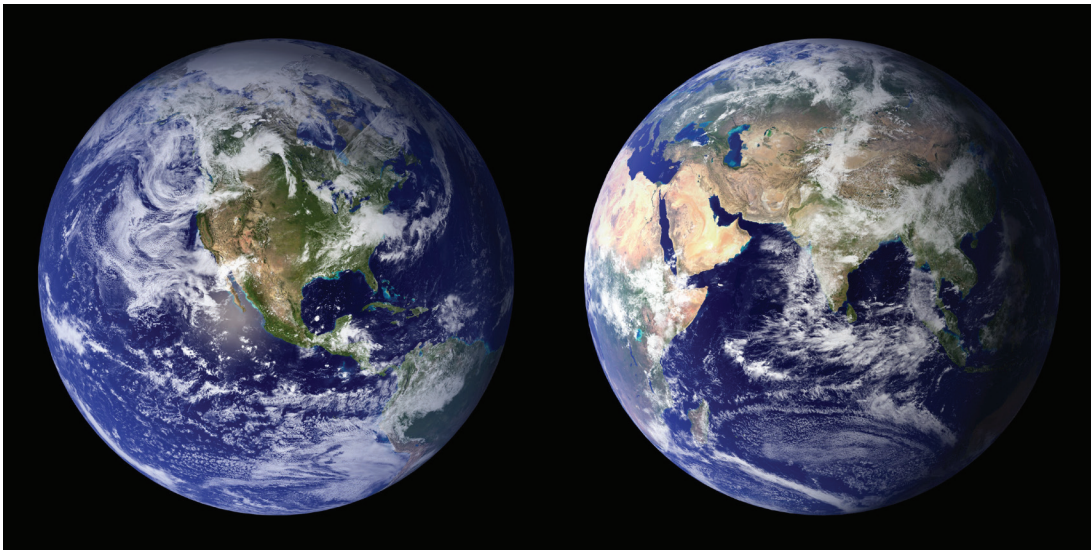


The  
**Teacher-Friendly**  
Guide™

to Climate Change



Edited by Ingrid H. H. Zabel, Don Duggan-Haas, & Robert M. Ross

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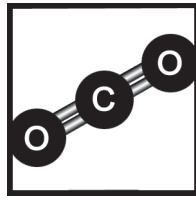
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On the front cover: the "Blue Marble." Composite images produced by NASA in 2001-2002.

On the back cover: Atmospheric CO<sub>2</sub> concentration at Mauna Loa Observatory from 1958 to 2014 (NOAA).



# Chapter 7: Climate Change Mitigation

## 1. What is Mitigation?

Human activities, especially burning **fossil fuels** for energy, are increasing the concentrations of **greenhouse gases** in our atmosphere, which results in a warmer planet and other changes in our climate. We can address this issue in several ways. One way, explored in Chapter 9: Climate Change Adaptation, is to prepare for how to live with these changes. The other, explored in this chapter, is to reduce the sources of greenhouse gas emissions, thereby reducing the potential impacts. This latter approach is called climate change mitigation.

Mitigation is a human intervention, and as such it involves the complex intersection of science, ethics, economics, politics, social equity, population growth, and industrial and land development. In addition, because greenhouse gases mix throughout the Earth's atmosphere, mitigation actions require international cooperation. Different countries and communities may take different actions, but ultimately we're all in this together.

### 1.1 Mitigation and Adaptation in Parallel

The Earth's climate system changes slowly, and the greenhouse gases that we have already emitted are going to change the climate over the next decades and centuries even if we stop emitting all greenhouse gases tomorrow. This is why **adaptation** strategies are necessary. Mitigation strategies, on the other hand, ultimately are intended to reduce the severity of climate change impacts by reducing future emissions of greenhouse gases. Future adaptation will be much harder if we don't reduce greenhouse gas emissions today.

Mitigation and adaptation strategies can sometimes conflict and sometimes go hand-in-hand. For example, one strategy to adapt to the more intense heat waves that much of the US can expect is to expand the use of air conditioning to protect people from heat-related illness. But more air conditioning means more energy use, which releases more heat-trapping greenhouse gases (if our power plants are the conventional, fossil-fuel burning ones we use predominantly today). On the other hand, we could adapt to more extreme heat by keeping buildings cooler through the use of insulation and reflective roofs. This could keep people cooler without using more air conditioning. In this example, the "green" building practices accomplish both adaptation and mitigation.

See Chapter 9: Climate Change Adaptation for more on adaptation strategies.

**fossil fuel** • a non-renewable, carbon-based fuel source like OIL, NATURAL GAS, or COAL, developed from the preserved organic remains of fossil organisms.

**greenhouse gas** • a gas that absorbs and re-radiates energy in the form of heat; carbon dioxide, water vapor, and methane are examples.

**adaptation** • in the context of climate change, action taken to prepare for unavoidable climate changes that are currently happening or are projected to happen in the future.

CHAPTER AUTHOR

Ingrid H. H. Zabel



# Climate Change Mitigation

Addressing climate change is going to require parallel efforts that implement both adaptation strategies and mitigation strategies simultaneously. We will need to help vulnerable populations (e.g., those at the lowest levels of income, and those living on ocean coasts) adapt to the changes that are already happening. We will also have to help the major emitters of greenhouse gases reduce (that is, mitigate) their emissions in order to limit future warming. We

## Box 7.1: Exercise: evaluating analogies to describe climate change mitigation and adaptation, and their relationships

Below are two analogies to describe responses to climate change. Evaluate the strengths and weaknesses of these analogies. Can you think of others?

### Analogy 1: credit card debt

Imagine climate change adaptation and mitigation to be like dealing with credit card debt. We've already put a lot of charges on our card, and we're going to have to take some action to pay this off, that is, adapt to the situation. We might have to earn more money or spend less. If we keep making charges to the card without mitigating the situation by paying down the charges that have built up, it's going to be harder to pay it off in the future. We might have to take on a second job or severely alter our lifestyle to cut expenses. If, on the other hand, we pay off some of the debt and we charge less to the card in the future, it will be easier to pay off the remaining debt.

### Analogy 2: laundry

Climate change adaptation and mitigation are like doing the laundry. If you let the laundry pile up for a while, you'll have to adapt by maybe not wearing your favorite shirt if it's not clean, or re-wearing clothes that are only a bit dirty. But if you don't mitigate the problem, that is, if you continue to insist on not doing the laundry, eventually you'll be left with some unpleasant choices: wear dirty, smelly clothes, wear no clothes, or go buy yourself an entirely new wardrobe. On Earth, of course, we can't just buy another planet.

On the other hand, if you do the laundry pretty consistently, you may still have to adapt sometimes if your favorite shirt isn't clean or you run out of detergent. But for the most part your adaptive actions and decisions will be small, and you can more easily get back to having enough clean clothes to wear.

Mitigation is taking action to do the laundry regularly. Adaptation is coming up with solutions to when the laundry isn't done. Right now we've let the laundry pile up, and we've got to start cleaning up our act.



# Climate Change Mitigation



cannot rely on adaptation alone because the ultimate impact of unmitigated emissions of greenhouse gases will be very severe, and we cannot rely on mitigation strategies alone because historical greenhouse gas emissions are already changing our planet and impacting people around the globe.

## Up Against

**anthropogenic** • made by humans, or resulting from human activity.

## 1.2 What We're Up Against

Mitigation efforts currently face an uphill battle, because the trends in **anthropogenic** greenhouse gas emissions (i.e., emissions resulting from human activities) show a continued increase in the last few decades. Below is a summary of these trends.<sup>1</sup>

- Global annual anthropogenic greenhouse gas emissions have increased from 27 GtCO<sub>2</sub>eq in 1970 to 49 GtCO<sub>2</sub>eq in 2010 (see Box 7.2 for an explanation of the unit GtCO<sub>2</sub>eq).
- Most of the anthropogenic greenhouse gas emissions (78%) during this time period came from fossil fuel combustion and industrial processes.
- About half of cumulative anthropogenic CO<sub>2</sub> emissions between 1750 and 2010 have occurred in the last 40 years.
- CO<sub>2</sub> is the main greenhouse gas emitted from human activities, making up 76% of the total in 2010. It is followed by CH<sub>4</sub> (16%), N<sub>2</sub>O (6.2%), and fluorinated gases (2%).<sup>2</sup>
- In 2010, direct anthropogenic greenhouse gas emissions came mainly from electricity and heat production (25%), agriculture, forestry, and other land uses (24%), and industry (21%), followed by transportation (14%), other energy sector activities besides electricity and heat production (9.6%), and buildings (6.4%).

### Box 7.2: What do the units GtCO<sub>2</sub>eq mean?

The "G" stands for the unit prefix giga, which represents a billion (10<sup>9</sup>). The "t" stands for tonne, which is a metric ton or 1,000 kg. CO<sub>2</sub> is carbon dioxide, and "eq" stands for equivalent.

The unit of GtCO<sub>2</sub>eq is used to describe a quantity called the Global Warming Potential (GWP) of a greenhouse gas. The GWP is a way to measure the relative warming effects of different greenhouse gases, and it tells you how much warming a certain mass of a greenhouse gas would lead to in a given time period, compared to warming from CO<sub>2</sub>. The typical time period used by climate scientists for calculating GWP is 100 years, though some argue that it is important to consider shorter time scales when considering effects of highly potent, short-lived (on the order of a decade) greenhouse gases such as methane (CH<sub>4</sub>). For the sake of clarity, we will use the term GWP<sub>100</sub> when considering a 100-year time horizon.

Example: Assume that nitrous oxide (N<sub>2</sub>O) has a GWP<sub>100</sub> of 280. This means that emissions of one ton of N<sub>2</sub>O is equivalent to emissions of 280 tons of CO<sub>2</sub> over the next 100 years.

<sup>1</sup> These data come from the latest report (as of this writing) from the Intergovernmental Panel on Climate Change: IPCC, 2014, Summary for Policymakers, In: Climate Change 2014, Mitigation of Climate Change. Cambridge University Press: NY.

<sup>2</sup> These numbers represent percentages of the total 2010 emissions of 49 GtCO<sub>2</sub>eq.



# Climate Change Mitigation

## Pathways and Wedges

**carbon sinks** • a system or part of a system which absorbs carbon.

**IPCC** • the Intergovernmental Panel on Climate Change, a large, international group of climate scientists working to understand climate change and to present reliable climate data and information to policy-makers and the public at large.

The statistics listed above are global. In the US, the recent picture gives reason for encouragement. According to the 2014 US National Climate Assessment,

*Over recent decades, the US economy has emitted a decreasing amount of carbon dioxide per dollar of gross domestic product. Between 2008 and 2012, there was also a decline in the total amount of carbon dioxide emitted annually from energy use in the United States as a result of a variety of factors, including changes in the economy, the development of new energy production technologies, and various government policies.<sup>3</sup>*

The economic changes referred to are likely associated with the recession following the 2008 financial crisis, and achieving emissions reductions as a by-product of an economic downturn is not a desirable path. But the encouraging aspects are that we *can* achieve emissions and energy use reductions through technology innovations, policies, and behavior changes.

