save both resources and money are recycling heat waste and closed-cycle manufacturing. Also viable approaches are remanufacturing and reconditioning. Both are labor-intensive approaches, which can serve to create jobs and also require relatively little capital investment.

## The Transportation Sector

The transportation sector is one of the largest challenges being faced today concerning $CO_2$ emissions, especially in developed countries. Not only is it a problem for emissions but also it is hazardous for human health and well-being and the environment in general. Transportation uses more than half of the earth's liquid fossil fuels and is responsible for nearly one-fourth of energy-related GHG emissions. It is responsible for widespread air pollution, over a million fatal traffic accidents per year, and needless traffic congestion—impacts that costs countries more than 10 percent of the gross domestic product.

Already a problem in developed countries—such as the United States, which has its transportation system geared toward motor vehicle traffic rather than mass transit due to the vast size of the country—but its use in developing countries is increasing at an alarming rate, as well. This includes countries such as China, India, and Russia. It is increasing so rapidly, that current projections estimate that the number of motor vehicles will triple by 2050. Studies conducted by the United Nations Environmental Programme (UNEP) show that investments in public transportation and vehicle efficiency could yield exceptional economic returns. They have determined that a green, low-carbon transportation sector could reduce GHG emissions by as much as 70 percent, with minimal additional investment. Furthermore, if sustainable regulatory policies are added to that, it could be improved further (UNEP, 2016). UNEP outlines that for this transformation to happen, there needs to be a major shift in the way the public thinks about investing in transportation. They proposed what they call a "three-pronged strategy: Avoid—Shift—Clean." It is defined as follows: Help users *avoid* or reduce trips—without restricting mobility—through smarter city planning and land use options. *Shift* passengers away from private vehicles to public and nonmotorized transportation, and freight users from trucks to rail or water transport. Finally, make vehicles cleaner, through both efficiency improvements and cleaner fuels. UNEP is currently working toward this paradigm shift through several initiatives and programs.

## The Tourism Sector

This may not be a sector that people often think of, but tourism can be fossil-fuel intensive. Tourism is one of the top five export earners in 150 countries, and the number one export in 60. This may seem like welcome news for national economies, but if not properly managed it can be unwelcome news for the environment and local populations. Tourists are traveling more often and to more distant destinations, using more energy-intensive, fossil fuel-based transport, and the sector's GHG contribution has increased to 5 percent of global emissions. Other unsustainable practices, such as excessive water use, waste generation, and habitat encroachment, are threatening ecosystems, biodiversity, and local culture.

If done with sustainability in mind, however, tourism can be a positive endeavor for both the local economy and the environment. Green tourism aims to reduce poverty by creating local jobs and stimulating local business, while establishing ecologically sustainable practices that preserve resources and reduce pollution. One drawback today is that far too little tourism profits reach the people living in and near tourist destinations. By increasing local involvement, it can not only generate income but also encourage communities to protect their environment. Investing in energy efficiency and waste management can reduce GHG emissions and pollution and also save hotel owners and service providers' money. If it is done right, natural areas, biodiversity, and cultural heritage can all receive the direct benefits of sustainable tourism.

### The Building Sector

Roughly one-third of the world's energy use takes place inside buildings. This makes the building sector one of the largest contributors to GHG emissions. In addition, the construction industry consumes more than one-third of the earth's natural resources and generates huge quantities of solid waste. This puts buildings and all that which is associated with it in line for mitigation, especially the acquisition of natural resources that are used in the industry.

If energy efficiency is improved in buildings through greener construction methods and retrofitting existing structures, it can make a huge difference in reducing GHG emissions. In addition, many of these improvements can be completed at a low cost, utilizing existing technology. Green construction can also have a positive effect on productivity, public health, and employment opportunities. According to estimates, every $1 million invested could result in 10 to 14 jobs (UNEP, 2016).

Cities present many opportunities for mitigation, and it is critical that they do. They are developing rapidly, especially in developing countries. Urban areas are now home to nearly half of the earth's population, which use approximately 60 percent of available energy and account for more than half of the carbon emissions. Other side effects include a heavy impact on water supplies, stresses on public health, environmental impacts, and pressures on the quality of life—especially for the poor. With continued growth, fundamental changes in urban development will have to occur in order to create a sustainable future.

Because of the density of urban areas, they are in a prime position to enable a strong collaboration between local governments, private partnerships between businesses, and academia, who together can work toward building a more sustainable society. With the right policies, practices, and infrastructures in place, cities can become green models for efficient transportation, water treatment, construction, and responsible resource utilization.

### The Waste Management Sector

Another key area that must become more sustainable is waste management. As countries' economies grow, so does the volume of their garbage. According to recent estimates, approximately 11.2 billion metric tons of solid waste are currently being collected around the world every year, and the decay of the organic portion is contributing around 5 percent of global GHG emissions (UNEP, 2016). The most rapidly growing type of waste in both developing and developed countries is electrical and electronic products, which contain hazardous substances that make disposal a challenge. Human health and the environment are becoming increasingly at risk, especially when dumpsites are uncontrolled or volume becomes unmanageable. Some of the major impacts include illnesses and infections, ground water pollution, GHG emission, and ecosystem destruction.

In order to mitigate this problem, it is possible to turn it into an economic opportunity instead. Managing waste, from collection to recycling, is currently a growing market estimated at $410 billion per year, not including the substantial informal segment in developing countries. Recycling, in fact, actually creates more jobs than it replaces. Investing in this greener style of waste management could produce many environmental and economic benefits for those who choose to get involved. Benefits include resource savings, nature protection, along with employment and business opportunities. It is also important to remember that the best way to manage waste is to produce less of it. Minimizing waste is the first step toward green living. The ultimate goal to keep in mind is to produce as little waste as possible, recycle, or remanufacture as much as possible, and treat any unavoidable waste in a manner that is the least harmful to the environment and humans.

## TEN EASY SOLUTIONS TO KEEP CLIMATE CHANGE AT BAY

Scientific American recommends the following easy steps that everyone can follow to keep the negative effects of a changing climate from wreaking havoc on our environment:

1. *Forego fossil fuels*: Eliminate the burning of coal, oil and, eventually, natural gas. Definitely an enormous challenge, there are alternatives that can be used when possible, such as commodities like plant-derived plastics, biodiesel, and wind and solar power.
2. *Infrastructure upgrade*: Investing in new infrastructure or drastically upgrading existing highways and transmission lines would help cut greenhouse gas emissions and help promote economic growth in developing countries. Using energy-efficient buildings and improved cement-making processes is important to include in this process to keep GHG at a lower level.
3. *Move closer to work*: In the United States, transportation is the second leading source of GHG emissions. For example, burning one gallon of gasoline produces 20 pounds of $CO_2$. This input of GHGs into the atmosphere could be heavily curtailed, however, if people moved closer to their place of employment, used mass transit, or switched to walking, cycling, or using some other type of transportation that did not require anything other than human energy. Other

considerations include teleworking (working from home) several days a week.

4. *Consume less*: The most obvious way to cut back on GHG emissions is to buy less stuff. This can be not using a car to relying on reusable grocery bags to buying less to buying local. One idea is to think purchasing green products—buying products that will have the least impact on the environment. For instance, when purchasing a car, look at a hybrid. Or when grocery shopping, buy in bulk so that you buy the product where less packaging material was used.
5. *Be efficient*: This is the idea of "doing more with less." When driving, make sure your car is well-maintained, your tires are properly inflated, and you do not speed (this can limit the amount of GHG emissions from a vehicle). Buy energy efficient appliances, such as Energy Star certified items. When you are home, turn the lights off when you are not in the room. Most of this is just common sense—you just need to be aware of it.
6. *Eat smart*: Much of the agriculture in the United States requires barrels of oil for the fertilizer to grow it and diesel fuel to harvest and transport it. Some grocery stores that stock organic produce that do not require fertilizer is still shipped from far away, so it still contributed GHGs due to the transportation part of the process. Buying local at farmers markets not only helps the local economy but also eliminates the GHGs that would have been added to the atmosphere if it had been transported a longer distance. Meat requires pounds of feed to produce just a single pound of protein. The problem with food from the grocery store is that there is no way to know for sure how far it has had to travel to get to its endpoint. University of Chicago researchers have estimated that each meat-eating American produces 1.5 tons more GHGs through their food choice than do vegetarians. In addition, it takes less land to grow crops that it does to raise animals.
7. *Stop cutting down trees*: Each year, 13 million hectares of forests are cut down. In the tropics alone, 1.5 billion metric tons of carbon are added to the atmosphere. Roughly 20 percent of human-caused GHG emissions come from this source, which could be avoided. If agricultural practices were improved, more people recycled paper, and better forest management practices were implemented (balancing the amount of wood harvested with trees being planted), it would offset this emission. To also help in this area, try to purchase and refurbish used goods or if buying new, make sure the wood is certified to have been sustainably harvested.
8. *Unplug*: It is a fact that U.S. citizens spend more money on electricity to power devices when off than when on. Televisions, computers, and so forth actually consume more energy when in sleeping mode or "switched off," so it is just better to completely unplug them. Just as a comparison, 1 billion kilowatt-hours of electricity ($100 million at current electricity prices) is the equivalent of the release of more than one million metric tons of greenhouse gases.
9. *One child*: There are at least 7.4 billion people living today. The United Nations predicts it will be at least 9 billion by 2050. UNEP currently estimates that it takes 22 hectares to sustain each person today. This includes food, clothing, and other resources. Projecting that to future populations, this is unsustainable.
10. *Future fuels*: Probably the greatest challenge of this century will be replacing fossil fuels with something else. Current ideas include ethanol derived from crops or hydrogen electrolyzed out of water, but they all have their own drawbacks and none is immediately available on a global scale.

