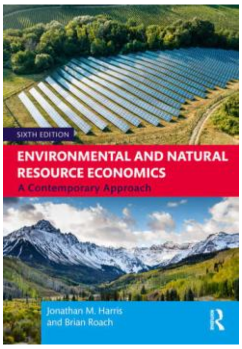


Chapter 11 from *Environmental and Natural Resource Economics: A Contemporary Approach*, 6th Edition.

Note: This sample chapter does not incorporate changes made during the proof stage. It may contain minor differences from the published chapter.

Chapter 11: Energy: The Great Transition

Chapter 11 Focus Questions

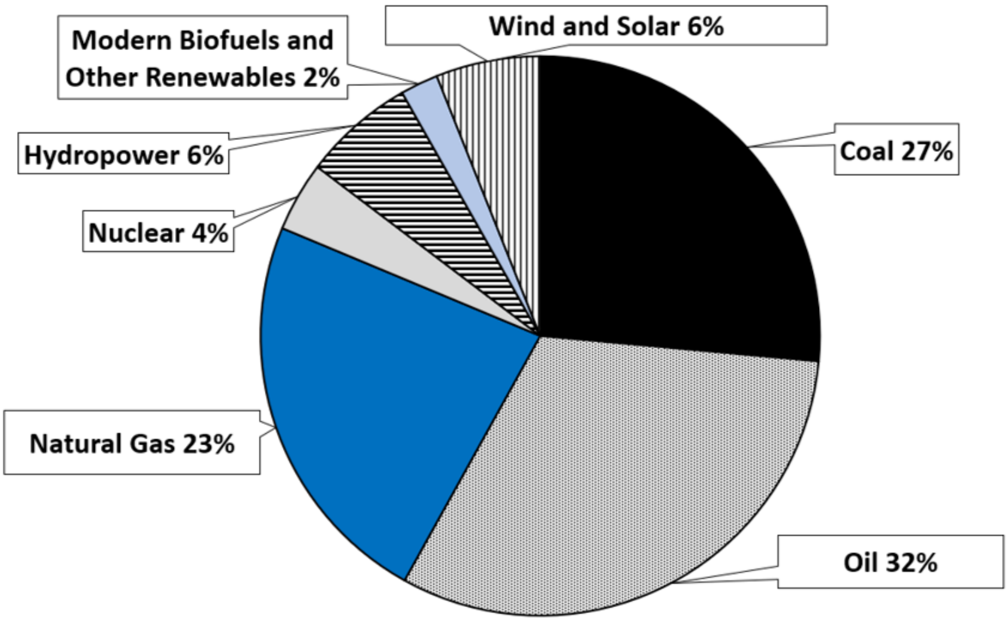
- What are the world's major energy challenges?
- How do different renewable and nonrenewable forms of energy compare?
- How are the economics of energy changing?
- What policies can be implemented to address the world's energy challenges?

11.1 Global Energy Challenges

The Industrial Revolution in the eighteenth and nineteenth centuries was driven by a transition away from traditional energy sources, such as wood and animal power, to fossil-fuel energy. If humanity is to achieve a sustainability revolution in the twenty-first century, it will be driven by a transition away from fossil-fuel energy to renewable sources, such as wind and solar power. Modern economies are absolutely dependent on a continual supply of energy. While energy expenditures represent only about 7% of GDP in the US, the other 93% of the economy would collapse without sufficient energy supplies.[1]

The great transition away from fossil fuels is already underway, driven by changes in technology, prices, and government policies. But the transition is not occurring fast enough to prevent unacceptable climate change—the world's first energy challenge we consider in this section.[2] (Climate change issues are discussed in detail in Chapters 12 and 13.) Currently, the world obtains over 80% of its energy from fossil fuels, as shown in Figure 11.1—a percentage which has remained essentially constant over the last few decades. While the amount of global energy obtained from wind and solar power increased by a factor of 5 over the period 2013–2023, these sources are still only a small percentage of total energy use.[3] According to a 2024 report:

Figure 11.1 Global Energy Supplies by Source, 2023



Source: Energy Institute. 2024. *Statistical Review of World Energy*. 73rd Edition.

> New analysis from the International Energy Agency shows the renewables race is picking up speed, with cleaner sources of energy being rolled out faster than any other time in the last three decades. The world added 50% more renewable capacity in 2023 than it did in the previous year, with solar PV accounting for three-quarters of additions worldwide. However, we are not yet on track to triple renewable capacity by 2030.[4]

The goal of tripling renewable energy capacity by 2030, accepted by international negotiators at an international conference on climate in 2023, is seen as an intermediate goal towards a complete transition to renewables by 2050—but requires significantly greater policy commitment by governments and corporations as well as local initiatives.

The challenge of transitioning away from fossil fuels raises the related challenge of electrification of the world's energy system. Fossil fuels provide energy both directly through combustion and indirectly by generating electricity. For example, when gasoline is burned in a car engine or natural gas is burned in a furnace, we use the resulting energy directly to drive a car or heat a home. Indirectly, fossil fuels can generate electricity that is then used for various purposes. The energy from renewable sources, such as wind and solar energy, can also be converted to electricity for final use.