Recent regulatory efforts and advancements in technology and efficiency are reducing the amount of greenhouse gases that developed nations emit each year, but even the most technologically advanced and environmentally conscientious nations (e.g., Germany) are still emitting greenhouse gases every year. Ultimately, to prevent climate change, we may need to develop methods and technologies that can remove greenhouse gases from the atmosphere. There are many current proposals for these methods and technologies that can serve as **carbon sinks** or negative emissions, but they have unknown risks and potentially huge financial and environmental costs, and none currently can be implemented at a large scale.

See Chapter 8: Geoengineering to learn more about potential ways to remove CO<sub>2</sub> from the atmosphere.

## 1.3 Mitigation Pathways and Stabilization Wedges

Mitigation pathways are different combinations of technological and behavioral solutions that lead to different levels of greenhouse gas reductions, and have different impacts on society. Pathways with larger and faster emissions reductions lead to smaller global temperature increases in the future, which will make adaptation to unavoidable change easier. These pathways may, however, be harder to implement for political and economic reasons. The Intergovernmental Panel on Climate Change (**IPCC**), a large, international group of scientists considered to be the most authoritative source of information on global climate change, has concluded that the mitigation pathways needed to keep the increase in the world's temperature to less than 2° C (3.6° F) above the pre-industrial temperature (see *Box 7.3*) by the end of the 21<sup>st</sup> century will likely require large scale changes in the world's energy supply systems.

For example, one potential mitigation pathway is to immediately cease all further emissions of greenhouse gases. This would require that we produce no more power, consume no additional fossil fuels, and basically shut down

<sup>3</sup>This analysis comes from Jacoby, H. D., Janetos, A. C., Birdsey, R., Buizer, J., Calvin, K., Chesnaye, F. D., . . . West, J. (2014). Ch. 27: Mitigation. *Climate Change Impacts in the United States: The Third National Climate Assessment*. US Global Change Research Program. doi:10.7930/J0C8276J



## Box 7.3: Why is 2° C considered the limit of acceptable warming for our planet?

The idea of an average surface warming of 2° C (3.6° F) above pre-industrial temperature as the upper limit of acceptable warming was born in the 1970s and grew in acceptance over the next few decades.<sup>4</sup> The temperature number came out of scientific considerations of the temperature conditions under which human societies developed and the impacts of increased warming, including drought and heat waves that would decrease the world's food supply, sea level rise that would flood coastal cities and lead to large-scale refugee migrations, and extreme weather events that would lead to loss of life and damage to infrastructure.

Scientists and policymakers have questioned the 2° C limit and continue to debate it. At the most recent United Nations Climate Change Conference (Paris, 2015), a group of countries pushed for actions to limit warming to 1.5° C (2.7 °F).

modern society. While this would stop all greenhouse gas emissions, and leave us only to adapt to the changes that we have already committed to, this mitigation pathway would shatter industries, collapse economies, and cause social, economic, and political havoc. While this could be considered the ultimate mitigation pathway, it is not a realistic pathway. On the other extreme, we could decide to not mitigate, and hope that our ability to adapt to any future changes will be enough. We could wait until someone somewhere invents some future technology that would cheaply and easily remove greenhouse gases from our atmosphere, thereby solving the issue. While this may be an alluring strategy, it is a risky one. What if it turns out we cannot adapt to the amount of climate change occurring before a large-scale removal technique is found? What if there is no magic bullet technology? Clearly, we need to come up with a combination of mitigation and adaptation strategies and implement them in parallel.

The actions in some mitigation pathways can have adverse side effects. For example, nuclear power plants emit far fewer greenhouse gases than do fossil fuel-burning power plants, but nuclear power plants also produce radioactive waste that is difficult to dispose of and raise serious concerns about catastrophic accidents. Mitigation pathways can also have co-benefits, that is, they can produce results that are beneficial beyond reducing greenhouse gas emissions. For example, strategies that reduce air particulate pollution improve the health of people and ecosystems, and create energy systems and communities that are more sustainable. These pathways are sometimes referred to as “win-win” pathways.

Another way to think about mitigation pathways is through the concept of “stabilization wedges.” *Figure 7.1* shows a plot of carbon emissions over time. Historical emissions have increased at a rapid rate in the 20<sup>th</sup> century and early 21<sup>st</sup> century, and if emissions continue at the rate of this current path they will lead to dangerous warming. If instead emission rates are flat in the future, it will be easier to adapt to climate change. The area between the dashed

<sup>4</sup> For a discussion of the politics behind the 2° C limit, see an article in *The Economist*: The Economist explains the 2° C limit on global warming, Dec. 6, 2015, <http://www.economist.com/blogs/economist-explains/2015/12/economist-explains-4>.



# Climate Change Mitigation

## Mitigation Strategies

**renewable** • able to be naturally replenished on a short time scale. While **FOSSIL FUELS** come from natural sources (the fossilized remains of plants and animals), they are not renewable on human time scales because they take many millions of years to form.

**wind energy** • electrical energy derived from the mechanical energy of a **TURBINE** which moves due to the action of the wind.

**hydropower** • electric power derived from the kinetic energy of falling or moving water.

**geothermal energy** • heat energy found below the surface of the Earth.

**biomass energy** • energy produced by burning plants, wastes, or their derivatives.

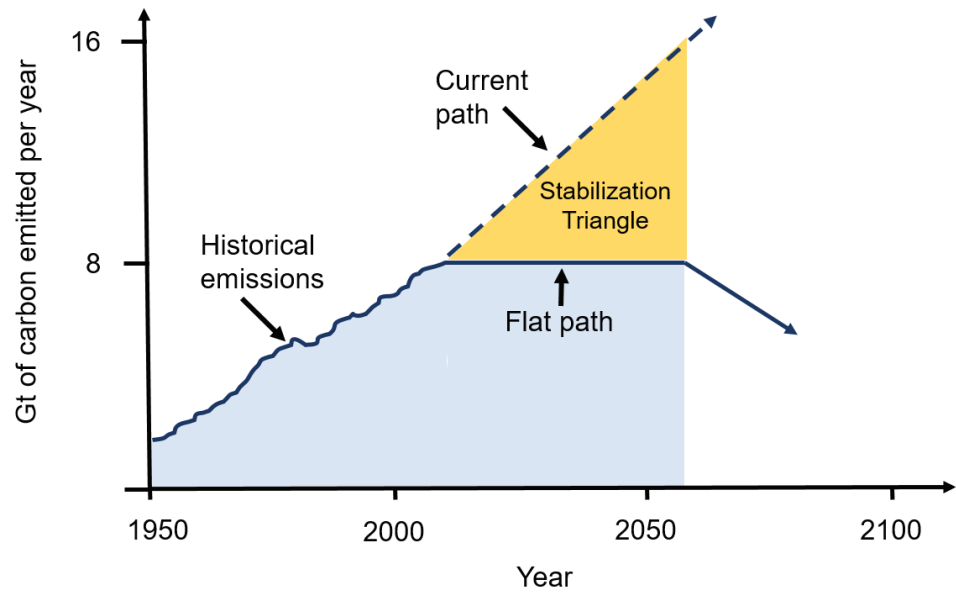


Figure 7.1: Carbon emissions over time, including historical emissions and two future paths, one following the current trend and one that remains flat and eventually decreases. The area between these paths is called the Stabilization Triangle, and represents the future emissions we will need to avoid to move from the current path to the flat path. (See Teacher-Friendly Guide website for a full color version.)

line (current path) and the flat path is called the Stabilization Triangle, and it represents the future carbon emissions we need to avoid in order to stay on the flat path.

How do we move from the current path to the flat path? In other words, how do we reduce carbon emissions represented by the area of the Stabilization Triangle? Like many big problems, the solution can be broken into parts, and we can undertake a variety of strategies. These are represented by Stabilization Wedges (Figure 7.2), which together can reduce the emissions of the entire Stabilization Triangle. Examples of these strategies are increasing energy efficiency in all sectors of the economy (using less energy), using **renewable energy (wind, solar, hydropower, geothermal, and biomass)**, using nuclear energy, replacing coal-burning power plants with natural gas-burning power plants, carbon capture and storage, and increasing natural carbon sinks through forestry and agricultural practices. These strategies are addressed in the remainder of this chapter.

## 2. Mitigation Strategies

Mitigation strategies vary, and they can involve different levels of effort and scope, from broad-ranging actions taken at the government level to actions by specific industries or companies, and to behavior changes made by individuals. A successful mitigation pathway will likely involve combinations of these strategies.

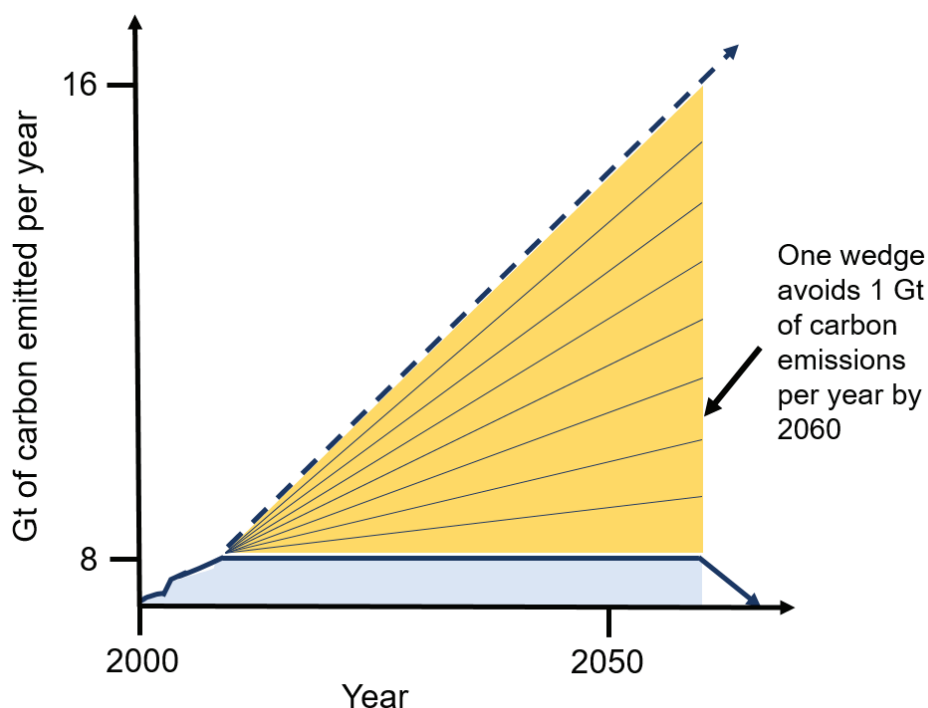


Figure 7.2: Carbon stabilization wedges: triangles representing carbon emissions reduced by different mitigation strategies. Used together, all these strategies could move emissions from their current path to a flat path. (See Teacher-Friendly Guide website for a full color version.)

## 2.1 Renewable Energy

Renewable energy is energy that comes from sources that are naturally replenished. In 2015, renewable energy accounted for about 13% of US energy generation and 10% of energy consumption, and it comes in many forms (Figure 7.3). Consumption of wind and solar energy has increased dramatically in the last decade (Figure 7.4), and businesses and governments are discovering new methods of capturing, storing, and distributing renewable energy.