These are just a starting point of ideas. The good thing about science is that it is innovative, creative, and new ideas come up often from creative minds. With everyone working together, it is possible to lower all of our collective GHG emissions.

(*Source: Biello, 2007*)

## Economics of Mitigation

Several models have been developed that attempt to reasonably calculate the expected costs of climate mitigation. Unfortunately, there is simply not an easy, one-size-fits-all answer for that. The latest analysis provided by the fifth IPCC Assessment on Mitigation of Climate Change puts it at 0.06 percent a year of global GDP growth. Others have put it slightly higher, others slightly lower. The problem is, there are so many variables involved and circumstances vary for place to place, making it a very hard number to hone in on. Besides that, models are predicting all the way through the year 2100, and it is nearly impossible to predict anything that far out. So, let us look at what we do know, perhaps a bit more realistically.

The models that climate economists use are called integrated assessment models (IAMs). They integrate models of energy markets and land use with GHG projections. They attempt to look at all the relevant factors but do come under some criticism because they can have inherent weaknesses, such as overstating costs of climate mitigation or understating the need for action, as discussed in a study of economic models by economists Richard Rosen and Edeltraud Guenther (Rosen and Guenther, 2015). What the climate models are good for, however, are for determining the effects of marginal changes in one or a small set of economic variables. These models can be used when isolating specific variables and looking at just them for shorter periods of time. The concept of being able to predict costs for time periods of 50–100 years into the future is not considered realistic, however, as too much can happen during that time period, changing the scenario. For example, if an oil crisis or a financial crisis were to occur that was not initially figured into the model it would disrupt the projections and the model would fail if it was not recalibrated (assuming the crisis had not been predicted). If a significant weather event were to occur, that would require that the model also be recalibrated to a new baseline, and so forth. Otherwise, the model is left to operate in a state of instability, eventually failing or giving false results.

Based on logic and the chance of random events occurring, Rosen and Guenther, when asked about whether or not it mattered if 100-year models could be reliably produced, candidly remarked "No, because humanity would be wise to mitigate climate change as quickly as possible without being constrained by existing economic systems and institutions, or risk making the world uninhabitable. This conclusion is clear from a strictly physical and ecological perspective, independent of previously projected economic trade-offs over the long run, and it is well-documented in the climate change literature. As climate scientists constantly remind us, even if the world successfully implemented a substantial mitigation program today, a much warmer world is already built into the physical climate system. And since we can never know what the cost of a hypothetical reference case would be, and since we must proceed with a robust mitigation scenario, we will never be able to determine the net economic benefits of mitigating climate change, *even in hindsight*."

Perhaps that is the most sound, straight-forward advice of all: taking action now. Projecting so far into the future may fall under the guise of "planning" ahead, but better served is the near future and what we can do now to make a difference. That said, looking more near term, the following is what the IPCC did have to say in their 2014 report on Mitigation of Climate Change as far as projections on where they foresee the direction countries need to be headed in mitigation efforts right now to get us headed down that 100-year road (Kille, 2014):

- Reducing carbon emissions from electrical generation is one of the most cost-effective ways to slow climate change. Plans include moving to low-carbon electricity supplies of up to 80 percent by 2050.
- The EPA proposed its "power plant rules" in June 2014, which are designed to accelerate the shift to natural gas and provide incentives to encourage the deployment of industrial-scale carbon capture and storage for coal-fired plants.
- Wind and other renewables have continued to grow rapidly and per-kilowatt prices are falling to near-parity with fossil fuels. States currently play a central role in the growth of renewables, especially wind and solar, and there are currently a wide range of incentives in place.
- Over the next 20 years, annual investments in renewables, nuclear, and electricity generation with carbon capture and storage are projected to rise by $147 billion, while those for fossil-fuel electrical generation capacity will decline by about $30 billion. (While the relative changes are significant, the average annual investment in energy systems is $1.2 trillion.)

Table 8.1 lists mitigation options suggested by the IPCC in their Fourth Assessment Report (IPCC, 2007).

## Cap and Trade

Cap and trade is the most environmentally and economically realistic approach to controlling GHG emissions. The "cap" sets a limit on emissions, which is lowered over time to reduce the amount of pollutants released into the atmosphere. The "trade" creates a market for carbon allowances, helping companies innovate in order to meet, or come in under, their allocated limit. The less they emit, the less they pay, so it is in their best interest by being an economic incentive to pollute less.

The cap is seen as the only real way to limit pollution. It sets a maximum allowable level of pollution and then penalizes companies that exceed their emission allowance. No other system can guarantee to lower emissions. There are various advantages to having a cap. They are as follows:

- *The cap acts as a limit*: It limits the amount of pollution that can be released. It is measured in billions of tons of carbon dioxide (or equivalent) per year. It is set based on science.
- *The cap covers all major sources of pollution*: The cap limits emissions economy-wide, covering electric power generation, natural gas, transportation, and large manufacturers.
- *Emitters can release only limited pollution*: Permits or "allowances" are distributed or auctioned to polluting entities—one allowance per ton of carbon dioxide, or $CO_2$ equivalent heat-trapping gases. The total amount of allowances will be equal to the cap. A company or utility may only emit as much carbon as it has allowances for.
- *Industry can plan ahead*: Each year, the cap is ratcheted down on a gradual and predictable schedule. Companies can plan well in advance to be allowed fewer and fewer permits—less global warming pollution—each year.

The trading portion of the plan is what leads to investment and innovation. Some companies find it fairly simple to reduce their pollution to match their number of permits, while others find it more difficult. Trading lets companies buy and sell allowances, leading to more cost-effective pollution cuts, as well

**TABLE 8.1**
**Mitigation Options**

| Sector | Key Mitigation Technologies and Practices Currently Commercially Available. *Key mitigation technologies and practices projected to be commercialized before 2030 shown in italics* | Policies, Measures, and Instruments Shown to be Environmentally Effective | Key Constraints and Opportunities to Implementation (Normal font = constraints; *italics = opportunities*) |
|---|---|---|---|
| **Energy supply** | Improved supply and distribution efficiency; fuel switching from coal to gas; nuclear power; renewable heat and power (hydropower, solar, wind, geothermal and bioenergy); combined heat and power; early applications of carbon dioxide capture and storage (CCS); *CCS for gas, biomass and coal-fired electricity generating facilities; advanced nuclear power; advanced renewable energy, including tidal and wave energy, concentrating solar, and solar photovoltaics* | Reduction of fossil fuel subsidies; taxes or carbon charges on fossil fuels<br>Feed-in tariffs for renewable energy technologies; renewable energy obligations; producer subsidies | Resistance by vested interests may make them difficult to implement<br>*May be appropriate to create markets for low-emissions technologies* |
| **Transportation** | More fuel-efficient vehicles; hybrid vehicles; cleaner diesel vehicles; biofuels; modal shifts from road transport to rail and public transport systems; nonmotorized transport (cycling, walking); land-use and transport planning; *second generation biofuels; higher efficiency aircraft; advanced electric and hybrid vehicles with more powerful and reliable batteries* | Mandatory fuel economy; biofuel blending and $CO_2$ standards for road transport<br>Taxes on vehicle purchase, registration, use and motor fuels; road and parking pricing<br>Influence mobility needs through land-use regulations and infrastructure planning; investment in attractive public transport facilities and nonmotorized forms of transport | Partial coverage of vehicle fleet may limit effectiveness<br>Effectiveness may drop with higher incomes<br>*Particularly appropriate for countries that are building up their transportation systems* |
| **Buildings** | Efficient lighting and daylighting; more efficient electrical appliances and heating and cooling devices; improved cook stoves, improved insulation; passive and active solar design for heating and cooling; alternative refrigeration fluids, recovery and recycling of fluorinated gases; *integrated design of commercial buildings including technologies, such as intelligent meters that provide feedback and control; solar photovoltaics integrated in buildings* | Appliance standards and labeling<br>Building codes and certification<br>Demand-site management programs<br>Public sector leadership programs, including procurement<br>Incentives for energy service companies | Periodic revision of standards needed<br>Attractive for new buildings. Enforcement can be difficult<br>Need for regulations so that utilities may profit<br>*Government purchasing can expand demand for energy-efficient products*<br>*Success factor: Access to third party financing* |
| **Industry** | More efficient end-use electrical equipment, heat and power recovery; material recycling and substitution; control of non-$CO_2$ gas emissions; and a wide array of process-specific technologies; *advanced energy efficiency; CCS for cement, ammonia, and iron manufacture; inert electrodes for aluminum manufacture* | Provision of benchmark information; performance standards; subsidies; tax credits<br>Tradable permits<br>Voluntary agreements | May be appropriate to stimulate technology uptake. Stability of national policy important in view of international competitiveness<br>Predictable allocation mechanisms and stable price signals important for investments<br>Success factors include: clear targets, a baseline scenario, third-party involvement in design and review and formal provisions of monitoring, close cooperation between government and industry |
| **Agriculture** | Improved crop and grazing land management to increase soil carbon storage; restoration of cultivated peaty soils and degraded lands; improved rice cultivation techniques and livestock and manure management to reduce $CH_4$ emissions; improved nitrogen fertilizer application techniques to reduce $N_2O$ emissions; dedicated energy crops to replace fossil fuel use; improved energy efficiency, *improvements of crop yields* | Financial incentives and regulations for improved land management; maintaining soil carbon content; efficient use of fertilizers and irrigation | *May encourage synergy with sustainable development and with reducing vulnerability to climate change, thereby overcoming barriers to implementation* |