Currently, about 20% of the world's energy comes from electricity, including electricity generated from renewable and nonrenewable sources. For a large-scale transition to renewable energy, many processes that currently rely on the direct burning of fossil fuels will have to be converted to electric power.

For example, rather than powering vehicles by burning gasoline, electric vehicles can be powered indirectly from wind, solar, or other renewable energy. Building heating by oil or natural gas can be replaced with electrically powered heat pumps. Electric technologies for transportation, heating, industrial production, and other uses are developing rapidly, along with battery technology to store electric energy. (See Box 11.1 for more on electric vehicles.) The global infrastructure to deliver electricity will need to be significantly expanded and modernized.

Box 11.1 The Advantages of Electric Vehicles

Global sales of electric vehicles (EVs) increased by 25% in 2024, mainly due to rapid sales growth in China. EVs now account for nearly one quarter of all new vehicle sales globally. EVs offer numerous economic and environmental advantages over traditional vehicles.

While producing an EV results in a larger carbon footprint than production of a similar gas-powered car, EVs have significantly lower operating emissions. A 2023 analysis by the US Department of Energy found that the "cradle-to-grave" carbon emissions of EVs in the US are less than half those of a comparable gas-powered vehicle. Lifecycle emissions from EVs are lower even if the electricity powering them comes from "dirty" sources such as coal and natural gas. As a greater share of electricity is generated from renewable sources, the environmental benefits of EVs will increase further.

With fewer moving parts, EVs also require less maintenance. For example, EVs require no oil changes or tune-ups and have no exhaust systems, belts, or complex transmissions. Another advantage of EVs is lower operating costs for "fuel". According to the US Department of Energy, drivers can save up to $2,200 annually in fuel costs by switching to an EV.

The adoption of EVs varies significantly across countries. In the US, EVs accounted for about 9% of new car sales in 2024. In China, nearly one-third of new vehicle sales were EVs in 2024. The leader in EV adoption is Norway, where EVs account for 90% of new vehicle sales. Norway demonstrates how government incentives can dramatically boost the sales of EVs. EV owners in Norway are exempt from most purchase taxes, including a 25% value-added tax, and pay reduced fees for parking and tolls. EV drivers can use bus lanes and have access to an extensive network of charging stations. Norway has also established charging rights for people who live in apartment buildings. As a result of these incentives, Norway appears on track to meet its goal of selling only zero-emissions vehicles (EVs and hydrogen vehicles) in 2025.

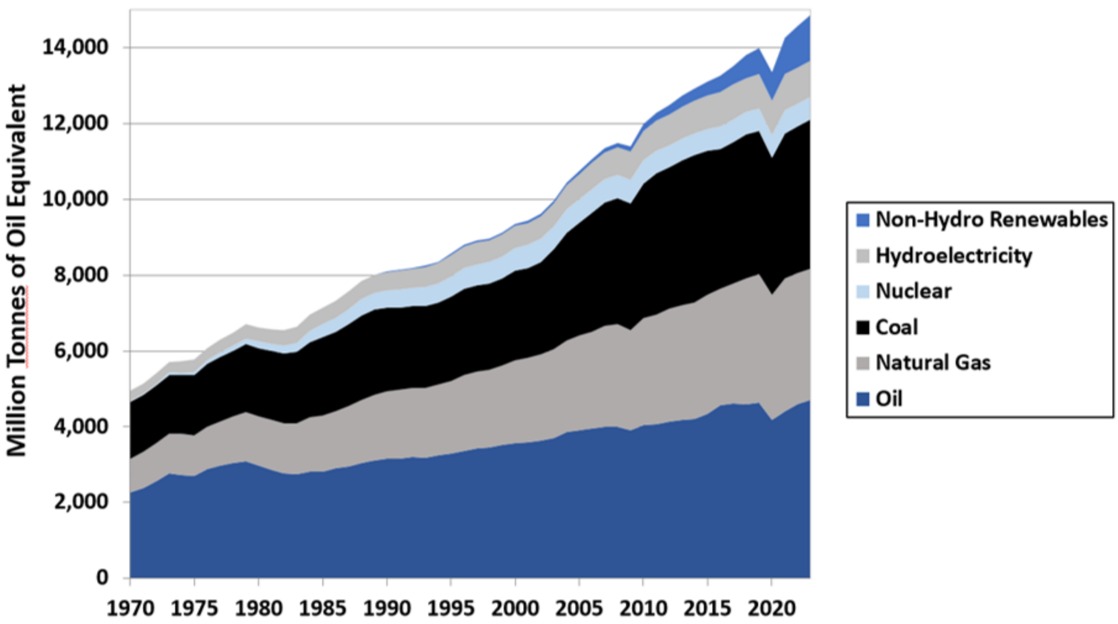
Source: Subramanian, Pras. 2025. "Global EV Sales Surge 25% in 2024, Led by China." Yahoo Finance, January 14; Kelly, Jarod C., Amgad Elgowainy, Raphael Isaac, *et al.* 2023. *Cradle-to-Grave Lifecycle Analysis of U.S. Light-duty Vehicle-fuel Pathways: A Greenhouse Gas Emissions and Economic Assessment of Current (2020) and Future (2030–2035) Technologies*. Argonne National Laboratory, Energy Systems Division. ANL-22/27 Rev. 1; Levin, Tim. 2022. "Yes, Electric Vehicles Are Greener than Gas Cars — Even When They Use Dirty Power." Business Insider. December 17; US Department of Energy. 2024. "Save Up to $2,200 a Year Driving an Electric Vehicle." Office of Policy. April 18; Adomaitis, Nerijus. 2025. "In Norway, Nearly All New Cars Sold in 2024 Were Fully Electric." Reuters. January 2; US Energy Information Administration. 2024. "U.S. Share of Electric and Hybrid Vehicle Sales Reached a Record in the Third Quarter." In Brief Analysis. December 4; Tang, Lucy. 2024. "China's EV Sales, Output Hit Fresh Record in Sep." S&P Global. October 14; Norsk Elbilforening. 2025. "Norwegian EV Policy." https://elbil.no/english/norwegian-ev-policy/.