One of the attractions of renewable energy is that, because it is naturally replenished, it has the potential to be sustainable. It also holds promise for climate change mitigation because, compared with fossil fuels, many renewable energy sources emit far fewer greenhouse gases. Renewable energy at a large, commercial scale is not without environmental costs, however. A mitigation pathway that combines renewable energy production and *less* energy use is ideal.

Biomass (Figure 7.5) has many thousands (if not millions) of years of history as an energy source and it is still the largest renewable source of energy. Wood and wood products still account for just over half of US commercial biomass energy production, but it is now nearly equaled by biofuels (ethanol and biodiesel). Estimates of amount of wood used for commercial energy do not take into account home heating provided by wood burning. Energy from waste, including landfill gas, is also included as biomass. Landfill gas is a mixture of methane and other gases produced by microorganisms breaking down biomass within a landfill.



# Climate Change Mitigation

## U.S. renewable energy supply

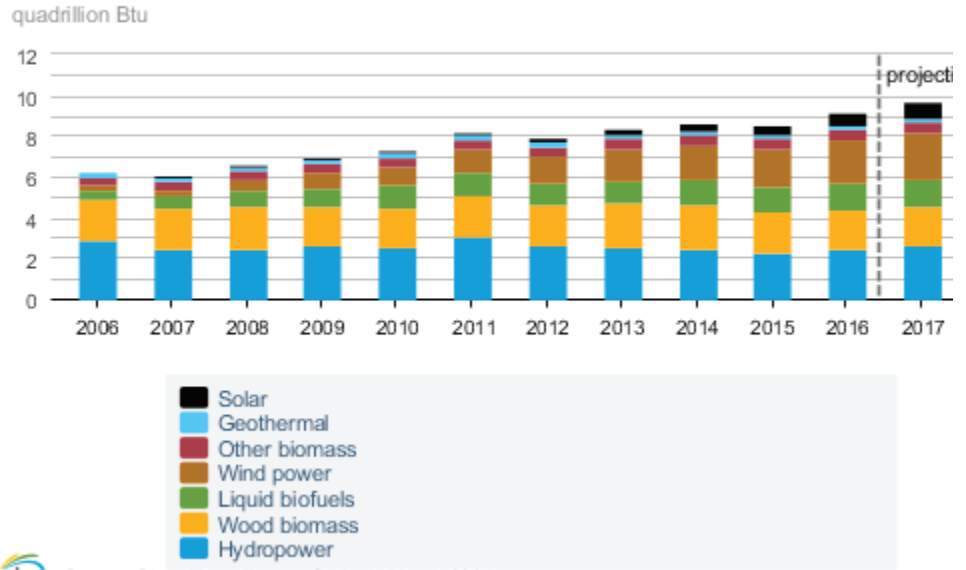
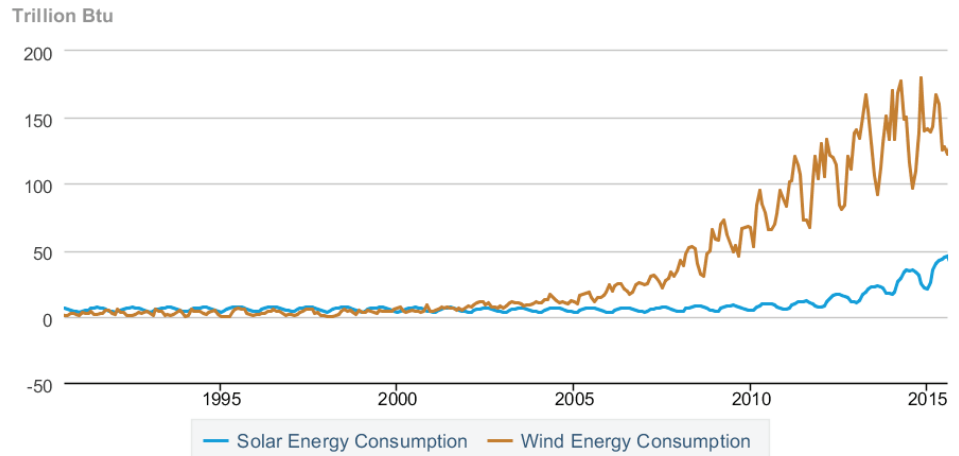


Figure 7.3: US renewable energy supply, for 2006-2016 (actual) and 2017-2018 (projected). (See Teacher-Friendly Guide website for a full color version.)



Data source: U.S. Energy Information Administration

Figure 7.4: Changes in US consumption of wind and solar energy from August 1990 to August 2015. (See Teacher-Friendly Guide website for a full color version.)



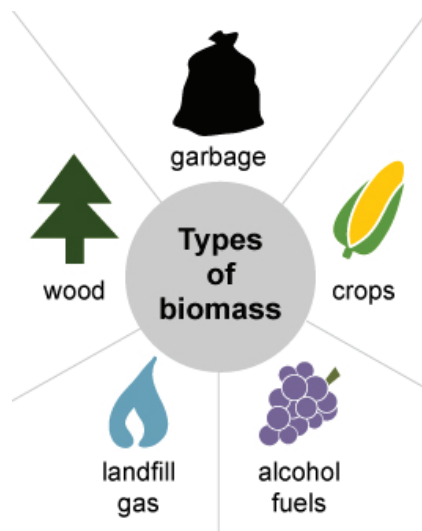


Figure 7.5: Types of biomass used for energy production.

The burning of biomass, like fossil fuels, yields carbon dioxide and often other emissions, although the carbon emitted into the atmosphere during the burning of biomass is balanced out by the carbon removed from the atmosphere during the growth of the biomass itself. This is because growing plants take in carbon dioxide from the atmosphere through photosynthesis. Recent studies suggest, however, that the net effect of biomass burning is warming.<sup>5</sup> This is because biomass burning releases soot and other particles— also known as black and brown carbon — that reduce sunlight-blocking cloud cover and make icy and snowy surfaces absorb more heat, warming the Earth.

Geothermal, hydropower, solar, and wind energy installations produce zero or almost no carbon emissions once they are up and running. The main carbon emissions associated with these sources of energy are in the production, transport, and maintenance of materials and installations.

Hydropower is the longest established renewable energy source used for electricity production, and still accounts for the largest portion of renewable electric generation in the US. The world's first commercial-scale hydropower plant began operation at Niagara Falls, New York, in 1881. Hydropower accounts for about 7% of US electricity use, and because most substantial river systems have already been dammed for electricity use or their damming has been deemed too environmentally costly to pursue, there is little likelihood that the US can obtain much more energy from traditional hydropower.<sup>6</sup> The environmental costs include habitat destruction from flooding of gorges or valleys typically required for hydropower generation. Indeed, many hydropower plants have been removed in recent decades because of their impact on wildlife, particularly fish migration.

<sup>5</sup> These studies include Bond, T. D. (2013). Bounding the role of black carbon in the climate system: A scientific assessment. *Journal of Geophysical Research: Atmospheres*, 118(11), 5380–5552 and Jacobson, M. Z. (2014). Effects of biomass burning on climate, accounting for heat and moisture fluxes, black and brown carbon, and cloud absorption effects. *Journal of Geophysical Research: Atmospheres*, 119, 8980-9002.

<sup>6</sup> An article that discusses this is Manahan, M., & Verville, S. (2005). FERG and dam decommissioning. *Natural Resources and Environment*, 19(3), 45-49.



## Renewable Energy

**turbine** • a machine that converts rotational mechanical energy into electrical energy. In its simplest form, a turbine consists of a shaft with a rotor with blades on one end and an electric generator on the other end. Water, wind, or steam pushes the blades and causes the rotor to rotate. Inside the generator, a coil of metal wire sits inside a large magnet. When the shaft rotates it spins the metal coil in a magnetic field, producing electric current by induction.

# Climate Change Mitigation



Figure 7.6: Aerial view of the Grand Coulee Dam taken in 2016, on the Columbia River in Washington.

Hydropower works by converting the kinetic energy of falling water into mechanical energy to operate a **turbine**, which then generates electricity. Most hydropower is produced at large dams such as the Grand Coulee Dam in Washington (Figure 7.6), but hydropower generation is possible on a small scale from undammed streams and rivers. The calculation in Box 7.4 gives an estimate of the power generated in a large dam.

Wind power generation in the US at large-scale facilities (i.e., utilities) grew by a factor of ten from 2005 to 2014. Wind power generation is not uniformly distributed across the country: in 2013, 80% of the US's wind power was produced by just twelve states (Texas, Iowa, California, Oklahoma, Illinois, Kansas, Minnesota, Oregon, Colorado, Washington, North Dakota, and Wyoming). Wind power works by using the force of wind to rotate turbine blades (Figure 7.7), and the turbine converts rotational mechanical energy to electrical energy. The physics and economy of wind turbines favors the construction of large diameter blades. This brings permanent structures to rural landscapes that are scores to hundreds of feet high. Although impacts upon bird populations appear smaller than initially believed, current designs of turbines could have substantial impacts on bat populations.

Geothermal both provides direct heat and generates electricity, using Earth's internal heat as an energy source. It has long been used on a small scale for heating where the heat release is high—at hot springs, for example. In recent decades, capturing Earth's heat for power production has grown substantially, but it remains a small part of the global energy portfolio. Such deep geothermal energy systems sometimes use hydraulic fracturing to increase the flow of water through the rock, which regulates heat and controls energy production. Also in the last few decades, small-scale, relatively shallow (less than 300 feet, or 91 meters) geothermal heat pumps have been effectively used to preheat air in winter or cool it in summer, thus reducing heating and air conditioning



### Box 7.4: Physics connection: hydropower generation

Suppose the hydropower station at the Grand Coulee Dam has a flow rate of  $2800 \text{ m}^3/\text{s}$ . That is, 2800 cubic meters of water flow through the station's turbines in one second. If the height of the dam is  $h=170 \text{ m}$  and the turbines are 100% efficient (an idealization), how much power does the station generate? Note: 100% efficiency means that we are ignoring energy losses due to friction in the turbines.

Ignoring frictional energy losses as the water drops down from the top of the dam, the kinetic energy of the water when it enters the turbines at the bottom of the dam is equal to the gravitational potential energy of the water at the top of the dam. One cubic meter of water has a mass  $m = 1000 \text{ kg}$ . For one cubic meter of water, this potential energy is

$$mgh = (1000 \text{ kg}) \times (9.8 \text{ m/s}^2) \times (170 \text{ m}) = 1.67 \times 10^6 \text{ J}$$

( $g$  is the acceleration due to gravity at the Earth's surface).

The kinetic energy of the water is used to do work, and power is the rate of doing work. A flow rate of  $2800 \text{ m}^3/\text{s}$  would generate a power of

$$P = (2800 \text{ m}^3/\text{s}) \times (1000 \text{ kg/m}^3) \times (9.8 \text{ m/s}^2) \times (170 \text{ m}) = 4.7 \text{ GW (gigawatts)}.$$

Follow-up question: How many homes can this dam power? Students will have to estimate the electricity use of a typical home.



Figure 7.7: Wind turbines in California.





## Nuclear Energy

**rare earth metals** • one of a group of seventeen chemical elements with similar properties and often found together in the Earth. Rare earth metals include the fifteen lanthanides, scandium, and yttrium.

**fission** • the process of bombarding atomic nuclei with neutrons, splitting the nuclei into those of lighter elements and more neutrons, and also resulting in the release of energy.