(*Continued*)

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| Sector | Key Mitigation Technologies and Practices Currently Commercially Available. *Key mitigation technologies and practices projected to be commercialized before 2030 shown in italics* | Policies, Measures, and Instruments Shown to be Environmentally Effective | Key Constraints and Opportunities to Implementation (Normal font = constraints; *italics = opportunities*) |
|---|---|---|---|
| **Forestry/ forests** | Afforestation; reforestation; forest management; reduced deforestation; harvested wood product management; use of forestry products for bioenergy to replace fossil fuel use; *tree species improvement to increase biomass productivity and carbon sequestration; improved remote sensing technologies for analysis of vegetation/soil carbon sequestration potential and mapping land-use change* | Financial incentives (national and international) to increase forest area, to reduce deforestation and to maintain and manage forests; land-use regulation and enforcement | Constraints include lack of investment capital and land tenure issues. *Can help poverty alleviation* |
| **Waste** | Landfill $CH_4$ recovery; waste incineration with energy recovery; composting of organic waste; controlled wastewater treatment; recycling and waste minimization; *biocovers and biofilters to optimize $CH_4$ oxidation* | Financial incentives for improved waste and wastewater management<br>Renewable energy incentives or obligations<br>Waste management regulations | *May stimulate technology diffusion*<br>Local availability of low-cost fuel<br>Most effectively applied at national level with enforcement strategies |

*Source:* IPCC, Fourth Assessment Report.

as incentives to invest in cleaner technology. Companies also have the flexibility to trade with companies anywhere because all carbon dioxide goes into the upper atmosphere and has a global effect. Therefore, it does not matter whether the factory making the emission cuts is in Los Angeles, New York, Paris, or Singapore—it reduces global emissions. Companies that participate in the cap and trade program see several advantages to it. Some of them include:

- Companies can turn pollution cuts into revenue. If a company is able to cut its pollution easily and cheaply, it can end up with extra allowances. It can then sell its extra allowances to other companies. This provides a powerful incentive for creativity, energy conservation, and investment.
- The option to buy allowances gives companies more flexibility. Conversely, some companies might have trouble reducing their emissions, or want to make longer-term investments instead of quick changes. Trading allowances gives these companies another option for how to meet each year's cap.
- The same amount of pollution cuts is achieved. While companies may exchange allowances with each other, the total number of allowances remains the same and the hard limit on pollution is still met every year. The goal is achieved through teamwork and cooperation.

The international trade in carbon credits is intended to promote investment in energy efficiency, renewable energy, and other ways of reducing emissions. In the majority of developed, industrialized countries, GHG-emitting companies have taken on the responsibility of running, regulating, and facilitating the trade of carbon credits in the carbon market.

## The Economics of Cap and Trade

Nat Keohane, PhD, newest member of the U.S. National Economic Council as of January 2011, serving as advisor on environmental and energy policy to President Obama, states that aggressive cap and trade is not only affordable but also critical to both the earth and humanity's future. The cost to the economy will be minimal—for example, it is estimated to be less than 1 percent of the U.S. GDP in 2030. Keohane also stresses that the longer action is delayed the more expensive it will be to make emission cuts. In addition, the more time that passes without addressing the issues, the more irreversible damage will be done by climate change. Through the use of economic models, Dr. Keohane determined that by continuing with a business as usual approach, the U.S. economy would reach $26 trillion by January 2030. With a cap on GHG emissions, however, the economy will reach the same level only 2–7 months later. Therefore, the impact on the economy would not be significant—"just pennies a day," according to Dr. Keohane (EDF, 2009).

He also stresses that total job loss would be minimal (the manufacturing sector would experience some impact), and the new carbon market would create a multitude of new jobs. Households will be most affected by energy costs, but even there the increase would be modest. Overall costs would be small enough to allow programs to be developed that would take any burden off low-income households.

Dr. Keohane believes that cap and trade is the best means to fight climate change because it not only gives each company the ability to choose how to cut their emissions, it gives the economy the most flexibility to reduce pollution in the most cost-effective way. He also says it turns market failure into market success: "Global warming is a classic example of what economists term 'market failure.'" GHG emissions have skyrocketed because their hidden costs are not factored into business decisions—factories and power plants pay for fuel but not for the pollution they cause. Putting a dollar value on the pollution fixes that failure and gives industry incentive to pollute less" (Keohane and Goldmark, 2008).

He also says it taps American ingenuity and that history clearly shows that Americans can overcome steep challenges. In two short years during World War II, for example, Americans redirected much of the U.S. economy. Manufacturers produced different goods against tight deadlines. Detroit converted car factories to munitions production. Fireworks factories made military explosives. A. C. Gilbert, a maker of model train engines, produced airborne navigational instruments. Therefore, based on past performance, given the right incentives, the United States can transform the way energy is made as well.

He also cautioned that we must act immediately, or costs and risks will rise. The longer we wait to curb pollution, the steeper the cuts must be to avoid catastrophic climate change. Time is required to develop new technologies and build infrastructure. Plus, developing countries like China and India are waiting for the United States to act before they take action. Because of these reasons, there is very little time remaining to cap GHG emissions before a large risk of climate catastrophe and heavy economic costs are incurred. But if action is taken now, it can be successfully done—affordably.

## Carbon Pricing

Carbon pricing is a market-based strategy for lowering global warming emissions. The aim is to put a price on carbon emissions—an actual monetary value—so that the costs of climate impacts and the opportunities for low-carbon energy options are better reflected in our production and consumption choices. Carbon pricing programs can be implemented through legislative or regulatory action at the local, state, or national level.

What is important to note is that in most cases, the real costs of climate change impacts today—such as the growing costs of wildfires (the loss of lives, property, habitat, and resources); public health and the damaging costs of heat waves (heat stroke, death, damage to power systems, and crop failure); the costs of catastrophic weather events (flooding, heavy downpours, hurricanes, and droughts)—are all currently borne by taxpayers, insurance companies, and the individuals who are directly affected. What is not happening, is that those who play a key part and hold an important stake in the environmental responsibility are not being held accountable, and that is the producers and consumers of the carbon-intensive goods that are causing the GHG emissions. While many do not stop to think about it like that, it is the producers and consumers of the products that are contributing to the climate change situation, yet the victims of the impacts are bearing the costs.

Putting a price on carbon helps to incorporate climate risks into the cost of doing business. Emitting carbon becomes more expensive, and consumers and producers seek ways to use technologies and products that generate less of it. The market then operates on an efficient means to cut emissions, which is geared to encourage a shift to a clean energy economy and move innovation toward low-carbon technologies. Along with this, complementary renewable energy and energy efficiency policies are also critical to cost-effectively drive down emissions.

Carbon pricing is considered to be a powerful, efficient, and flexible tool for helping address climate change. It is supported by experts, businesses, policymakers, various civil groups, investors, states, and several countries. In fact, carbon pricing programs are already in use in many states and countries, such as California, the Regional Greenhouse Gas Initiative States (a cooperative effort among Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New York, Rhode Island, and Vermont) to reduce $CO_2$ emissions from the power sector, and Europe (EU emissions trading system).