While technological changes and market forces increasingly favor renewable energy and electrification over fossil fuels, government policies will ultimately determine how fast the transition occurs. Policies that focus on changing a society's energy mix, such as shifting from fossil fuels toward renewables, are referred to as **supply-side energy management**. For example, Germany has set a target of obtaining 80% of its electricity from renewable sources by 2030.[5]

supply-side energy management energy policies that seek to change the energy mix in a society, such as switching from fossil fuels to renewables.

The world's energy challenge is not simply about switching energy sources. Global energy demand has been increasing steadily, as shown in Figure 11.2. While the world's consumption of renewable energy increased by a factor of 23 between 2000 and 2023, overall demand for fossil fuels is also increasing. During this same period, the global demand for oil increased by 32%, and demand for natural gas increased by 59%. Despite growth in renewables (seen as the top two sections in Figure 11.2), the main trend of recent decades has been overall growth in almost all energy sources. (An exception is nuclear energy, with global demand declining slightly since 2010.)

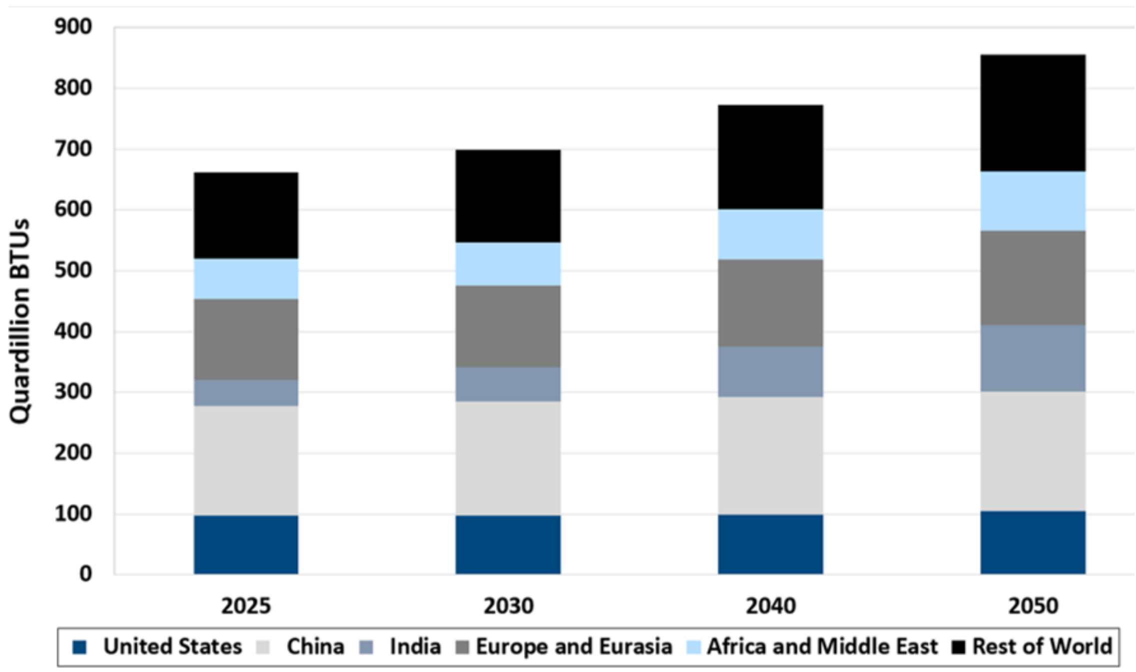
Figure 11.2 Global Energy Demand by Source, 1970–2023



Source: Various editions of the *Statistical Review of World Energy*, published by BP (prior to 2023) and the Energy Institute (since 2023).

Most projections indicate that global energy demand will continue to increase. The US Energy Information Administration (EIA) projects that the world's energy demand will increase by 27% between 2025 and 2050, as shown in Figure 11.3. Most of this increase is expected to occur in lower-income countries, with energy demand increasing by 84% in Africa and 254% in India.