# Climate Change Mitigation

costs in homes and other buildings. These systems take advantage of nearly constant temperature (approximately 50–60°F) below the surface and do not require fracturing bedrock. Globally, geothermal electricity production grew 44% from 2004 to 2014, but its total contribution is still comparatively small at 12.8 GW (gigawatts) of installed electric generating capacity in 2014.

Solar power works in two ways: solar thermal uses the sun for heat, and photovoltaic cells (PV) convert light into electric current. Both types are growing rapidly, with global PV generating capacity growing from 2.6 to 177 GW between 2004 and 2014. Both solar thermal and PV systems can range in scale from very small household systems to very large power plants. Further, passive solar building design coupled with good insulation and control of airflow can eliminate or practically eliminate the need for heating systems. Solar energy produces no emissions once systems are installed, but there are concerns about the manufacture and disposal of photovoltaic solar cells, and related to the mining practices, particularly outside the US, of **rare earth metals** used in PV and battery production. Whether a commercial-scale solar energy installation generates heat or electricity, it must cover and industrialize considerably more physical area compared to other kinds of power plants that generate the same amount of energy, although smaller-scale solar energy systems can be roof-mounted, reducing these concerns.

## 2.2 Nuclear Energy

Carbon emissions from nuclear energy are very low compared with fossil fuel sources, and are comparable to those from renewable energy technologies such as solar and wind.<sup>7</sup> As with those technologies, most of the emissions come from processes that occur ahead of operating a power plant, i.e., from extracting and transporting raw materials and constructing the plant.

Nuclear power is produced by the **fission** (“splitting”) of the nuclei of relatively heavy atoms, such as uranium (*Figure 7.8*). Typically, the method for electricity production from nuclear fission is similar to that from fossil fuel power plants—the energy from nuclear reactions (rather than fossil fuels) is used to boil water that produces steam to turn turbines. In 2015 nuclear power accounted for 20% of US electricity generation.

Nuclear power has only been a commercial source of electricity since 1957 and its substantial growth stopped (or paused) in the United States in the late 1970s as a result of a combination of prohibitive economic costs and environmental concerns, highlighted by the 1979 accident at Pennsylvania’s Three Mile Island nuclear generating station, and the long-term handling of nuclear waste. Unlike in later catastrophic nuclear power plant accidents at Chernobyl, Soviet Union and Fukushima, Japan, there were no documented deaths associated with the US’s best-known nuclear accident.

There are very serious concerns about nuclear power, especially related to accidents and the long-term management of highly toxic waste material. While

<sup>7</sup> It is important to consider the greenhouse gas emissions across all stages of a method’s or product’s life cycle when making comparisons. The US National Renewable Energy Laboratory (NREL) provides a comparison of life cycle greenhouse gas emissions for different types of electricity generation in this handout: <http://www.nrel.gov/docs/fy13osti/57187.pdf>.

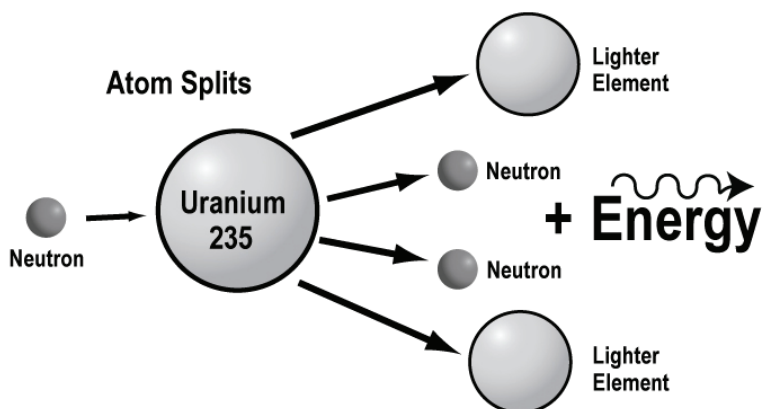


Figure 7.8: Diagram of the process of nuclear fission. A neutron is fired into the nucleus of a uranium atom, which then splits into nuclei of lighter elements and additional neutrons. Energy is released in this process. The additional neutrons then collide with other uranium nuclei and the process repeats in a chain reaction.

accidents in the nuclear industry are rare, the ones that have happened have been extremely dangerous. While technological advances have drastically cut the amount of radioactive waste used by newly designed nuclear power plants, there are still many costs and environmental concerns.

Humans are not always good at analyzing and comparing risks at different scales. For instance, would you rather live near a nuclear power plant that produces 100% clean energy, but has a one-in-a-million chance of having a meltdown, or would you ban all nuclear power plants, but rely on fossil fuels that are changing the entire planet's climate? This is a difficult problem to quantify and compare: the risk of a nuclear meltdown is catastrophic for the people who live nearby, while the risk of burning fossil fuels is applied around the world, gradually over time.

### Box 7.5: There's no such thing as a free megawatt<sup>8</sup>

One large nuclear plant produces the same amount of electricity as 3,000 large wind turbines or 130 square kilometers (50 square miles, the equivalent of 24,200 football fields) of photovoltaic cells. It is not a simple question to determine the most environmentally benign energy source, and the answer can vary depending on local contexts. There is no such thing as a free megawatt, which is why efforts to increase our energy efficiency are so important. The environmental impact of an energy source is a complicated issue, and although it is clear that some energy sources are more environmentally friendly than others, all commercial-scale energy production has negative environmental impacts. For any energy source, there is a wide range of factors to consider and those factors should be considered not in isolation but in contrast to current or likely future energy practices.

<sup>8</sup> This title comes from a presentation by Don Duggan-Haas, published in the Journal of Sustainability Education Vol. 8, Jan. 2015, and freely available online here: [http://www.jsedimensions.org/wordpress/content/theres-no-such-thing-as-a-free-megawatt-hydrofracking-as-a-gateway-drug-to-energy-literacy\\_2015\\_01/](http://www.jsedimensions.org/wordpress/content/theres-no-such-thing-as-a-free-megawatt-hydrofracking-as-a-gateway-drug-to-energy-literacy_2015_01/).



**energy efficiency** • methods which enable machines to perform functions while minimizing energy loss or using less energy than previously.

**energy conservation** • an approach to processes and activities that results in using less energy, on scales ranging from individual to industrial to national and global.

**green infrastructure** • structures that use plants, soil, and other natural features to perform functions such as providing shade, absorbing heat, blocking wind, or absorbing and filtering stormwater.

# Climate Change Mitigation

## 2.3 Energy Efficiency and Conservation

**Energy efficiency** and **conservation** measures may be the most important and effective mitigation actions we can take. Energy production and use are by far our biggest contributors to greenhouse gas emissions. According to the 2013 data from the US Energy Information Administration (eia.gov),

*In the United States, greenhouse gas (GHG) emissions come primarily from the burning of fossil fuels in energy use. Fossil fuels supply 82% of the primary energy consumed in the United States and are responsible for 94% of total carbon dioxide emissions.<sup>9</sup>*

Our success in mitigating climate change will depend on finding ways to use less energy and different energy. This section explores strategies for using less energy.

### 2.3.1 Buildings

Buildings are one of the sectors with the biggest potential for energy savings. Buildings use energy for heating, cooling, lighting, and other electrical systems, and, according to the US Energy Information Administration, residential and commercial buildings accounted for 40% of the US's total energy consumption in 2013.

One large-scale mitigation initiative that addresses energy use in buildings is the 2030 Challenge (<http://architecture2030.org>). Launched by a group of architects, the 2030 Challenge asks the building design and construction community to set a series of goals for new buildings and major renovations. The final goal is to design buildings so that by the year 2030 they use no fossil fuel energy to operate. Strategies for doing this include innovations in design that reflect heat away from buildings in the summer or trap heat in the winter, generating power on-site using renewable sources, or purchasing renewable energy (up to a 20% limit). Many cities, including large ones such as Seattle, Pittsburgh, Denver, Dallas, Cleveland, and Los Angeles, have set up "2030 Districts" within their boundaries where they have committed to meeting their goals.

The use of **green infrastructure** is a mitigation strategy for buildings and communities. Green infrastructure refers to structures that use plants, soil, and other natural features to perform functions such as providing shade, absorbing heat, blocking wind, or absorbing stormwater (*Figure 7.9*). Green infrastructure can also help us *adapt* to climate change hazards such as heat waves and heavy rainfalls. As a mitigation tool, green infrastructure helps to reduce energy use.

Anyone who has walked through a neighborhood with tree-lined streets on a hot summer day has felt the cooling effect of plants. Trees reduce the need for air conditioning by providing shade. Trees and other plants also cool the air itself

<sup>9</sup> These data and more can be found on the United States Energy Information Administration's website. This particular statistic came from What are greenhouse gases and how much are emitted by the United States? (2014), Retrieved February 12, 2015, from Energy in Brief: [http://www.eia.gov/energy\\_in\\_brief/article/greenhouse\\_gas.cfm](http://www.eia.gov/energy_in_brief/article/greenhouse_gas.cfm)



# Climate Change Mitigation



# 7

## Efficiency & Conservation



Figure 7.9: Green roof on an urban building.

**evapotranspiration** • a combination of evaporation of liquid water on plant leaves and in the soil around the plant and transpiration, the transfer of water from a plant's roots to its leaves and then to water vapor in the air. Evapotranspiration cools the air because it takes heat from the air to convert liquid water to water vapor.

**wastewater** • water that has been used in residential or commercial activities and which needs to be treated before being released back into the environment.

through **evapotranspiration**. Studies have shown that the presence of mature trees in a suburban neighborhood can have a cooling effect of 4 to 6°F (2 to 3°C). Another energy-saving type of green infrastructure is a green roof – a roof with a layer of plants growing on it. The plants shade the underlying roof and the layer insulates the building, reducing energy costs for cooling and heating. Green infrastructure can also save energy when it is used to conserve water, recharge groundwater, and prevent sewer system overflows during storms, because managing water uses energy. In most cities electric water pumps are the largest portion of municipal electric use; the exceptions are cities with electrified mass transit, which uses a lot of energy. A Congressional Research Service Report<sup>10</sup> found that estimates for water-related electric use ranged from 4% to 13% of US electric generation, depending on different factors included in the analyses, and demand varies substantially with geography. According to the EPA, the activities of drinking water and **wastewater** utilities in the US result in about 116 billion pounds of CO<sub>2</sub> emissions annually (*Box 7.6*).

Certification and ratings systems can be very useful for architects and builders as well as for consumers in figuring out how to save energy in buildings. LEED (Leadership in Energy & Environmental Design) is a green building certification program that provides guidance and recognition for those wanting to create energy-efficient buildings. ENERGY STAR ratings (see *Box 7.7*) help consumers choose appliances such as dishwashers, refrigerators, computers, and furnaces that use less energy. The US EPA reports that between 1993 (when the ENERGY STAR program began) and 2012, the program has prevented the emission of 1.9 GtCO<sub>2</sub>eq of greenhouse gases.

<sup>10</sup> The report, titled Energy-Water Nexus: The Water Sector's Energy Use, can be found at <https://fas.org/sgp/crs/misc/R43200.pdf>.