There are two basic approaches to putting a price on carbon: one is the *cap-and-trade program*, the other is with a *carbon tax*. The cap-and-trade has already been discussed. With a carbon tax, laws or regulations are enacted that establish a fee per ton of carbon emissions from a sector or the whole economy. Owners of emission sources that are subject to the tax would have an incentive to lower their emissions, by transitioning to cleaner energy and using energy more efficiently. A rising carbon tax helps ensure a decline in emissions over time. Figure 8.3 shows the areas worldwide that participate in carbon pricing.

There are also *hybrid approach* options. These include programs that limit carbon emissions but set bounds on how much the price can vary in order to keep them within a specified range. Other approaches could include tailoring the tax to meet specific emission reduction goals, or creating a hybrid model for an area where some participants might pay a carbon tax and others might operate under a cap-and-trade arrangement. Still, others might have a cross between a cap-and-trade and renewable electricity. These arrangements can be as flexible and innovative as needed to meet the end goal. On another level, gasoline taxes, severance taxes for coal mining and natural gas or oil drilling are yet other ways of indirectly factoring a price on carbon into consumer or business decisions, with the end goal of ultimately cutting GHG emissions.

## Carbon Sequestration and Storage

In a computer model developed by Scott Doney of the Woods Hole Oceanographic Institution (WHOI), it indicates that the land and oceans will absorb less carbon in the future if current trends of emissions continue, which could mean significant shifts in the climate system. According to Doney, "Time is of

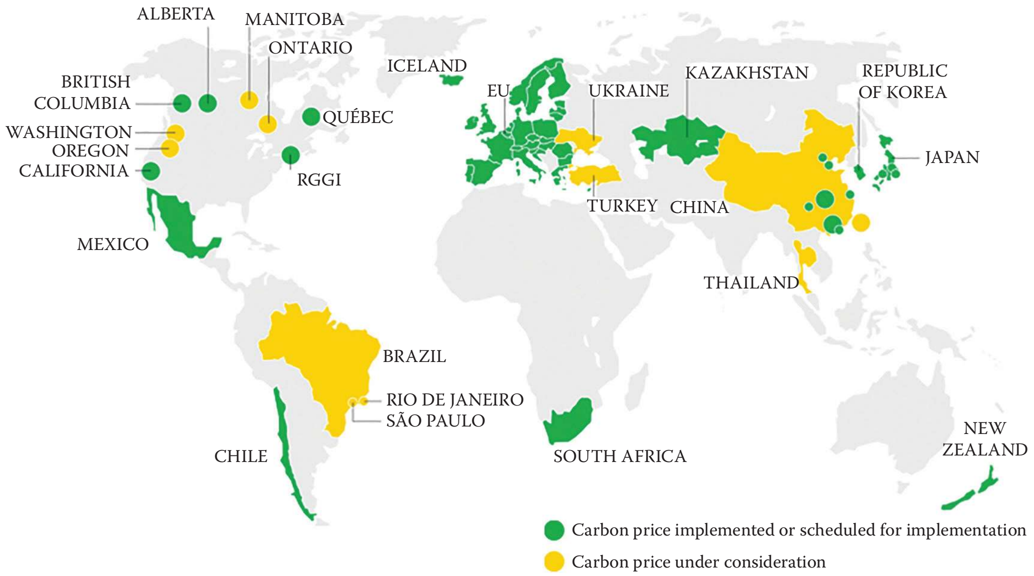


**FIGURE 8.3** Carbon pricing worldwide. Thirty-nine countries and 23 subnational jurisdictions have some form of carbon pricing in place, covering 12 percent of all greenhouse gas emissions. (Courtesy of World Bank, Washington, DC.)

the essence in dealing with greenhouse gas emissions. We can start now or we can wait 50 years, but in 50 years we will be committed to significant rapid climate change, having missed our best opportunity for remediation." He also stressed that the Earth's ability to store carbon in its natural reservoirs is inversely related to the rate at which carbon is added to the atmosphere. In other words, as soon as humans cut GHG emissions, the easier it will be for the Earth to naturally store carbon. He stresses that the study suggests that land and oceans can absorb carbon at a certain rate, but at some point they may not be able to keep up (ScienceDaily, 2010). Therefore, because of all the excess GHG that we are pumping into the atmosphere at a furious rate, we can no longer rely on natural mechanisms to solve the problem. One possible solution is to store the excess $CO_2$ somewhere—a process known as carbon sequestration (or capture).

Carbon sequestration is a geoengineering technique focused on mitigating climate change by finding methods to store $CO_2$ or other forms of carbon released from fossil fuel combustion. It is one method designed to slow the atmospheric and marine accumulation of GHGs. It is not a way to cut back the production of GHGs, it is a way to store those already emitted. There are two basic categories: indirect and direct sequestration. Indirect sequestration does not require human-controlled manipulation of $CO_2$. Instead, it is accomplished through natural processes, such as the uptake of $CO_2$ by living organisms—such as photosynthesis. Direct sequestration is an active process, which is the deliberate human-controlled separation and capture of $CO_2$ from other by-products of combustion. It is then transferred to some nonatmospheric reservoir for permanent (or semi-permanent) storage.

## Indirect Sequestration

Currently, the primary means of indirect sequestration is through the growth of forests. The least expensive method, it is limited of course by the amount of the Earth's land held in forests. In this setting, the plants accumulate $CO_2$ naturally. This type of sequestration is actually lowering every year due to accelerating rates of deforestation. As more land is destroyed, less land remains forested, resulting in less land holding $CO_2$ in natural reservoirs. Not only does this deforested land no longer store $CO_2$, but as forests are burned during the deforestation process, the $CO_2$ that has been stored long-term is also released to the atmosphere.

Photosynthesis is the core process of indirect sequestration. This is what converts airborne $CO_2$ along with water into energy that is stored in plant tissue as glucose ($C_6H_{12}O_6$) or other compounds for later use. Oxygen is released from the plant as a by-product. We are producing roughly 9 Gt of $CO_2$ annually. Annual rates of sequestering in a growing forest could be as high as 1–3 kg $CO_2/m^2$. Therefore, more than 400 million hectares of growing forest would need to be added annually in order to accomplish this. Unfortunately, deforestation continues. On the brighter side, however, world deforestation has slowed down as more forests are becoming better managed and lands are being put under protection (FAO, 2015).

There are several advantages of indirect sequestration. They include:

- They are a relative low-cost alternative.
- Forests can prevent flooding and reduce topsoil runoff in some regions, thereby preventing soil erosion and loss of nutrients.

- Forests are capable of moderating extremes in local climate in the vicinity of the forest.
- Forests provide, with careful management practices, sustainable harvesting of forest products, such as specialized timbers, edible products, resins, extracts, and so forth.
- They provide a source of employment opportunities for local populations.

There are also some concerns about indirect sequestration, such as:

- It is only a short-term solution.
- The future costs are unknown.
- Projects must be certified.
- There is an element of uncertainty in carbon retention properties during climate change. For example, if a drought occurs and the trees perish, they can no longer store $CO_2$.
- There is a need to maintain forests in equilibrium long-term.
- There may be unexpected costs in the future.

There have been proposals for man-made projects, similar in nature to the natural indirect tree model. Global Research Technologies (GRT) has devised a new technology prototype above-ground collector system to perform the same basic function as what forests do: collect atmospheric $CO_2$ over the next few years to evaluate it as a secondary energy collections system (ScienceDaily, 2010).

## Direct Sequestration

There are several mechanisms in effect for direct sequestration. Presently, about one-third of all human-generated carbon emissions have dissolved in the ocean, but how fast the ocean can remove $CO_2$ from the atmosphere depends on atmospheric $CO_2$ levels, ocean circulation, and mixing rates. The more $CO_2$ in the atmosphere, the more the ocean needs to absorb. Also, the more rapid the circulation the greater the volume of water that is exposed to the higher $CO_2$ levels, which increases uptake by the ocean. Climate change, however, will cause ocean temperatures to rise, and warmer water holds less dissolved gas, which means the oceans will not be able to store as much anthropogenic $CO_2$ as climate change progresses. This means that the rate will slow down and lower the effectiveness of ocean sequestration as an efficient mechanism for carbon sequestration. Another negative side effect on the oceans from climate change is that increasing amounts of $CO_2$ in the water will increase its acid content. When $CO_2$ gas dissolves in ocean water, it combines with water molecules ($H_2O$) and forms carbonic acid ($H_2CO_3$). The acid releases hydrogen ions into the water. The more hydrogen ions in a solution, the more acidic it becomes. According to the WHOI, hydrogen ions in ocean surface waters are now 25 percent higher than in the pre-industrial era, with an additional 75-percent increase projected by 2100.