Figure 11.3 Projected Global Energy Demand 2025–2050, by Country/Region



Source: US Energy Information Administration. 2023. *International Energy Outlook 2023.*
Note: Btu is British thermal units (the amount of heat or energy required to raise the temperature of one pound of water by one degree Fahrenheit).

Figure 11.3 illustrates another major energy challenge—a focus on **demand-side energy management**, or policies that seek to reduce total energy demand (or at least reduce the rate of growth in demand). The projection in Figure 11.3 is from the EIA's "reference case," which is based on current national energy policies and specific assumptions about future energy prices, technology, and economic growth. Later in the chapter we will consider whether significant growth in global energy demand can be avoided through energy efficiency improvements, energy pricing, and other policies.

Efforts to slow the increase in global energy demand should complement policies that transition the world's energy mix away from fossil fuels, speeding the attainment of a sustainable energy system. By "lowering the ceiling" of total demand and "raising the floor" of renewable capacity, the world's dependence on fossil fuels can be steadily reduced and perhaps even eventually eliminated.

demand-side energy management energy policies that seek to reduce total energy consumption, such as through energy efficiency improvements.

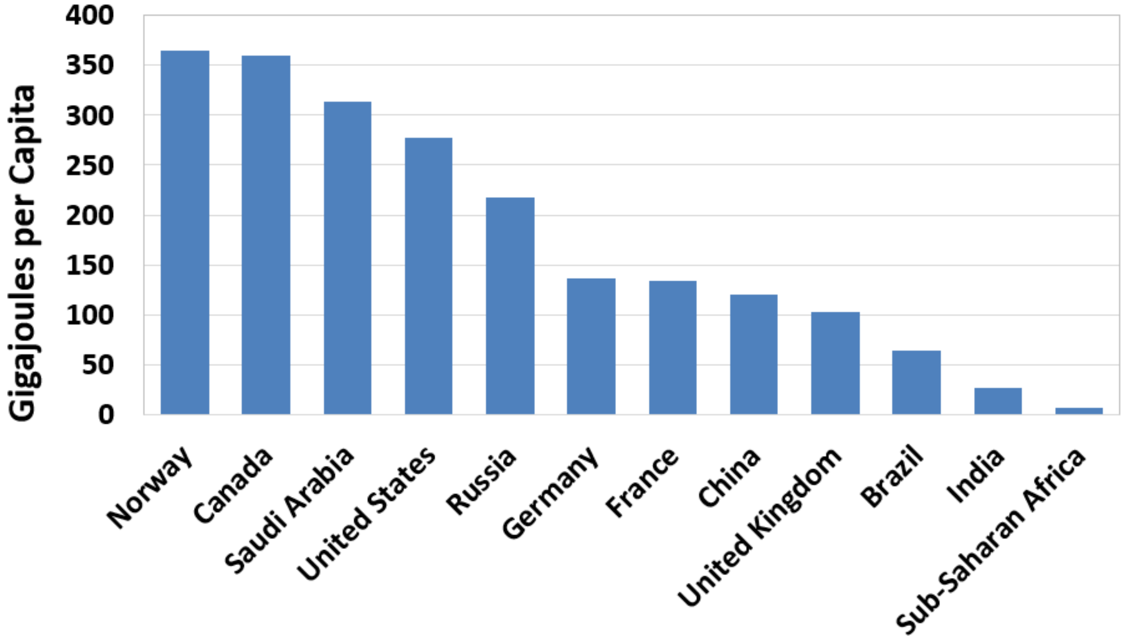
One interpretation of Figure 11.3 is that policy efforts should be directed toward limiting the growth in energy demand in lower-income region of the world. But this perspective neglects a final energy challenge—addressing the global disparity in access to, and consumption of, energy. According to the World Bank, about 1.3 billion people globally suffer from energy poverty, including 730 million without any electricity access at all and over 600 million more who lack "adequate, reliable, and affordable energy."[6] As of 2022, there are 22 countries, most in sub-Saharan Africa, where less than half of the population have access to electricity.[7]

The global disparity in energy consumption is illustrated in Figure 11.4, which shows annual energy consumption per capita in various countries. The average American consumes more than twice as much energy as the average European or Chinese person, ten times as much as the average Indian, and 40 times as much as the average person in sub-Saharan Africa.

A 2020 paper finds that the lowest-income 50% of the global population consume less than 20% of total energy use, while the highest-income 10% consume nearly 40% of the world's energy. The authors note that:

> Energy provision is considered a fundamental and integral development challenge. A minimum level of energy consumption is required to enable decent well-being. Our results demonstrate that energy consumption is far from equitable and varies to extreme degrees across countries and income groups …. Many people suffer from energy deprivation and quite a few are consuming far too much.[8]

Figure 11.4 Annual Energy Consumption per Capita in Select Countries/Regions, 2023



Source: Energy Institute. 2024. *Statistical Review of World Energy 2024.*

Most economic studies find that access to energy is an important factor explaining long-term economic growth.[9] Thus, reducing disparities in access to energy is critical to reducing global economic inequality. The world cannot equitably meet its other energy challenges by limiting the development aspirations of the world's lowest-income people. But lower-income countries cannot take the same energy path that advanced economies took, which has been heavily dependent on fossil fuels. International cooperation and aid will be required to ensure that developing countries can utilize their energy resources in a sustainable manner.