# Climate Change Mitigation

## Box 7.6: How do CO<sub>2</sub> emissions from US water utilities compare to emissions from cars?

As stated above, the activities of drinking water and wastewater utilities in the US result in about 116 billion pounds of CO<sub>2</sub> emissions annually. For cars, burning one gallon of gasoline releases 19.64 pounds of CO<sub>2</sub>.

Assume a car is driven 10,000 miles annually and has a gas mileage of 25 miles per gallon (mpg). For this car,

the number of gallons of gas used per year is  $10,000 \text{ miles} / 25 \text{ mpg} = 400$  gallons.

This car thus releases  $400 \text{ gallons} \times 19.64 \text{ lbs. CO}_2/\text{gallon} = 7,856$  pounds of CO<sub>2</sub> in one year. The equivalent of CO<sub>2</sub> released from water utilities, expressed in terms of CO<sub>2</sub> released through driving cars, is

$116 \text{ billion pounds} / 7856 \text{ pounds per car} = 14.8$  million cars.

In other words, the annual CO<sub>2</sub> emissions from US water and wastewater utilities are equivalent to that of about 15 million cars.

## Box 7.7: How to read an energy guide label

The US Federal Trade Commission runs a program that provides Energy Guide labels for many types of appliances, to help consumers make purchasing decisions that lead to energy savings. Below is an example of an Energy Guide label for a refrigerator.

The image shows an Energy Guide label for a refrigerator. The label is yellow with black and red text. It includes the following information:

- U.S. Government** and **Federal law prohibits removal of this label before consumer purchase.**
- ENERGYGUIDE** logo with a downward arrow.
- Refrigerator-Freezer** with features: Automatic Defrost, Side-Mounted Freezer, Through-the-Door Ice.
- XYZ Corporation**, **Model ABC-L**, **Capacity: 23 Cubic Feet**.
- Estimated Yearly Operating Cost** of **\$67**. A scale below shows a **Cost Range of Similar Models** from \$57 to \$74.
- Estimated Yearly Electricity Use** of **630 kWh**.
- Your cost will depend on your utility rates and use.**
- ENERGY STAR** logo.

Annotations on the left side of the label:

- Typical features of this and similar appliances. (points to the feature list)
- The energy cost range for similar appliances, to help consumers compare. (points to the cost range scale)
- The annual energy use of this appliance. Consumers can calculate the annual cost of operating the appliance using this number and their local electricity prices. (points to the 630 kWh value)

Annotations on the right side of the label:

- Specific information about this model, so consumers know what refrigerator is being described. (points to the model and capacity information)
- The amount of money you might pay to run this appliance for a year, based on its energy use and average national electricity prices. (points to the \$67 cost)
- The ENERGY STAR label, for appliances which are more energy efficient than standard models. (points to the ENERGY STAR logo)

## 2.3.2 Transportation

After electric power generation, the transportation sector is the second biggest contributor to the US's energy-related greenhouse gas emissions, accounting for 25% of the total. The transportation sector also is a primary source of

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## Efficiency & Conservation

other kinds of emissions that degrade air quality and threaten human health. Reducing transportation emissions will both mitigate future climate change *and* improve air quality and human health. Such benefits that go beyond reducing emissions are sometimes referred to as a **co-benefits**. Increasing efficiency and reducing emissions in the transportation sector has tremendous potential.

We can save energy at the individual level by driving less: carpooling, combining errands into fewer trips, and walking, biking, or taking public transportation instead of cars. The vast majority of adult Americans drive to work alone, as illustrated in this visualization: <http://flowingdata.com/2015/01/20/how-americans-get-to-work>. We can also choose to buy products that involve less transportation, such as buying locally- or regionally-grown produce instead of imported fruits and vegetables. When we do drive, we can use less energy by not idling, driving at lower speeds on the highway (see *Box 7.8*), keeping tires properly inflated, and doing regular maintenance. We can choose to buy more fuel-efficient cars. Sometimes we can choose to live in neighborhoods where employers, services, and activities are close by and require less driving. Sometimes some of us can choose to work from home.

**co-benefit** • sometimes called multiple benefit, is an improvement or positive outcome from an action that was not the primary one intended. For example, a person might choose to use a highly energy-efficient appliance in order to reduce energy use and thus carbon emissions, and saving money might be a co-benefit of this choice.



### Box 7.8: Physics connection: why does driving at lower speed on the highway save energy?

In the 1970s, highway speed limits around the US were set to 55 mph in order to save energy. This has since changed, but it can be instructive to consider why this speed limit was set.

One of the main reasons is that cars are designed to perform optimally in a range of speeds, and pushing to high speeds beyond that range can reduce their efficiency. Friction from the air around the car also makes a difference. Aerodynamic drag is the force of air on a moving object. The drag force on a moving car resists the car's motion, and the car has to use energy to overcome it. The faster the car goes, the higher the drag force. In fact, the drag force is proportional to the square of the relative velocity between the car and the air:

$F_{\text{drag}}$  is proportional to  $v_{\text{rel}}^2$ .

Calculate how much higher the drag force is for a car traveling at 75 mph than for a car traveling at 55 mph. Note: this is a simple, “back-of-the-envelope” calculation that doesn't account for all the complexities of the drag force on a car and all the differences between driving 55 and 75 mph. But, it can give students an idea of the issues involved.

Solution: The ratio of drag forces on a car traveling at 75 mph compared to that at 55 mph is

$$F_{\text{drag},75} / F_{\text{drag},55} = (v_{75}/v_{55})^2 = (75\text{mph}/55\text{mph})^2 = 1.86.$$

That is, the drag force on a car traveling at 75 mph is 1.86 times higher than the drag force on a car traveling 55 mph. It costs energy to fight the drag force, and thus it is more energy efficient to drive at 55 mph than at 75 mph.





# Climate Change Mitigation

On a larger scale, we can make societal decisions to reduce our transportation energy use. For example, cities can choose to build public transportation networks so we use less energy driving individual cars, or cities can build infrastructure that makes it easier to ride a bicycle (*Figure 7.10*).<sup>11</sup> Communities can choose to develop neighborhoods where jobs and stores are close to where people live. Businesses can create incentives and mechanisms for employees to telecommute and carpool. Governments can set fuel efficiency standards for vehicles. Most of these changes, both on the small and large scale, not only reduce energy demand and therefore emissions, but also contribute to good health and save money.



*Figure 7.10: Roadway jammed with cars, with space available in an adjacent bike lane.*

## Box 7.9: Discussion: commuting to school and work

What could adults learn from kids and from the way kids get to school, in terms of saving energy and reducing carbon emissions?

What constraints do adults have that might limit them from using the same methods as kids?

What are some solutions, and how can we implement them?

<sup>11</sup> Cities such as Minneapolis, MN, San Francisco, CA, and Portland, OR, are often at the top of lists of bike-friendly cities, because they have built infrastructure to make bike riding easier.



## Box 7.10: Exercise: what difference do vehicle fuel efficiency improvements make?

Compare a car that gets 28 miles per gallon and a light truck that gets 23 miles per gallon. If each is driven 10,000 miles per year,

the car uses  $10,000 \text{ miles} / 28 \text{ mpg} = 357$  gallons of gas in a year and

the truck uses  $10,000 \text{ miles} / 23 \text{ mpg} = 434$ .

In 2013, US auto dealers sold 7.9 million new light duty trucks and 7.6 million new cars.<sup>12</sup> Assuming that these vehicles have the gas mileages above, the new light trucks would burn about 482 million more gallons of gas than the new cars. That releases about 9.5 billion pounds more CO<sub>2</sub> into the air, and that difference is just from new vehicles sold in one year in the US.

Many technologies exist today that can increase the fuel efficiency of vehicles. One example is turbocharging, where engine exhaust is re-used to run a fan that blows compressed air back into the engine's cylinders. Combustion requires air and fuel, and the addition of more fuel together with the compressed air results in combustion that generates more power with each explosion in the car's cylinders. The US Energy Information Administration estimates that with existing and soon-to-be-available technologies a gasoline-powered midsize passenger car could achieve a fuel efficiency of 53 miles per gallon by the year 2025, about a 50% increase from 2014. This would come with a 10% increase in the price of the car.<sup>13</sup>

Other vehicle options that use significant energy but may produce less greenhouse gas emissions include electric and hybrid gas-electric cars (*Figure 7.11*). The emissions reductions depend not only on the energy used while driving, but the emissions from generating electricity that the car needs for charging. If an electric car uses electricity generated at a coal-fired power plant, the net emissions may not be significantly less than a conventional gasoline-powered vehicle. But if the electric car uses electricity from a lower-emissions source, the emissions reductions can be significant. You can learn about the impact of electric power sources on vehicle emissions at the Alternative Fuels Data Center website, which allows you to enter your zip code and find out the types of energy sources in your area and the impact on vehicle emissions: [http://www.afdc.energy.gov/vehicles/electric\\_emissions.php#wheel](http://www.afdc.energy.gov/vehicles/electric_emissions.php#wheel) .

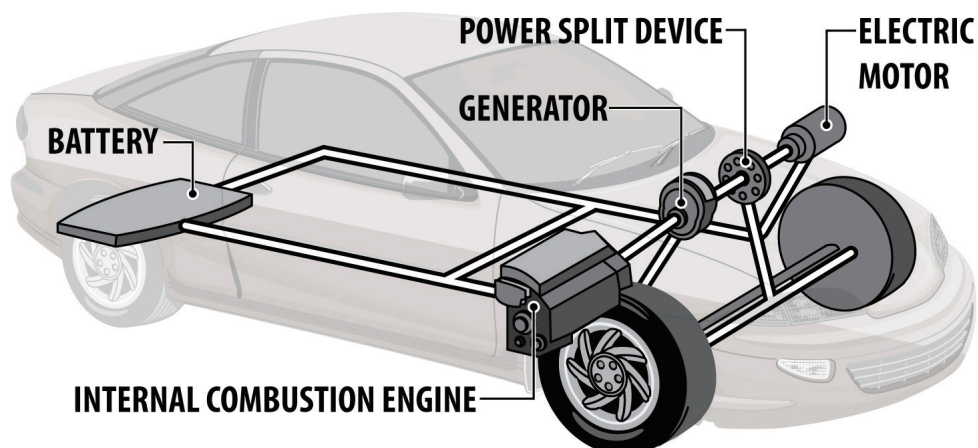
An interesting future technology to consider when discussing reduced energy use in transportation is driverless cars. Driverless cars on a smart transportation network might use less energy for several reasons. Because they remove human error they presumably wouldn't require as many safety features and could be built out of lighter materials, and a lightweight car needs less energy to run than a heavier one. They can be programmed to drive in ways that

<sup>12</sup> You can find this vehicle data and more at the National Automobile Dealers Association website, <https://www.nada.org/nadadata/>.

<sup>13</sup> Information about fuel economy improvements was published by the United States Energy Information Administration in 2014: Significant fuel economy improvement options exist for light-duty gasoline vehicles. United States Department of Energy. Retrieved February 25, 2015, from <http://199.36.140.204/todayinenergy/detail.cfm?id=17111>.



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Hybrid electric vehicles combine the benefits of gasoline engines and electric motors. Typically, the wheels are powered by an electric motor, and in some cases, the internal combustion engine assists. Hybrid electric vehicles do not need to be plugged in to charge the battery because they are charged by an onboard generator.