Therefore, it is also necessary to look at direct carbon storage options, as well. Carbon capture and storage (CCS) is a process that involves capturing the $CO_2$ arising from the combustion of fossil fuels (such as in power generation or refining fossil fuels), transporting it to a storage location, and isolating it long-term from the atmosphere. Before $CO_2$ gas can be sequestered from power plants and other point sources, however, it must be captured as a relatively pure gas. The U.S. Department of Energy reports that, on a mass basis, $CO_2$ is the 19th largest commodity chemical in the United States, and it is routinely separated and captured as a by-product from industrial processes such as synthetic ammonia production and limestone calcinations (DOE, 2011) (Figure 8.4). CCS has the potential to reduce overall mitigation costs, but its widespread application would depend on overall costs, the ability to successfully transfer the technology to developing countries, regulatory issues, environmental issues, and public perception. The capture of $CO_2$ would need to be applied to large point sources, such as energy facilities or major $CO_2$-emitting industries to make it cost effective. Potential storage areas for the $CO_2$ would be in geological formations (such as oil and gas fields, nonminable coal seams, and deep saline formations), in the ocean (direct release into the ocean water column or onto the deep sea floor), and industrial fixation of $CO_2$ into inorganic carbonates.

Current technology captures roughly 85–95 percent of the $CO_2$ processed in a capture plant. A power plant that has a CCS system (with an access geological or ocean storage) uses approximately 10–40 percent more energy than a plant of equivalent output without CCS (the extra energy is for the capture and compression of $CO_2$). The final result with a CCS is that there is a reduction of $CO_2$ emissions to the atmosphere by 80–90 percent compared to a plant without CCS.

When $CO_2$ is captured, it must be separated from a gas stream. Techniques to do this have existed for 60 years. Used in the production of town gas by scrubbing the gas stream with a chemical solvent, $CO_2$ removal is already used in the production of hydrogen from fossil fuels. This practice helps remove $CO_2$ from contributing to climate change. When the $CO_2$ is transported to its storage site, it is compressed in order to reduce its volume; when it is compressed it only occupies 0.2 percent of its normal volume. Each year, several million tons of $CO_2$ are transported by pipeline, ship, and road tanker.

Today, there are several options for storing $CO_2$. Initially, it was proposed to inject $CO_2$ into the ocean where it would be carried down into deep water where it would stay for hundreds of years. In order for any CCS scheme to be effective, however, it needs to sequester huge amounts of $CO_2$—comparable to what is currently being submitted into the atmosphere—in the range of gigatons per year. Due to the size requirement, the most feasible storage sites are the Earth's natural reservoirs, such as certain geological formations or deep ocean areas.

The technology of injecting $CO_2$ underground is very similar to what the oil and gas industry uses for the exploration and production of hydrocarbons. It is also similar to the underground injection of waste practiced in the United States.

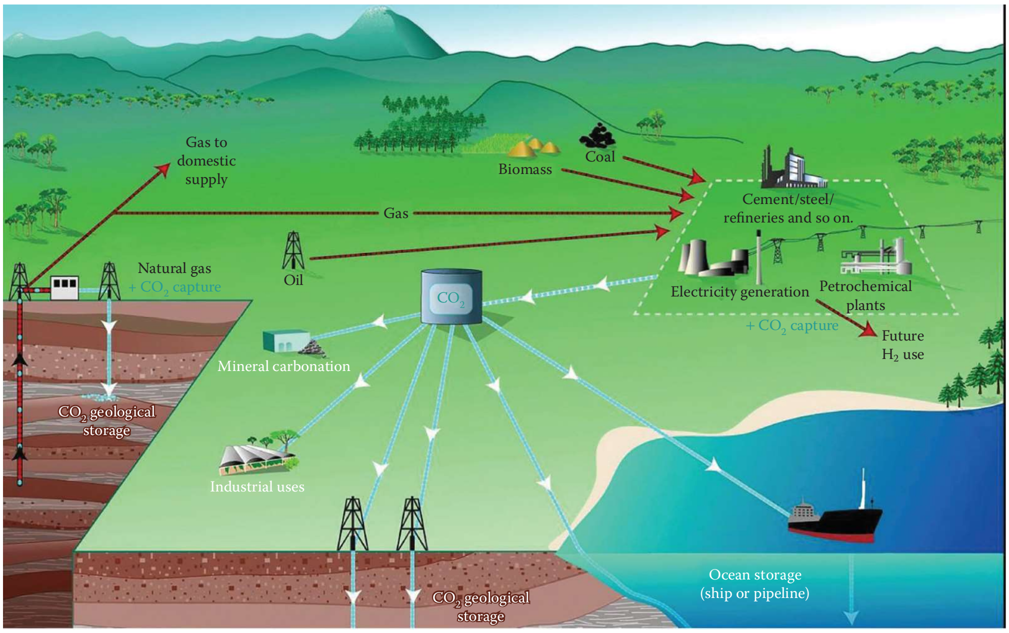


**FIGURE 8.4** The PICC's schematic diagram of possible CCS systems, showing the sources for which CCS might be relevant, transport of $CO_2$, and storage options. (Courtesy of Rubin, E. et al., IPCC special report: Carbon dioxide capture and storage technical summary, http://www.ipcc.ch/pdf/special-reports/srccs/srccs_technicalsummary.pdf, 2011.)

In the same manner, wells would be drilled into geological formations and the $CO_2$ would be injected. This is also the same method used today for enhanced oil recovery. In some areas, it has been proposed to pump $CO_2$ into the ground for sequestration while simultaneously recovering oil deposits. There are arguments both for and against this strategy; on one hand, recovering oil would offset the cost of sequestration. On the other hand, burning the recovered oil as a fossil fuel adds additional $CO_2$ to the atmosphere, which offsets some of the positive effects of the sequestration.

Two other strategies involve injecting $CO_2$ into saline formations or into nonminable coal seams. The world's first $CO_2$ storage facility, located in a saline formation deep beneath the North Sea, began operation in 1996. Other alternatives have been proposed as well, such as using $CO_2$ to make chemicals or other products, fixing it in mineral carbonates for storage in a solid form, such as solid $CO_2$ (dry ice), $CO_2$ hydrate, or solid carbon. Another option is to capture $CO_2$ from flue gas using micro-algae to make a product that can be turned into a biofuel. In order to decide where to find feasible sites for carbon sequestration, it is important to know where large carbon sources are geographically distributed in order to assess their potential. This enables managers to estimate the costs of transporting $CO_2$ to storage sites.

The IPCC believes that more than 60 percent of global $CO_2$ emissions originate from the power and industry sectors. Geographically, 66 percent of these areas occur in three principal regions worldwide: Asia (30 percent), North America (24 percent), and Western Europe (12 percent). In the future, however, the geographical distribution of emission sources is expected to change. Based on data from the IPCC, by 2050 the bulk of emission sources will be from the developing regions, such as China, South Asia, and Latin America. The power generation, transport, and industry sectors are still expected to be the leading contributors of $CO_2$.

Global storage options are focusing primarily on geological or deep ocean sequestration. It is expected that $CO_2$ will be injected and trapped within geological formations at subsurface depths greater than 800 meters where the $CO_2$ will be supercritical and in a dense liquid-like form in a geological reservoir, or injected into deep ocean water with the goal of dispersing it quickly or depositing it at great depths on the ocean floor with the goal of forming $CO_2$ lakes. Current estimates place both types of sequestration as having ample potential storage space—estimates range from hundreds to tens of thousands of gigatons (Gt) of $CO_2$.