In summary, four major energy challenges confronting the world are:

1. The transition away from fossil fuels toward renewable energy sources needs to be accelerated if the world is to avoid unacceptable climate change.
2. Expanding the world's reliance on renewable energy will require the electrification of most of the world's energy systems.
3. Restraining the growth in global energy demand is essential. In higher-income countries, energy demand should be reduced through improvements in energy efficiency.

4. Global energy inequality must be reduced, ensuring that low-income countries have access to the clean energy that is needed to increase their well-being.

While these challenges are significant, implying a major transformation of national and global energy systems, in the remainder of this chapter we will see that there are reasons for optimism. In the next section, we will discuss nonrenewable energy sources—fossil fuels and nuclear energy. Then we will discuss renewable energy sources, including wind, solar, hydroelectric, and geothermal energy. In the final two sections, we will focus on energy economics and policies to address the world's energy challenges.

11.2 Nonrenewable Energy Sources

Nonrenewable energy sources are those that do not regenerate through natural processes, at least on a human time scale. We consider four nonrenewable energy sources in this section: oil, coal, natural gas, and nuclear energy.

nonrenewable energy sources energy sources that do not regenerate through natural processes, at least on a human time scale, such as oil and coal.

The first three energy sources are fossil fuels, formed from the fossilized remains of plants and animals that lived millions of years ago. As these energy sources are nonrenewable, one issue to consider is the availability of supplies. Is running out of any of these sources a significant concern? We also need to consider the environmental impacts of relying on these sources. Average prices, along with the volatility of prices, is another important factor to consider when evaluating different energy sources.

Oil

Oil is a broad term including all liquid petroleum products such as gasoline, diesel fuel, aviation fuel, and motor oils. Oil is predominately used for transportation—currently over 90% of the world's energy for transportation comes from oil.[10] As an energy source for transportation, oil offers the advantages of being easier to store than other fossil fuels and having a relatively high energy density (i.e., a high energy to weight ratio). In our evaluation of oil, we consider three main issues: oil supplies, oil prices, and environmental impacts.

From the mid-twentieth century until recently, many oil analysts expressed concern over limited oil supplies. Like other fossil fuels, oil is ultimately a nonrenewable resource that is available in a fixed global quantity. The theory of "peak oil" production projected that global oil production would eventually peak and decline due to the depletion of economically viable supplies. Along with rising demand, declining oil production would lead to rapidly rising oil prices, with broader negative economic and social impacts such as economic recessions and conflicts over limited oil supplies. So far, though, this theory has not been borne out.

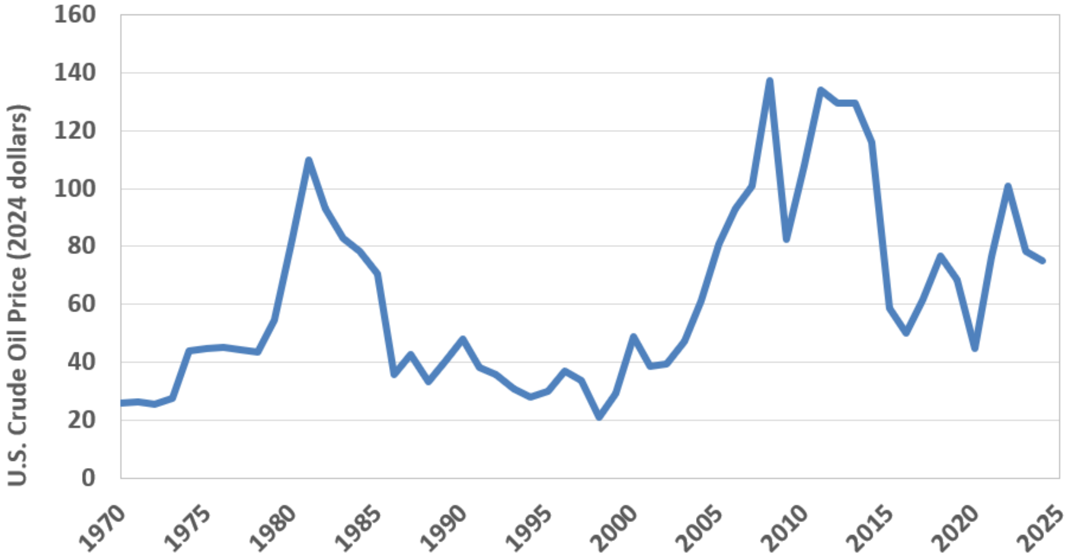
While the global quantity of oil is ultimately limited, new discoveries and technologies have expanded the known reserves (we'll discuss the different types of reserves in more detail in Chapter 17). Current proven oil reserves are actually 2.4 times larger now than they were in 1980, even as global oil demand has steadily increased.[11] Proven reserves could meet global demands for over 40 years at current consumption rates, and new discoveries continue to be made.