Figure 7.11: Diagram of a hybrid gas-electric car.

minimize energy use, unlike human drivers. Groups of driverless cars could take advantage of aerodynamic advantages like drafting, where cars following close behind a lead car benefit from reduced air resistance. Driverless cars also have the potential to reduce the demand for everyone to own their own vehicles, not only reducing the energy use for vehicle production, but also allowing the conversion of parking spaces to other uses. On the other hand, people might use driverless cars more than they use conventional cars because of the benefits and conveniences, and this could cancel out energy savings.<sup>14</sup> It remains to be seen whether driverless car networks will come into existence and what their energy impact will be.

## 2.3.3 Industry

Industrial production is energy-intensive. Industries use energy for processes that students learn about in chemistry and physics classes: driving reactions, producing heat, and doing mechanical work.<sup>15</sup> The industrial sector has potential for reducing energy use. According to the IPCC,

*The energy intensity of the industry sector could be directly reduced by about 25% compared to the current level through the wide-scale upgrading, replacement and deployment of best available technologies.*

<sup>14</sup> This dilemma is sometimes called Jevon's Paradox. For a discussion of this, see [https://en.wikipedia.org/wiki/Jevons's\\_paradox](https://en.wikipedia.org/wiki/Jevons's_paradox).

<sup>15</sup> An extensive review of industrial processes and the potential for lowering their energy use and emissions is found in the IPCC's report: Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., . . . (eds.), J. M. (2014). *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press: NY.



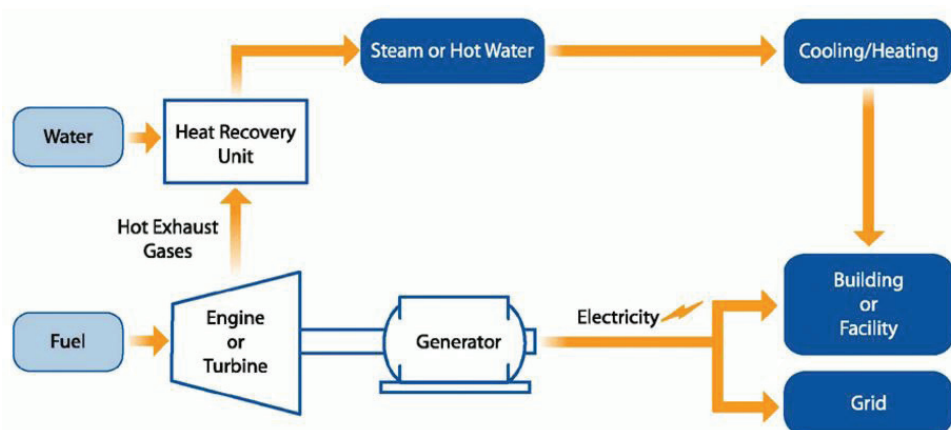


Figure 7.12: Diagram of a combined heat and power system: gas turbine or engine with heat recovery unit.

**combined heat and power**  
• an approach that uses a single fuel source to generate both electricity and usable heat. Combined heat and power systems are typically located near where the energy is consumed, and they use the heat which is wasted in traditional electrical power generation processes.

Industries and businesses are motivated to reduce energy use because this reduces their energy costs. They may be deterred by upfront costs for more energy efficient systems and not enough information about options. Examples of industrial systems with potential for energy efficiency improvements are electrical motors and systems that produce steam and heat.

One example of an industrial energy efficiency improvement is the use of on-site **combined heat and power** (CHP). Conventional electricity generation produces heat that is simply wasted, released to the atmosphere. With an on-site CHP system, a facility produces its own electricity instead of buying it from the grid, and it uses the heat generated instead of wasting it. The heat can be used to produce steam or hot water to drive industrial processes or heat and cool buildings.<sup>16</sup> The energy efficiency gain, and thus energy savings, can be tremendous: from about 50% efficiency for a conventional system to over 80% efficiency for a CHP system. The diagram in Figure 7.12 shows an example of a CHP system.

Finally, industrial processes can produce greenhouse gases not only through their energy use but from the processes themselves. One example is the production of cement, where limestone is heated, breaking down calcium carbonate and releasing CO<sub>2</sub>. Worldwide, about 5% of CO<sub>2</sub> emissions come from cement production. Carbon emissions have risen dramatically since the beginning of industrialization, and changes in the industrial sector — in the way we produce things — are an important part of climate change mitigation. We may need to find different ways to product cement, or find other materials to use instead.

## 2.4 Carbon Capture and Storage (CCS)

Imagine a coal-fired power plant or oil refinery where CO<sub>2</sub> was removed from the final waste products. After removal, the CO<sub>2</sub> could be stored away or reused for other purposes. A technological solution that could achieve this for power plants would be a huge step, because energy production is the world's largest source of greenhouse gas emissions.

<sup>16</sup> It may seem obvious to students how steam can heat a building, but not how steam can cool a building. To learn more, students can research steam turbine chillers and/or steam absorption chillers.



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## Capture and Storage

**flue gas separation** • a process which uses a liquid solvent to chemically remove CO<sub>2</sub> molecules from a gas as the molecules make their way through a flue.

**oxy-fuel combustion** • burning a fuel in pure or enriched oxygen instead of in air.

**pre-combustion** • taking place before burning.

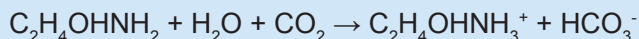
This solution, carbon capture and storage (CCS), exists today although it is mostly used in fossil fuel refining and extraction. It is not in wide use in power plants for economic and environmental reasons. The world's first large-scale, coal-burning power plant with a CCS system — the Boundary Dam plant in Saskatchewan, Canada — began operations in October, 2014. This plant has a new CCS facility, built at the cost of about \$1.1 billion (US dollars), which is expected to emit about 90% less CO<sub>2</sub> than the other parts of the plant that don't use CCS technology.

The CCS process can work in several ways, and each way has a financial and an energy price tag. For a power plant, the energy cost is taken out of the output and can be substantial. For example, a coal-fired power plant might need to use 20 to 30% of its electrical output to power its CCS system.



### Box 7.11: Chemistry connection: chemical reactions in carbon capture systems

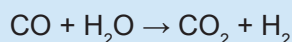
There are three main methods of capturing carbon in a CCS system. A post-combustion method called **flue gas separation** uses a liquid solvent to chemically remove the CO<sub>2</sub> molecules as they make their way through a column. The chemical reaction with the solvent monoethanolamine is shown below.



In the next step, the solvent passes through a unit where it is heated and the reaction runs in reverse, releasing condensed water vapor, the original solvent (to be reused), and concentrated CO<sub>2</sub>. This CO<sub>2</sub> can then be compressed for storage or reuse.

A second method of carbon capture, **oxy-fuel combustion**, burns the fossil fuel in pure or enriched oxygen instead of in air. This results in mostly CO<sub>2</sub> and H<sub>2</sub>O as combustion products, instead of a waste gas that contains only 3 – 15% CO<sub>2</sub>. Condensing out the water vapor leaves behind CO<sub>2</sub>, which can then be compressed and stored or reused. This process still requires a lot of energy to separate gases, but the separation takes place on incoming air before combustion — to produce the pure or enriched oxygen — instead of in the flue after combustion.

The third method, **pre-combustion**, captures CO<sub>2</sub> before burning the fossil fuel. With coal, the process begins with gasifying the coal by reacting it with oxygen and steam at high pressure and temperature, producing a gas of mostly CO and H<sub>2</sub>. The next step uses water to react with the CO to produce CO<sub>2</sub> and more H<sub>2</sub>.



In the final step, the CO<sub>2</sub> is captured and the H<sub>2</sub> is used as fuel for a turbine, to generate electricity.



## 2.4.1 Carbon Capture Costs and Benefits

The IPCC reports that carbon capture technologies can reduce CO<sub>2</sub> emissions from new power plants by 81 – 91%, depending on the method.<sup>17</sup> This reduction comes at a cost, however, ranging from a 33 to 57% increase in the cost of electricity production and a 37 to 76% increase in the capital cost. While these seem like significant costs that will lead to higher energy costs, this may be a more realistic representation of the actual cost of using energy that emits CO<sub>2</sub>. Economists often refer to this as “internalizing the externalities.” These numbers do not include any costs associated with transporting and storing the CO<sub>2</sub> after it has been captured. The tradeoffs between emissions reductions, financial costs, and environmental costs need to be evaluated when deciding whether CCS makes sense as a mitigation option.

## 2.4.2 Carbon Storage

Storing the captured CO<sub>2</sub> involves transporting it to a site where it can be injected into the Earth to be trapped under an impermeable rock layer, injected into the ocean where it would either dissolve in seawater or form a slowly-dissolving CO<sub>2</sub> lake at the sea floor, or injected together with water into rock such as basalt where it would mineralize and remain underground. All of these methods have environmental concerns and require more research. Storage under an impermeable rock layer has the risk of leakage, especially with seismic activity. It would require long-term monitoring (and the associated costs) to test whether leaks are occurring. Dissolution in the ocean only adds to the problem of ocean acidification that is taking place from atmospheric CO<sub>2</sub> dissolving in the ocean, affecting aquatic life. Carbon mineralization is appealing in that once completed there’s no risk of leakage, but it requires large amounts of water.

## 2.4.3 Carbon Reuse

Carbon reuse is an alternative to carbon storage, and one example already taking place on an industrial scale is a process called Enhanced Oil Recovery. In this process, captured CO<sub>2</sub> is injected underground into an oil reservoir in which the oil is difficult to extract through other means. The CO<sub>2</sub> mixes with or dissolves in the oil and makes it flow more readily. A full-cycle analysis of Enhanced Oil Recovery is necessary to determine whether it is a mitigation option, since the end product is a fossil fuel which, when burned, releases more CO<sub>2</sub>.

Other ways to reuse captured CO<sub>2</sub> are under research or are viable at a small scale. One example comes from the lab of Cornell University professor Geoffrey Coates, whose research group is working on creating polymers from CO<sub>2</sub> and limonene, an extract found in orange peels and other plants (*Figure 7.13*). These polymers can be used to make plastic, a product typically made from **petroleum**. Other research groups are exploring synthetic photosynthesis, a

## Capture and Storage

**petroleum** • a naturally occurring, flammable liquid found in geologic formations beneath the Earth's surface and consisting primarily of hydrocarbons. Petroleum, also called OIL, is a fossil fuel, formed when large masses of dead organisms (usually algae or plankton) are buried underneath sediments and subjected to intense heat and pressure.

<sup>17</sup> For more detail see Working Group III of the Intergovernmental Panel on Climate Change, M. B. (2005). IPCC Special Report on Carbon Dioxide Capture and Storage. Cambridge University Press: NY.

<sup>18</sup> For a news article on some of this research, see Yarris, L. (2015, April 16). Major Advance in Artificial Photosynthesis Poses Win/Win for the Environment. Retrieved December 10, 2015, from Berkeley Lab News Center: <http://newscenter.lbl.gov/2015/04/16/major-advance-in-artificial-photosynthesis/>.