## Geological Formation Sequestration

Many of the technologies required for large-scale geological storage of $CO_2$ already exist. Because of extensive oil industry experience, the technologies for drilling, injection, stimulations, and completions for $CO_2$ injection wells exist and are being patterned after current $CO_2$ projects. In fact, the design of a $CO_2$ injection well is very similar to that of a gas injection well in an oil field or natural gas storage project. Capture and storage of $CO_2$ in geological formations provides a way to eliminate the emission of $CO_2$ into the atmosphere by capturing it from large stationary sources, transporting it (usually by pipeline) and injecting it into suitable deep rock formations. Geologic storage of $CO_2$ has been a natural process within the Earth's upper crust for millions of years; there are vast reservoirs of carbon held today in coal, oil,

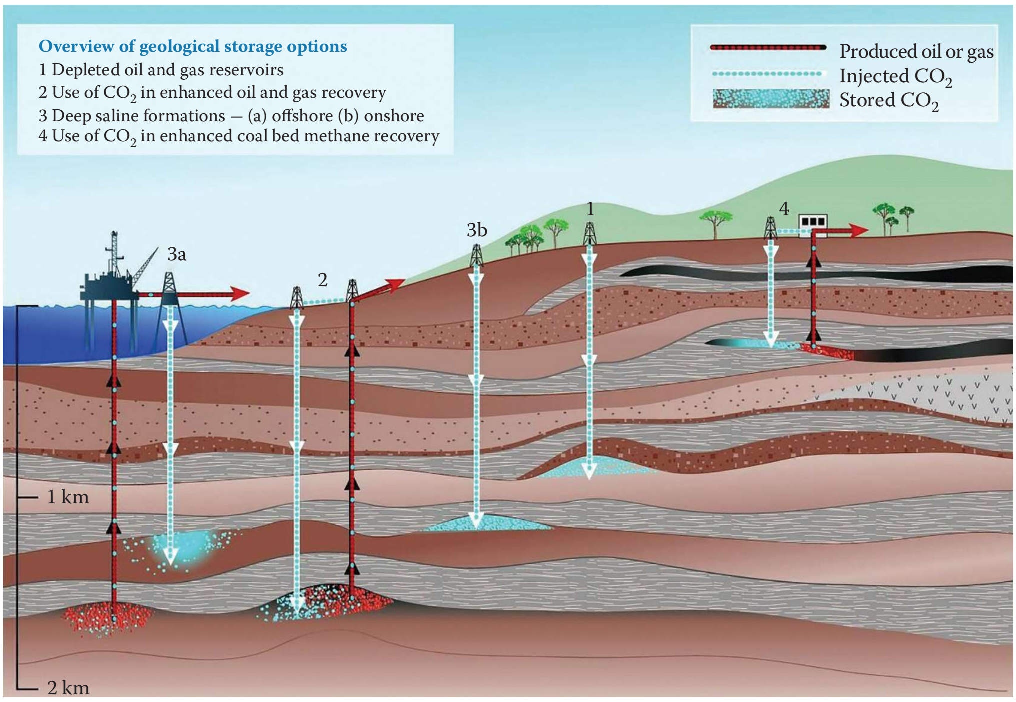


**FIGURE 8.5** $CO_2$ can be sequestered in deep underground geological formations. (Courtesy of Rubin, E. et al., IPCC special report: Carbon dioxide capture and storage technical summary, http://www.ipcc.ch/pdf/special-reports/srccs/srccs_technicalsummary.pdf, 2011.)

gas, organic-rich shale, and carbonate rocks. In fact, over eons $CO_2$ has been derived from biological activity, igneous activity, and chemical reactions that have occurred between rocks, and fluids and gases have naturally accumulated in the subsurface layers (Figure 8.5).

The first time $CO_2$ was purposely injected into a subsurface geological formation was in Texas in the early 1970s as part of an "enhanced oil recovery" effort. Based on the success of this effort, applying the same technology to store anthropogenic $CO_2$ as a GHG mitigation option was also proposed around the same time, but not much was done to pursue any actual sequestration. It was not until nearly 20 years later, in the early 1990s that research groups began to take the idea more seriously. In 1996, Statoil and its partners at the Sleipner Gas Field in the North Sea began the world's first large-scale storage project. Following their lead, by the end of the 1990s, several research programs had been launched in the United States, Europe, Canada, Japan, and Australia. Oil, coal mining, and electricity-generating companies spurred much of the interest in this technology as a mitigation option for waste byproducts in their respective industries.

Since this initial push, environmental scientists—many connected with the IPCC—have become involved in geologic sequestration as a viable option to combat climate change. The significant issues now are whether the technique is: (1) safe, (2) environmentally sustainable, (3) cost effective, and (4) capable of being broadly applied. Geologic storage is feasible in several types of sedimentary basins, such as oil fields, depleted gas fields, deep coal seams, and saline formations. Formations can also be located both on and offshore. Offshore sites are accessed through pipelines from the shore or from offshore platforms. The continental shelf and some adjacent deep-marine sedimentary basins are also potential sites, but the abyssal deep ocean floor areas are not feasible because they are often too thin or impermeable. Caverns and basalt are other possible geological storage areas.

Not all sedimentary basins make good candidates, however. Some are too shallow, some not permeable enough, and others do not have the ability to keep the $CO_2$ properly contained. Suitable geologic formations require a thick accumulation of sediments, permeable rock formations saturated with saline water, extensive covers of low porosity rocks to act as a seal, and structural simplicity. In addition, a feasible storage location must also be economically feasible, have enough storage capacity, and be technically feasible, safe, environmentally and socially sustainable, and acceptable to the community. Most of the world's populations are concentrated in regions that are underlain by sedimentary basins. The table lists some of the current geological storage projects around the world (Table 8.2).

The most effective geologic storage sites are those where the $CO_2$ is immobile because it is trapped permanently under a thick, low-permeability seal, is converted to solid minerals, or is absorbed on the surface of coal micropores or through a combination of physical or chemical trapping mechanisms. If done properly, $CO_2$ can remain trapped for millions of years. When converting possible local and regional environmental hazards, the biggest danger is if $CO_2$ were to seep from storage, human exposure to elevated amounts of $CO_2$ could cause respiratory problems. This is why these storage facilities are closely monitored.

**TABLE 8.2**
**Current Carbon Sequestration Projects Within Geological Formations**

| Country | Name | Location | $CO_2$ Capacity (Mtpa[a]) | Project Start Date | Storage Formation (Depth and Type) |
|---|---|---|---|---|---|
| United States | Shute Creek | Wyoming | 7 Mtpa | 1986 | 3400 m sandstone/limestone |
| United States | Lost Cabin | Wyoming | 0.9 Mtpa | 2013 | 1400 m sandstone |
| United States | Illinois Industrial | Illinois | 1 Mtpa | 2016 | 2130 m sandstone |
| United States | Coffeyville | Kansas | 1 Mtpa | 2013 | 914 m sandstone |
| United States | Enid Fertilizer | Oklahoma | 0.7 Mtpa | 1982 | 2865 m carboniferous deposit |
| United States | Val Verde | Texas | 1.3 Mtpa | 1972 | 2135 m limestone |
| United States | Texas Clean Energy | Texas | 2.4 Mtpa | 2019 | Not specified |
| United States | Century Plant | Texas | 8.4 Mtpa | 2010 | Not specified |
| United States | Petra Nova | Texas | 1.4 Mtpa | 2016 | 2066 m sandstone |
| United States | Air Products | Texas | 1 Mtpa | 2013 | 1700 m sandstone |
| United States | Kemper County | Mississippi | 3 Mtpa | 2016 | Not specified |
| United States | Riley Ridge | Wyoming | 2.5 Mtpa | 2020 | Not specified |
| Canada | Quest | Alberta | 1 Mtpa | 2015 | 2 km Cambrian Basal Sands |
| Canada | Boundary Dam | Saskatchewan | 1 Mtpa | 2014 | 1.5 km Weyburn Oil Unit |
| Canada | Great Plains Synfuel Plant | Saskatchewan | 3 Mtpa | 2000 | 1500 m carbonate |
| South America | Petrobras Lula | Brazil | 0.7 Mtpa | 2013 | 7000 m Pre-salt carbonate |
| Europe | Snøhvit | Norway | 0.7 Mtpa | 2008 | 2670 sandstone |
| Europe | Sleipner | Norway | 0.85 Mtpa | 1996 | 1100 m sandstone |
| Europe | Caledonia | United Kingdom | 3.8 Mtpa | 2022 | 2200 m sandstone |
| Europe | Don Valley | United Kingdom | 1.5 Mtpa | 2020 | Offshore deep saline formations |
| Europe | Rotterdam Opslag | Netherlands | 1.1 Mtpa | 2019 | 3500 m sandstone |
| Africa | In Salah | Algeria | Under revision | 2004 | 1900 m sandstone |
| Middle East | Uthmaniyah | Saudi Arabia | 0.8 Mtpa | 2015 | 2100 m mudstone |
| UAE | Abu Dhabi | Abu Dhabi | 0.8 Mtpa | 2016 | Complex carbonate |
| Europe | Teesside Collective | United Kingdom | 2.8 Mtpa | 2020s | Under evaluation |
| South Pacific | Gorgon | Australia | 4 Mtpa | Not specified | 2.3 km sandstone |
| South Pacific | Southwest Hub | Australia | 2.5 Mtpa | 2025 | 3000 m sandstone |
| South Pacific | Carbon Net | Australia | 5 Mtpa | 2020s | 1500 m sub-sea |
| Asia | China Resources | China | 1 Mtpa | 2019 | Not specified |
| Asia | Korea-CCS 1 | Korea | 1 Mtpa | 2020 | Under evaluation |
| Asia | PetroChina Jilin | China | 0.5 Mtpa | 2017 | 2.4 km oil-bearing formation |
| Asia | Korea-CCS 2 | Korea | 1 Mtpa | 2023 | Under evaluation |
| Asia | Sinopec Qilu | China | 0.5 Mtpa | Retrofit | 3000 m |
| Asia | Huaneng GreenGen IGCC | China | 2 Mtpa | 2020 | 3000 m |
| Asia | Shanxi Intl Energy | China | 2 Mtpa | 2020 | Not specified |
| Asia | Yanchang Integrated CCS | China | 0.44 Mtpa | 2017 | 2200 m Yanchang Formation |
| Asia | Shenhua Ningxia | China | 2 Mtpa | 2020 | Not specified |

*Source:* Global CCS Institute. The global status of CCS: 2015 summary report. https://www.globalccsinstitute.com/projects/large-scale-ccs-projects#map.