Given that oil supplies do not appear to be a limitation on production for the foreseeable future, the focus in oil markets has shifted from the supply side to the demand side. As transportation becomes less reliant on oil and more reliant on electricity and other energy sources, oil market experts are now asking when peak oil demand, rather than peak oil production, will occur.

While, as of 2025, the global demand for oil continues to rise, peak oil demand is expected to occur within the next decade.[12] The International Energy Agency (IEA) projects that global oil demand will level off sometime before 2030.[13] A 2024 analysis by Goldman Sachs sees oil demand declining after about 2035.[14]

One of the main reasons for oil's historical dominance in the transportation sector is that it is normally quite affordable. But the price of oil is also highly volatile, as shown in Figure 11.5. After adjusting for inflation, oil prices were particularly high in the late 1970s and early 1980s, and again in the late 2000s and early 2010s. The price of oil is more difficult to forecast than any other energy source, as the price depends not only on economic conditions but also on political factors, such as conflicts in the Middle East.

Figure 11.5 Crude Oil Prices in Constant Dollars, 1970–2024



Source: US Energy Information Administration, "U.S. Crude Oil First Purchase Price."; Federal Reserve Bank of Minneapolis. "Consumer Price Index 1913–."

Significant uncertainty about future oil prices complicates long-term investment decisions between energy sources. Consider, for example, a delivery business trying to decide whether to purchase a fleet of delivery vehicles that operate on gasoline or electricity from renewable energy. The business may reasonably assume the price of renewable energy will decline in the future, but it will not be able to predict the future price of oil with any certainty. Thus, even if the current price of oil is slightly lower than the price of renewable energy, a business may favor renewables, as future costs will be known with more certainty.

All fossil fuels are carbon-based, meaning they emit carbon dioxide (the main greenhouse gas) when burned. In addition, using fossil fuels also generates local air pollutants including nitrogen oxides, particulate matter, and sulfur oxides. Other environmental impacts of fossil fuels include habitat destruction and water pollution from mining and damage from accidental spills.

Table 11.1 compares the human health impacts and greenhouse gas emissions of various energy sources per unit of energy generated. We see that coal is the most environmentally destructive energy source, both in terms of human health impacts and climate change. Oil is the second most-damaging energy source per unit of energy. Oil is responsible for about 32% of the world's carbon emissions.[15] Other types of pollution from oil are widespread. While large oil spills receive a great deal of media attention, the majority of oil that is released into coastal and marine environments comes from runoff that washes oil from roads and parking lots and leakage from ships other than oil tankers.[16]

Table 11.1 Human Health Impacts and Greenhouse Gas Emissions of Various Energy Sources, per Unit of Energy

Energy Source	Human Deaths from Accidents and Air Pollution per Terawatt of Energy	Greenhouse Gas Emissions per Gigawatt of Energy (Tonnes)
Coal	24.6	970
Oil	18.4	720
Natural Gas	2.8	440
Biomass	4.6	78–230
Nuclear	0.03	6
Hydropower	1.3	24
Wind	0.04	11
Solar	0.02	53

Source: Ritchie, Hannah. 2020. "What Are the Safest and Cleanest Sources of Energy?" Our World in Data.

Coal

Coal is the world's second-largest source of energy, behind only oil. Coal is primarily used to generate electricity—it provides over one third of the world's electricity, more than any other source. China is by far the world's largest consumer of coal, with 56% of global demand in 2023, followed by India with 13% of global demand. While the US was the world's largest coal consumer up to 1985, it has since fallen to third, with demand declining by about half between 2014 and 2023.[17]

Although coal is a nonrenewable resource, the world's coal reserves are extensive. Coal is the most abundant fossil fuel, with known reserves sufficient to meet current global demand for more than 130 years.[18] As shown in Table 11.1, it is also the most environmentally destructive energy source. Even though the world obtains more energy from oil than coal, coal is responsible for more CO_2 emissions than oil—41% of global emissions.[19]

Coal is also the main source of local air pollutants, such as sulfur dioxide and nitrogen oxides. The World Health Organization estimates that local outdoor air pollution kills over 4 million people per year, mainly from burning coal, with nearly 90% of these deaths in middle- and low-income countries.[20] Coal pollution is also a significant source of premature mortality in developed countries. A 2023 study found that coal pollution was responsible for 460,000 premature deaths in the US from 1999 to 2020.[21]

Similar to oil, global demand for coal is still rising but a peak is expected soon. According to the IEA, peak coal demand is expected around 2027 "as a surge in renewable power helps to meet soaring demand for electricity around the world."[22]

Natural Gas

Natural gas is sometimes touted as a "transitional" or "bridge" fuel as societies move away from coal and oil but are not able to expand renewable energy rapidly enough due to technical or financial reasons. Natural gas's main advantage over other fossil fuels is that it is generally less environmentally damaging, as we saw in Table 11.1. Natural gas is more flexible than other fossil fuels. It can be burned directly to power vehicles, heat buildings, and operate industrial machinery. It can generate electricity more efficiently than coal, and generally at lower cost per unit of energy.