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Figure 7.13: Polymers created using carbon dioxide and limonene oxide derived from orange peels.

way to produce energy and materials in a laboratory using sunlight and  $\text{CO}_2$ , mimicking the process occurring naturally within a leaf.<sup>18</sup>

## 2.5 Land Use: Forests, Soils, and Agriculture

Plants and soils sequester (hold) carbon when left untouched by large-scale human activity. Plants take in carbon through photosynthesis, release some to the atmosphere through respiration and some to the soil through their roots, and store the remainder in their tissues. A tree's dry weight is almost half from carbon.<sup>19</sup> The soil takes in carbon when plants die and decompose. When people burn forests or till soil, carbon is released into the atmosphere. The practices we use in managing forests and land can have a big impact on carbon emissions.

### 2.5.1 Forests

The story of human impacts on the world's forests over time has mainly been one of deforestation. Even the Northeastern United States, whose forests have grown back significantly after a period of extensive deforestation in the 18<sup>th</sup> and 19<sup>th</sup> centuries, is not covered with as much forested land as it was before European settlement. Today, tropical forests in the Amazon River basin, Indonesia, and central Africa are being cut and burned at a rapid rate.

Some forestry options for mitigating the release of carbon are afforestation, reforestation, reducing deforestation, and planting forests that grow rapidly. Afforestation is the process of planting trees on land that was not previously covered by a forest, or was only covered by a forest a long time ago. Reforestation is the rebuilding of forests that have recently been cut down. As with any land use, people make assessments and calculations of the value of using the land for forest versus some other use. Some forestry projects are supported through carbon offset programs: systems set up so that actions that release carbon into

<sup>19</sup> For more information on carbon stored in trees and an exercise on calculating how much carbon one tree stores, see activities from the Science Education Resource Center at Carleton College: A) Trees – the Carbon Storage Experts (<http://serc.carleton.edu/eslabs/carbon/1a.html>) and B) Carbon Storage in Local Trees (<http://serc.carleton.edu/eslabs/carbon/1b.html>).



## Box 7.12. Exercise: Discussion of Carbon Offset Programs

Air travelers may see signs at airports offering purchase of carbon offsets to offset the carbon emissions associated with air travel (which are large!). Some people think this is a good idea, because the money from these purchases goes to real actions to mitigate climate change, like establishing forests and setting up renewable energy installations. Others think that these carbon offset programs just encourage people to fly more, increasing their carbon emissions, because travelers feel they can buy their way out of environmental responsibility.

What do you think? What would be required of a carbon offset program to really make it have the intended effect of reducing carbon emissions?

## Box 7.13. Exercise: Locking Up Carbon in Biomass

An idea for removing carbon from the atmosphere is to grow a lot of trees, cut them down, put the biomass from these trees into buildings or structures that will be around for decades or centuries, and then grow more trees. How many trees would be required to make a difference? What might be the impact on total carbon uptake of replacing larger mature trees with smaller young ones? What are some other ways you can think of to “lock up” carbon?

the atmosphere (such as air travel or industrial production) are offset by paying to support actions that take in carbon, such as reforestation (see *Box 7.12*).

## 2.5.2 Soils

Soils lose carbon from natural processes such as weathering, erosion, and leaching over very long time scales. Soils that have been exposed over many thousands of years contain much less carbon than younger soils. For example, the soils of the northern Great Plains and Northeastern US are relatively young, having been scraped away by continental ice sheets and redeveloped since retreat of glaciers about 14,000 and 11,000 years ago. In contrast, the soils of the southern Appalachian Mountains have not been stripped away by glaciers, so have been in a constant state of erosion and renewal by new weathering over spans of millions of years. The northern Great Plains soils contain about 4 to 7% organic matter (that is, materials that were carbon-containing organic tissues of organisms), whereas soils in the southern Appalachian Mountains typically contain less than 1% organic matter.

Human activity depletes soil carbon at a much faster rate than natural processes do. Most soils in the Midwest retain only 50 to 70% of the carbon that they contained before people began building farms on the prairie. Tilling the soil exposes organic matter to the air where it can oxidize, releasing carbon. Carbon is also lost through wind erosion, leaching, and water runoff, processes that are accelerated when the soil is disturbed from agricultural practices.

Agricultural practices also can play a role in returning carbon to the soil. For example, instead of leaving a field fallow over the winter, farmers may plant a cover crop: a crop of rye or some other plant that will prevent erosion of exposed soil and loss of carbon through water runoff. The crop adds carbon to the soil through its roots, and in the spring the crop is killed and plowed





# Climate Change Mitigation

## Waste Management

**pyrolysis** • a method of decomposing organic material by heating it at high temperatures in the absence of oxygen.

**pre-consumer** • created before being used by a consumer. For example, pre-consumer recycled items are recycled before they have been used.

**post-consumer** • created after use by a consumer, and not involving production of any new material.



Figure 7.14: Field windbreaks in North Dakota to protect the soil against wind erosion.

under the soil, adding more carbon. *Figure 7.14* shows the practice of planting trees around fields as windbreaks, which slow the wind locally and reduce wind erosion of soil.

Other ways of sequestering carbon in soil include planting deep-rooted grasses and adding biochar to soils. Deep-rooted grasses can remove more carbon from the atmosphere simply by moving carbon deeper into the soil than shallower-rooted plants. Biochar is a solid byproduct of **pyrolysis** of plant wastes, similar to charcoal. The main products of the pyrolysis of plant wastes are liquid and gaseous biofuels. The biochar can also be used as a fuel, but if instead it is returned to the soil, improving the soil for new plant growth, biochar restores about 50% of the carbon in the soil where the plants originally grew.<sup>20</sup> The advantages of this process are that it produces renewable biofuels and sequesters carbon.

## 2.6 Waste Management

Garbage is something most people would rather not think about, and yet the ways we manage waste products in society have significant environmental impacts, including on greenhouse gas emissions. Wastes generated by human activity are classified as **pre-consumer** or **post-consumer**. Our household garbage is an example of post-consumer waste. Water use also leads to post-consumer waste that needs to be treated at wastewater facilities. Pre-consumer wastes include those from manufacturing, energy production, agriculture, and forestry.

<sup>20</sup> For more on carbon sequestration using biochar see Lehmann, J. (2007). Biochar for mitigating climate change: carbon sequestration in the black. *Forum Geookul.*, 18(2), 15-17.





Post-consumer waste accounts for less than 5% of global greenhouse gas emissions. Although this is a small fraction of total greenhouse gas emissions, pursuing proper waste management makes sense because technologies exist today to mitigate much of the emissions, and mitigation has co-benefits such as reducing pollution that is harmful to human health and providing renewable energy. Landfills, which produce methane and carbon dioxide, are the main source of greenhouse gas emissions from waste. The second largest source is wastewater, particularly from sewer systems, which can emit methane and nitrous oxide.

A direct way to reduce greenhouse gas emissions from waste is landfill gas recovery. This technique focuses on capturing and using the methane generated from bacterial anaerobic decomposition of landfill waste. Over a few decades, a landfill gas recovery project can cut methane emissions from a landfill by 60 to 90%. The captured methane can be burned to produce heat or electricity, avoiding use of fossil fuels for these needs. Although the process of burning methane produces CO<sub>2</sub>, it is a far less potent greenhouse gas than methane. A landfill gas recovery project that produces electricity can use some of the electricity to power the system and sell the rest to help pay for the required technology and infrastructure.

Waste management techniques that mitigate climate change indirectly include recycling and material reuse. These techniques avoid waste generation and avoid greenhouse gas emissions from the energy used to produce new materials. They also have the co-benefits of preventing degradation of land that often accompanies obtaining new raw materials such as metals. *Table 7.1* shows data on some of the energy and resource savings from recycling.

Composting organic matter rather than landfilling it also reduces greenhouse gas emissions. When bacteria in a landfill decompose food scraps and plant matter anaerobically, they generate methane. Organic matter in a well-tended

*Table 7.1: Energy and resource savings from recycling.*<sup>21</sup>

Material and amount	Energy saved by recycling (KWh)	Resource savings from recycling	Landfill space saved (cubic yards)
1 ton aluminum	14,000	40 barrels of oil	10.0
1 ton newsprint	601	1.7 barrels of oil and 7,000 gallons of water	4.6
1 ton office paper	4,100	9 barrels of oil and 7,000 gallons of water	3.3
1 ton plastic	5,774	16.3 barrels of oil	30.0
1 ton steel	642	1.8 barrels of oil	4.0
1 ton glass	42	5 gallons of oil	2.0

<sup>21</sup> These data come from a nice summary of the benefits of recycling from the Stanford University Buildings and Grounds Maintenance department: Frequently Asked Questions: Benefits of Recycling. Retrieved Dec. 9, 2015, from [http://bgm.stanford.edu/pssi\\_faq\\_benefits](http://bgm.stanford.edu/pssi_faq_benefits).



## Social Innovation

**life cycle analysis** • a way of determining the total environmental impact of a product, including all steps from beginning (extraction of raw materials) to end (disposal, recycling, or reuse) and quantifying all inputs and outputs.

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compost pile, with access to oxygen, will decompose aerobically and produce carbon dioxide instead of methane. In an accounting of greenhouse gas emissions this carbon dioxide is balanced by the carbon dioxide taken in to grow the organic matter, resulting in net zero emissions. In practice, compost piles can emit methane and nitrous oxide, formed in parts of the pile that are low in oxygen and high in nitrogen, respectively. The amounts are small compared with the methane that would have been generated from the organic matter in a landfill.

When considering the carbon footprint of any process, one needs to conduct a detailed and full **life cycle analysis**. This accounts for the energy use and carbon emissions from all parts of the process, including things like transportation and packaging. For composting, the sources of emissions include: transporting the organic material to the composting site; using water and running equipment to set up and maintain the site; and running equipment to transport and apply prepared compost. On the other side of the equation are: the reduction in emissions compared with landfilling; carbon sequestration in the soil when compost is used; and less use of synthetic fertilizers and herbicides, resulting in less emissions associated with their production.

Another way of managing waste to reduce carbon emissions is through waste incineration for heat and electricity generation, often called “waste-to-energy.” This process reduces carbon emissions by avoiding the use of fossil fuels for heating and electricity production. Modern waste-to-energy plants are a far cry from the household backyard burning seen in some areas. They involve sophisticated systems to efficiently generate heat and electricity and to prevent toxic air pollution. As such, they are currently expensive and are used in developed countries that have the means to build and operate them. Sweden incinerates about 50% of household waste in waste-to-energy plants, and has recently become so successful at reducing waste through recycling and reuse that it needs to import waste from other countries to burn in its plants. While waste-to-energy has certain advantages over landfills or recycling, it does produce carbon emissions and ash that must be disposed of.

## 2.7 Social Innovation

The way we go about our everyday lives within our cultural norms has an impact on our energy use and greenhouse gas emissions. For example, 76% of Americans drove to work alone in 2013.<sup>22</sup> Changing this behavior is one way to help mitigate climate change, though behavior is not the only factor. Change will also require changes in transportation systems, such as more public transportation options, and in workplace practices, such as scheduling that would allow for carpooling.

Energy savings from social innovation can be significant. For energy consumption in buildings, for example, the IPCC estimates that “for developed countries, scenarios indicate that lifestyle and behavioural changes could reduce energy demand by up to 20% in the short term and by up to 50% of

<sup>22</sup> These data came from a summary of US auto commuting statistics: McKenzie, B. (2015, August). Who Drives to Work? Commuting by Automobile in the United States: 2013. Retrieved December 10, 2015, from [www.census.gov: https://www.census.gov/hhes/commuting/files/2014/acs-32.pdf](https://www.census.gov/hhes/commuting/files/2014/acs-32.pdf)

<sup>23</sup> See the source in note 15.