[a] Mtpa: million tons per annum.

## Ocean Sequestration

Various technologies have been identified to enable and increase ocean $CO_2$ storage. One suggested option would be to store a relatively pure stream of $CO_2$ that has been captured and compressed. The $CO_2$ could be loaded onto a ship and injected directly into the ocean or deposited on the sea floor. $CO_2$ loaded on ships could be either dispersed from a towed pipe or transported to fixed platforms feeding a $CO_2$ lake on the sea floor. The $CO_2$ must be deeper than 3 kilometers, because at this depth, $CO_2$ is denser than seawater. Relative to $CO_2$ accumulation in the atmosphere, direct injection of $CO_2$ into the ocean could reduce maximum amounts and rates of atmospheric $CO_2$ increase over the next several centuries. Once released, it would be expected that the $CO_2$ would dissolve into the surrounding seawater, disperse, and become part of the ocean carbon cycle.

C. Marchetti was the first scientist to propose injecting liquefied $CO_2$ into waters flowing over the Mediterranean sill into the mid-depth North Atlantic, where the $CO_2$ would be isolated from the atmosphere for centuries—a concept that relies on the slow exchange of deep-ocean waters with the surface to isolate $CO_2$ from the atmosphere. Marchetti's objective was to transfer $CO_2$ to deep waters because the degree of isolation from the atmosphere increases with depth in the ocean. Injecting the $CO_2$ below the thermocline would enable the most efficient storage. In the short-term, fixed or towed pipes would be the most viable method for oceanic $CO_2$ release because the technology is already available and proven.

One proposed option would be to send the $CO_2$ down as "dry ice torpedoes." In this option, $CO_2$ could be released from a ship as dry ice at the ocean's surface. If $CO_2$ has been formed into solid blocks with a density of 1.5 $tm^{-3}$, they would sink quickly to the seafloor and could potentially penetrate into the seafloor sediment. Another method, called "direct flue-gas injection," would involve taking a power plant fire gas and pumping it directly into the deep ocean without any separation of $CO_2$ from the flue gas. Costs for this are still prohibitive, however.

It would be possible to monitor distributions of injected $CO_2$ using a combination of shipboard measurement and modeling approaches. Current analytical monitoring techniques for measuring total $CO_2$ in the ocean are accurate to about ±0.05 percent. According to the IPCC, measurable changes could be seen with the addition of 90 metric tons of $CO_2$ per 1 $km^3$. This would mean that 1 metric gigaton of $CO_2$ could be detected even if it were dispersed over an area $10^7$ $km^3$ (or 5,000 km × 2,000 km × 1 km), if the dissolved inorganic carbon concentrations in the region were mapped out with high-density surveys before the injection began (Figure 8.6).

In the case of monitoring the injection of $CO_2$ into the deep ocean via a pipeline, several monitoring techniques could be employed. At the point of entry from the pipeline into the ocean, an inflow plume would be created of high $CO_2$/low pH water extending from the end of the pipeline. The first monitoring array would consist of sets of chemical, biological, current sensors, and underwater cameras in order to view the end of the pipeline. An array of moored sensors would monitor the direction and magnitude of the resulting plume around the pipe. Monitors would also be set along the pipeline to monitor leaks. A shore-based facility would provide power to the sensors and could receive real-time data. In addition, a forward system would monitor the area and could provide data over broad areas very quickly. Moored systems could monitor the $CO_2$ influx, send the information to surface buoys, and make daily transmissions back to the monitoring facility via satellite.

Kurt Zenz House, a Harvard researcher who was one of the first to propose undersea carbon storage, says "Under immense pressure and cold temperature below the seafloor, $CO_2$ forms a very dense liquid that is much heavier than sea water. In addition, gravity would prevent the liquefied gas from seeping upward, just as it prevents water in a well from flying into the air" (Doughton, 2008).

## Economic Benefits of Carbon Storage

There are several economic benefits of carbon storage. Both the carbon tax and cap-and-trade, and their hybrid options, all with any auctioned allowances are able to generate significant revenues. The use of the revenues is currently a hot topic. They need to be used to further mitigate climate change, improve air quality, create jobs in the sustainable energy sector, develop low-carbon or zero emission passenger transportation, and so forth. Some potential uses of carbon revenues could include, for example,

- Offsetting the disproportionate impacts of higher energy prices for low-income households (e.g., rebates on electricity bills for low income households).
- Investing in communities that are exposed to a high amount of pollution from fossil fuels.

Methods of ocean storage

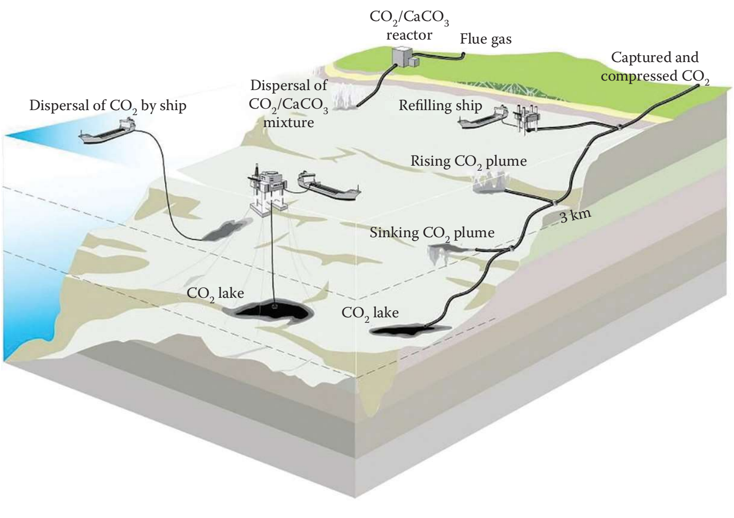


**FIGURE 8.6** There are several proposed methods of $CO_2$ sequestration in the world's oceans. (Courtesy of Rubin, E. et al., IPCC special report: Carbon dioxide capture and storage technical summary, http://www.ipcc.ch/pdf/special-reports/srccs/srccs_technicalsummary.pdf, 2011.)

- Investing in climate-resilient infrastructure or relocation costs for communities at high risk.
- Contributing to efforts to cut carbon and prepare for climate change in developing countries.
- Providing transition assistance to workers and communities that depend on fossil fuels for their livelihoods (such as funding for job training and investments in economic diversification).
- Investing in renewable energy technology, such as clean vehicles, fuels, and transit options.

There are limitless opportunities to invest in technology that can make a difference. There are also opportunities to educate society about climate change so that everyone understands what the real issues are, enabling them to make better choices and become informed in policymaking and key political decisions that must be decided in the future. The more you know and understand, the wiser and better informed choices you can make.

## Adaptation Strategies

In a report issued by NASA in 2009, due to the increasing challenges caused by climate change, several scientists and policymakers in the United States came together to take part in the newly established United States National Assessment on the Potential Consequences of Climate Variability and Change—called the National Assessment for short (USGCRP, 2009). The National Assessment currently consists of 16 separate regional projects. Project leaders are charged with assessing their region's most vulnerable aspects—the resources that would be impacted most by climate change. These include resources such as water supply and quality, agricultural productivity, and human health issues. Once potential impacts are identified, strategies are proposed and developed to cope and adapt to climate change impacts should they occur.

Michael MacCracken, head of the coordinating national office, says "The goal of the assessment is to provide the information for communities, as well as activities to prepare and adapt to the changes in climate that are starting to emerge."

The more successful mitigation strategies apply toward the effects of climate change today, the less human populations will have to adapt in the short- and long-term. According to the PEW Center on Global Climate Change, however, recognition that the climate system has a great deal of inertia and is increasing, mitigation efforts alone are now insufficient to protect the Earth from some degree of climate change. Even if extreme measures to combat climate change were taken immediately to slow or even stop emissions, the momentum of the Earth's climate is such that additional warming is inevitable. Some of the warming that is unstoppable now is due to emissions of GHG that were released into the atmosphere decades ago. Because of this, humans have no choice but to adapt to the damage that has already been done.