The displacement of coal by natural gas has been facilitated by new natural gas extraction technologies, specifically improvements in hydraulic fracturing (or "fracking"). Fracking involves injecting water and chemicals deep underground to fracture surrounding rock, releasing pockets of natural gas, and potentially oil as well, that are then pumped to the surface. While fracking has been used to a limited extent for several decades, it became much more common in several countries in the 2000s and 2010s. In 2000, only about 10% of the natural gas produced in the US came from fracking, but by 2015 that share rose to two thirds.[23]

Despite (or perhaps because of) this rapid expansion, fracking is a controversial technology, and some countries have banned the practice (see Box 11.2).

Box 11.2 Tainted Water and Earthquakes Linked to Hydraulic Fracturing for Natural Gas

Fracking can contaminate drinking water supplies in several ways. The chemicals injected during fracking or the natural gas extracted can leak through the well casing, normally constructed out of steel or cement, into groundwater aquifers. Fracking wastes are temporarily stored in above-ground ponds, with toxic chemicals that can leach into drinking water supplies. Final disposal of fracking wastes is commonly done by deep well injections, presenting another opportunity for water contamination. A comprehensive 2016 report on fracking by the US EPA concluded that it "can impact drinking water resources under some circumstances." Regulation of fracking in the US is largely left to the individual states, with different requirements regarding disclosure, containment, and monitoring.

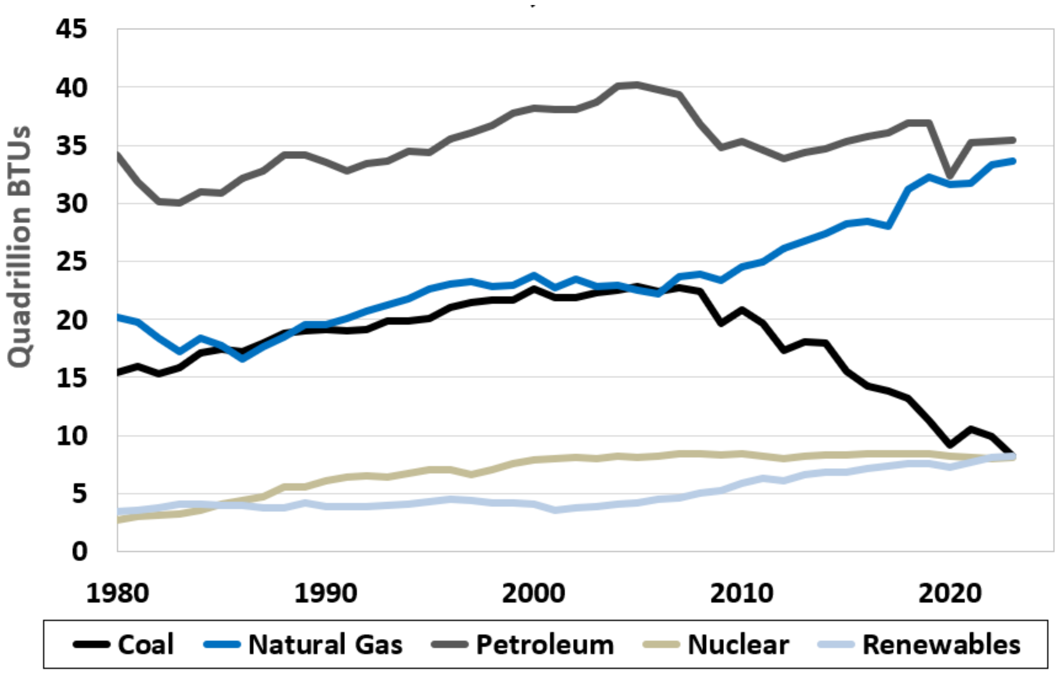
Another concern with fracking is that disposal of the wastes in deep wells increases pressure on underground rock structures, leading to an increase in earthquakes. Fracking has been linked to a three-fold increase in earthquakes in parts of British Columbia. Near fracking locations in central Texas up to 60 earthquakes per week were recorded in 2024, including a 5.1-magnitude quake.

Some energy analysts assert that fracking for natural gas is an important tool in reducing carbon emissions (as compared to using coal) and can be done safely with better regulations. For example, stricter requirements for the lining of wastewater ponds can reduce leakage into water supplies. Stronger standards for well casing construction can also reduce leaks. Other analysts conclude that the risks of fracking outweigh the benefits, and that the practice should be banned. Four US states (Maryland, New York, Vermont, and Washington) have banned fracking, along with four of Canada's ten provinces. Countries that have banned fracking include Germany, France, and the United Kingdom.

Source: US Environmental Protection Agency (EPA). 2016. "Hydraulic Fracturing for Oil and Gas: Impacts from the Hydraulic Fracturing Water Cycle on Drinking Water Resources in the United States." *Final Report. EPA/600/R-16/236F*, Washington, DC; Ormiston, Susan, and Jill English. 2025. "The Fracking Frenzy in B.C. and Texas Is Leading to Record-Breaking Earthquakes." CBC (Canada). February 1; Lin-Schweitzer, Anna. 2022. "Integrated Effort Needed to Mitigate Fracking while Protecting Both Humans and the Environment." Yale School of Public Health. March 30; https://en.wikipedia.org/wiki/Fracking_by_country.