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present levels by mid-century.<sup>23</sup> One example of social innovation for reducing energy use in buildings is Japan's "Cool Biz" campaign, starting in 2005. This campaign aimed to reduce air conditioning use in buildings by encouraging office workers to wear cool clothing instead of business suits. It involved changing cultural norms of how people dress at work. The campaign has been viewed as successful, and official estimates for the resulting reduction in carbon dioxide emissions per year range from 0.9 million tons (2005) to 2.2 million tons (2012).<sup>24</sup>

Another aspect of social innovation to mitigate climate change involves dietary choices in food consumption, and gives added weight to the old call to "eat your veggies." Transporting food leads to greenhouse gas emissions, but recent research has shown that by far the largest contribution to greenhouse gas emissions comes from food production, which is 83% of the average American household's food consumption carbon footprint. Red meat and dairy production are the most greenhouse gas emission-intensive. A 2008 study found that "shifting less than one day per week's worth of calories from red meat and dairy products to chicken, fish, eggs, or a vegetable-based diet achieves more GHG reduction than buying all locally sourced food."<sup>25</sup> Switching from a meat-eating diet to an entirely plant-based (vegan) diet would reduce dietary-based greenhouse gas emissions by about 50%.<sup>26</sup>

Sadly, about 30% to 40% of the US post-harvest food supply is wasted<sup>27</sup>, which has not only ethical and economic impacts but also consequences for greenhouse gas emissions. Food that ends up in landfills contributes to methane emissions. Food production uses water and energy, and researchers estimate that about 25% of the water used in agriculture goes into wasted food.<sup>28</sup> Irrigation and water treatment systems use energy, which leads to greenhouse gas emissions, so using water for wasted food is simply releasing greenhouse gases into the atmosphere for no reason. Similarly, approximately 300 million barrels of oil are used each year in US production of food that is eventually wasted. As individuals we can reduce food waste with better planning and food management (for example, freezing leftover food to eat later). As a society, we can support programs that help food producers, markets, and restaurants donate more food to those in need.<sup>29</sup> For food that is not eaten, we can prevent it from entering landfills by composting, feeding it to animals, or using it to generate energy through biomass burning (*Figure 7.15*).

<sup>24</sup> For more information about this campaign, see Yotsumoto, J. (2015, May 1). Cool Biz Campaign Heats up. Retrieved December 10, 2015, from NHK (Japan Broadcasting Corporation) World: <http://www3.nhk.or.jp/nhkworld/english/news/onbusiness/20150501.html>

<sup>25</sup> The results of this research are published here: Weber, C. L., & Matthews, H. S. (2008). Food-Miles and the Relative Climate Impacts of Food Choices in the United States. *Environ. Sci. Technol.*, 42, 3508–3513

<sup>26</sup> See Scarborough, P., Appleby, P. N., Mizdrak, A. B., Travis, R. C., Bradbury, K. E., & Key, T. J. (2014). Dietary greenhouse gas emissions of meat-eaters, fish-eaters, vegetarians and vegans in the UK. *Climatic Change*, 125(2), 179-192.

<sup>27</sup> Food that is edible but is not consumed is considered wasted. Food is wasted in many ways, such as in not using all that could be used in cooking, in being allowed to get moldy or eaten by pests before people can eat it, or in not being stored properly so its spoils and becomes inedible.

<sup>28</sup> A study that gives details on food waste in America is Hall, K. D., Guo, J., Dore, M., & Chow, C. C. (2009). The Progressive Increase of Food Waste in America and its Environmental Impact. *PLoS One*, 4(11), e7940. doi:10.1371/journal.pone.0007940 .

<sup>29</sup> Learn more about national efforts to reduce food waste here: <http://www.epa.gov/sustainable-management-food>.



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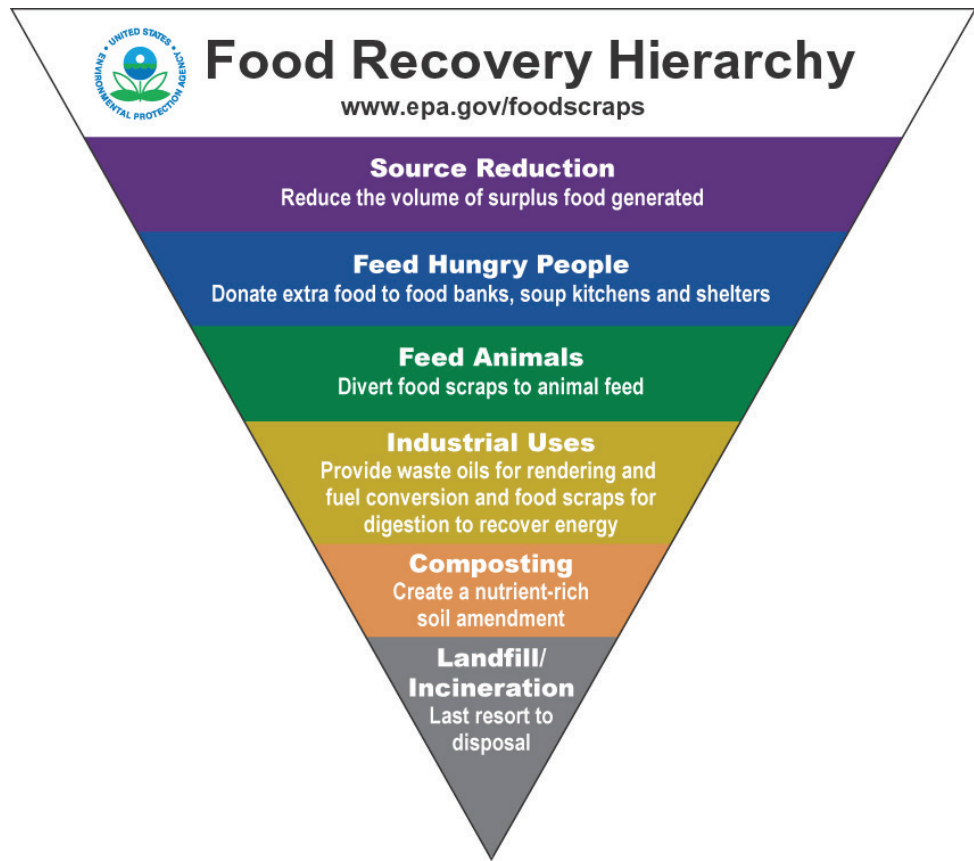


Figure 7.15: A hierarchy of options for using uneaten food.

## 3. Summary

The decisions made by humans over the past few centuries have already committed us all to unavoidable climate consequences. We are going to have to adapt to these consequences, which we explore in detail in Chapter 9. However, this does not mean that we are committed to the most catastrophic climate change scenarios. We have the capability to mitigate the factors that could lead to the worst climate changes by reducing our greenhouse gas emissions and thereby taking responsibility for the future of our planet and all the living things—include us—that live on it.

These dual efforts—adaptation and mitigation—must occur concurrently if we are to both manage the changes that are already in the pipeline and prevent the most catastrophic possibilities for our future. Climate change mitigation efforts are occurring across a wide range of systems: energy, infrastructure, transportation, industry, land use, waste management, and society. Many of the strategies for non-energy sectors are of comparable magnitude to historical technological revolutions, such as the invention of distributed electricity, or the invention of the internet. It should be noted, however, that these two examples have contributed to—and are currently dependent upon—fossil fuel based greenhouse gas emissions.



# Climate Change Mitigation

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## Summary

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On a geological timescale, humans have been using fossil fuels for only a short amount of time. Coal and peat have been used in modest quantities (compared to today) in China and Europe for several thousand years, and coal use accelerated in Europe (especially England) from the 1500s to 1700s. It wasn't until the invention of the steam engine and industrial revolution in England the late 1700s that coal became a primary energy source.<sup>30</sup> In the US, it was around 1885 when coal began to produce more energy than wood combustion, and only around 1950 that petroleum products produced more energy than coal. To avoid catastrophic climate change over the next century and beyond, we are going to need to transition away from coal and petroleum fossil fuel products towards a renewable- and/or nuclear-powered future.

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<sup>30</sup> A readable account of the history of coal use can be found in Barbara Freese's 2003 book *Coal: A Human History*, Penguin Books: NY.



# Climate Change Mitigation

## Resources

### Mitigation

For a comprehensive overview of climate change mitigation in many sectors of the economy, see the Intergovernmental Panel on Climate Change (IPCC) report. The latest IPCC report as of the writing of this guide (2017) was published in 2014: <http://www.ipcc.ch/report/ar5/wg3/>.

Links to information from the US Environmental Protection Agency (EPA) on US greenhouse gas emissions, the EPA's efforts to reduce emissions, and what you can do: <https://www3.epa.gov/climatechange/reducing-emissions.html>.

### Energy

A useful resource for teaching about energy is *Energy Literacy: Essential Principles and Fundamental Concepts for Energy Education*: <http://energy.gov/eere/education/energy-literacy-essential-principles-and-fundamental-concepts-energy-education>.

The US Department of Energy's website (<http://energy.gov/>) has information about energy, including education resources: <http://energy.gov/science-innovation/science-education>.

A vast amount of information, data, and graphics on energy production, energy use, greenhouse gas emissions, and more is available from the US Energy Information Administration Independent Statistics and Analysis: <http://www.eia.gov/>.

The National Energy Education Project website contains teaching resources, information for students, and more: <http://www.need.org/>.

### Renewable Energy

US Department of Energy Office of Energy Efficiency and Renewable Energy: <http://energy.gov/eere/office-energy-efficiency-renewable-energy>.

Information on microhydropower: <http://energy.gov/eere/energybasics/articles/microhydropower-basics>.

The Wind Prospector: An interactive mapping tool to assess potential wind energy resources in the US. <https://maps.nrel.gov/wind-prospector/>.

A video on how geothermal heat pumps work: <https://energy.gov/eere/education/videos/energy-101-geothermal-heat-pumps>.

The Geothermal Prospector: An interactive mapping tool to assess potential geothermal energy resources in the US. <https://maps.nrel.gov/geothermal-prospector/>.

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Map of solar energy potential in the US (zoom out to see Alaska and Hawaii):

<https://energy.gov/maps/solar-energy-potential>.

## **Information on What Individuals and Schools Can Do**

### **Carbon Footprint Calculators**

- One geared towards secondary school students: <http://web.stanford.edu/group/inquiry2insight/cgi-bin/i2sea-r2a/i2s.php>
- <http://www.nature.org/greenliving/carboncalculator/>
- <https://www3.epa.gov/carbon-footprint-calculator/>

### **A Few Websites/Documents on Energy Use in Schools**

- <https://www.energystar.gov/buildings/tools-and-resources/datatrends-energy-use-k-12-schools>
- [https://www.epa.gov/sites/production/files/2015-08/documents/k-12\\_guide.pdf](https://www.epa.gov/sites/production/files/2015-08/documents/k-12_guide.pdf)
- <https://www.ase.org/projects/powersave-schools>