Adaptation is not a simple, straight-forward issue for humans or ecosystems. Each system has its own "adaptive capacity." In systems that are well managed (such as in developed countries and regions like the United States, Canada, Western Europe, and Australia), wealth, the availability of technology, responsible decision-making capabilities, human resources, and advanced communication technology help tremendously in successful adaptation to climate change. Societies that are able to anticipate environmental changes and plan accordingly ahead of time are also more likely to succeed.

The ability of natural ecosystems to successfully adapt is another issue, however. While biological systems are usually able to adapt to environmental changes and inherent genetic changes, the time scales are usually much longer than a few decades or centuries (such as the case with climate change). With changes in climate, even minor changes can be detrimental to natural ecosystems. An example of this is the polar bear in the Arctic. Today, sea ice is melting at a rapid rate leaving the polar bear with limited areas to breed and hunt. The situation has already become so grave in a short period of time that the polar bear's survival is now in jeopardy. The polar bear is now listed as threatened under the Threatened and Endangered Species Act based on evidence that the animal's sea ice habitat is shrinking and is likely to continue to do so over the next several decades. The polar bear was listed as threatened on May 14, 2008. Listing the polar bear as "threatened" means the animal is at risk of becoming an "endangered" species—in danger of extinction—in the foreseeable future if its habitat continues to be destroyed or adversely changed.

Like the polar bear, many of the world's ecosystems are stressed by several types of disturbances, such as pollution, fragmentation (isolation of habitat), and invasion of exotic species (this includes weed invasions). These factors coupled with climate change are likely to impact ecosystems' natural resiliency and prevent them from being able to adapt over the long term.

As far as human adaptability, some adaptation will involve the gradual evolution of present trends; other adaptations may come as unexpected surprises. Changes will involve sociopolitical, technological, economic, and cultural aspects. Because of the reality that populations are increasing, more people live in coastal areas, and more people live in flood plains and in drought-prone areas, adaptation measures will be required as climate changes. Fortunately, however, technology has developed to a point that there are better means today to successfully respond to climate change than there were in the past. For example, agricultural practices have evolved to the point where most crop species have been able to be translocated thousands of miles from their regions of origin by resourceful farmers.

A critical key to success is reactive adaptation; how willing will populations be to permanently change behaviors in order to adapt to changing climates and environmental conditions? Situations populations will have to adapt to will encompass issues such as:

- Rationed water
- Changes in water use habits
- Changes in crop type
- Resource conservation plans
- Mandatory use of renewable energy
- Restricted transportation types

Waiting to act until change has occurred can be more costly than making forward-looking responses that anticipate climate change, especially with coastal and floodplain development. A "wait-and-see" approach would be unwise with regard to ecosystem impacts. According to the PEW Center, "Proactive adaptation, unlike reactive adaptation, is forward-looking and takes into account the inherent uncertainties associated with anticipating change. Successful proactive adaptation strategies are flexible; they are designed to be flexible under a wide variety of climate conditions" (Kerr Gines, 2012).

An extremely important part in adaptation that cannot be overlooked is government influence and public policy. Governments have a strong influence over the magnitude and distribution of climate change impacts and public preparedness. When climate and environmental disasters occur, it is usually government institutions that provide the necessary funding, develop the technologies, management systems, and support programs to minimize the occurrence of a repeat situation. A well-known example of this is the Dust Bowl that occurred in the Midwestern United States in the 1930s. It was through the efforts of the U.S. government that conservation efforts were started in order to properly manage the nation's soil and agriculture in order to prevent a repeat disaster of that nature. Table 8.3 lists some adaptation strategies suggested by the IPCC.

In view of climate change today and the already unstoppable effects into the future, adaptation and mitigation are necessary (and complementary concepts). Adaptation is

**TABLE 8.3**
**Adaptation Strategies**

| Sector | Adaptation Option/Strategy | Underlying Policy Framework | Key Constraints and Opportunities to Implementation (Normal font = constraints; *italics = opportunities*) |
|---|---|---|---|
| **Water** | Expanded rainwater harvesting; water storage and conservation techniques; water reuse; desalination; water-use and irrigation efficiency | National water policies and integrated water resources management; water-related hazards management | Financial, human resources and physical barriers; *integrated water resources management; synergies with other sectors* |
| **Agriculture** | Adjustment of planting dates and crop variety; crop relocation; improved land management, e.g., erosion control and soil protection through tree planting | R&D policies; institutional reform; land tenure and land reform; training; capacity building; crop insurance; financial incentives, e.g., subsidies and tax credits | Technological and financial constraints; access to new varieties; markets; *longer growing season in higher latitudes; revenues from "new" products* |
| **Infrastructure/ settlement (including coastal zones)** | Relocation; seawalls and storm surge barriers; dune reinforcement; land acquisition and creation of marshlands/wetlands as buffer against sea level rise and flooding; protection of existing natural barriers | Standards and regulations that integrate climate change considerations into design; land-use policies; building codes; insurance | Financial and technological barriers; availability of relocation space; *integrated policies and management; synergies with sustainable development goals* |
| **Human health** | Heat-health action plans; emergency medical services; improved climate-sensitive disease surveillance and control; safe water and improved sanitation | Public health policies that recognize climate risk; strengthened health services; regional and international cooperation | Limits to human tolerance (vulnerable groups); knowledge limitations; financial capacity; *upgraded health services; improved quality of life* |
| **Tourism** | Diversification of tourism attractions and revenues; shifting ski slopes to higher altitudes and glaciers; artificial snow-making | Integrated planning (e.g., carrying capacity; linkages with other sectors); financial incentives, e.g., subsidies and tax credits | Appeal/marketing of new attractions; financial and logistical challenges; potential adverse impact on other sectors (e.g., artificial snow-making may increase energy use); *revenues from "new" attractions; involvement of wider group of stakeholders* |
| **Transport** | Realignment/relocation; design standards and planning for roads, rail and other infrastructure to cope with warming and drainage | Integrating climate change considerations into national transport policy; investment in R&D for special situations, e.g., permafrost areas | Financial and technological barriers; availability of less vulnerable routes; *improved technologies and integration with key sectors (e.g., energy)* |
| **Energy** | Strengthening of overhead transmission and distribution infrastructure; underground cabling for utilities; energy efficiency; use of renewable sources; reduced dependence on single sources of energy | National energy policies, regulations, and fiscal and financial incentives to encourage use of alternative sources; incorporating climate change in design standards | Access to viable alternatives; financial and technological barriers; acceptance of new technologies; *stimulation of new technologies; use of local resources* |

*Source:* IPCC.

a key requirement in order to lessen future damage. It is important to understand, however, that even though society will have to adapt, losses suffered will be inevitable and certain geographical areas will experience more extreme losses than others, particularly the developing countries.

While it is understood today that both mitigation and adaptation must occur simultaneously, each country will be faced with different issues to resolve and overcome Developing nations may face different issues of climate change than developed nations. Varying geographic locations will also experience differing ranges of change. The only way to manage this overwhelming issue is for nations to work together in a global effort to control GHG emissions, working to understand universal cause-and-effect relationships. Without international cooperation, there is little hope of stopping the problem before it is too late.

## CONCLUSIONS

While it is true that many underdeveloped countries are now beginning to cause a climate change problem because they are industrializing and making the same mistakes that currently developed countries once made (which can be corrected with assistance and guidance from developed countries), there is also the issue of the undeveloped countries that are facing the worst effects of climate change—such as sea level rise—who have not ever significantly contributed to the problem. This suggests an uneven balance of responsibility. If a global climate policy is going to work, many argue that all countries must participate in the solution to some degree because emerging and developing economies are expected to produce 70 percent of global emissions during the next 50 years. Other experts add that any framework that does not include large and fast-growing economies (China, India, Brazil, and Russia) would be very costly and politically unwise. Others believe that undeveloped countries should not be held accountable. Like most issues, reality—and morality—most likely lies somewhere in between.

This chapter has presented several financial and technological strategies to handle the mitigation of climate change. Whichever methods are used will ultimately depend on the region, available technology, available finances, political policy, and prevailing social paradigm. What is critical is that action be taken immediately to fight climate change in order to lower the negative consequences of sea-level rise, flooding, drought, disease, and other disasters. Perhaps facing the issue realistically is through a combination of some workable means of adaptation, mitigation, and prevention. All three approaches have been discussed in this book and all are viable, workable components to the ultimate solution. While changing our personal behavior, mindset, and attitudes is perhaps the most critical element in the mix, we cannot overlook the assistance and good that can come from mitigation efforts, either, and where they are technologically, environmentally, and economically feasible, they are also worth looking at. And as we have learned, climate change is already in progress and its effects are not completely eradicable at this point, so adaptation is also a necessity. In this instance, developed countries need to help those that need assistance in a struggling world. The battle needs to be fought—and won—by all.

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