The switch away from coal toward natural gas in the US is shown in Figure 11.6. Up to about 2005, coal and natural gas each provided about one quarter of the US energy supply. But as improvements in fracking technology reduced the cost of natural gas extraction, a rapid increase in natural gas consumption coincided with a reduction in coal consumption. As the total energy obtained from coal and natural gas combined has changed little since 2005, it is accurate to say that natural gas has been directly displacing coal in the US. According to the IEA, switching electricity generation from coal to natural gas reduces greenhouse gas emissions by 50% on average.[24] The displacement of coal by natural gas in the US is largely responsible for the country's 20% decrease in carbon emissions from 2005 to 2023.[25]

Figure 11.6 Energy Consumption in the United States, by Source, 1980–2023



Source: US Energy Information Administration. 2024. "U.S. Energy Facts Explained." July 15.
Note: Btu is British thermal units (the amount of heat or energy required to raise the temperature of one pound of water by one degree Fahrenheit).

The environmental benefits of natural gas relative to other fossil fuels, however, are not unambiguous. Natural gas is primarily composed of methane, which is a greenhouse gas that causes about 25 times the warming effect of an equivalent amount of CO_2 (although its lifetime in the atmosphere is less, about 12 years rather than hundreds of years). When burned, methane is converted into CO_2, but methane can be directly released to the atmosphere during natural gas extraction and transportation by leaking production facilities and pipelines.

Recent analyses indicate that methane leakage rates are higher than previously estimated. A 2024 article in the journal *Nature* found that actual methane emissions for oil and gas facilities in the US are about three times higher than government estimates.[26] Satellite data identified over 1,000 methane "super emitter events" in 2022—leaking more than one ton of methane per hour—with the majority of the sites in Turkmenistan, India, the US, Russia, and Pakistan.[27]

According to some analyses, with higher leakage rates natural gas may be as bad as or worse than coal in terms of medium-term global climate impacts. "To achieve and maintain a climate edge over coal, the natural gas industry may have to nearly eliminate methane leaks. That's difficult, and it comes as critics are working to find more leaks regulators and the industry may be missing."[28]

The other concern with switching to natural gas as a transitional energy source is that it postpones the adoption of renewable energy. Though natural gas is generally "greener" than coal or oil, it is clearly more environmentally damaging than renewables (see Table 11.1).

Further, natural gas's role as a transitional fuel rests on the assumption that it should be used until renewable energy technologies develop to the point where they can be widely deployed and cost competitive. As we will see shortly, renewable energy technologies have progressed much faster than anticipated, leading to dramatic price reductions. The role of natural gas as a transitional fuel thus appears unnecessary, as a direct transition from all fossil fuels to renewable energy becomes more feasible.

Nuclear Energy

The final nonrenewable energy source we consider is nuclear energy. Nuclear is a nonrenewable energy source as its fuel, drawn from uranium reserves, is a nonrenewable mineral. In the 1950s, nuclear power was promoted as a safe, clean, and cheap source of energy. Proponents of nuclear power stated that it would be "too cheap to meter" and predicted that nuclear power would provide about one quarter of the world's commercial energy and most of the world's electricity by 2000.[29]

Currently, nuclear power provides only about 4% of the world's primary energy consumption and about 9% of the world's electricity. Most of the world's installed nuclear power capacity predates 1990. The decommissioning of older plants, which had an expected life span of 30 to 40 years, has already begun. Recently, however, some people have called for a "nuclear renaissance," mainly because carbon emissions from the nuclear power life cycle are much lower than with fossil fuels (see Table 11.1).

The catastrophic 2011 Fukushima accident in Japan caused many countries to reconsider their nuclear power plans. Japan is currently re-evaluating its use of nuclear power, with most of its reactors sitting idle. Germany decided to phase out the use of nuclear power, with its last sites closing in 2023. In Italy, the debate over nuclear power was put to voters, with 94% rejecting plans for an expansion of nuclear power. But other countries are moving ahead with plans to expand their use of nuclear power, particularly China. China has over 50 nuclear plants currently operating with dozens more under construction or planned. Other countries increasing their production of nuclear power are India, Russia, and South Korea.

The role of nuclear power in the future global energy mix thus remains uncertain. The Fukushima accident has lowered baseline projections of future energy supplies from nuclear power. While some see the accident as evidence that we need to focus more on renewables, such as wind and solar, others worry that a decline in nuclear power will make it more difficult to meet climate targets. Despite the initial promise of affordable nuclear energy, the cost of building and operating nuclear power plants has generally increased, while the cost of renewable energy has declined. The only two new US nuclear plants, at the Vogtle complex in Georgia, cost $30 billion—a $17 billion cost overrun—and came online seven years late, in 2023.[30] Ultimately, economic factors, rather than safety concerns, may present the main barrier to a nuclear renaissance.

11.3 Renewable Energy Sources

Renewable energy sources are those that are supplied by nature on a continual basis, including wind, solar, hydroelectric, and geothermal. They are clearly less environmentally damaging than fossil fuels, both in terms of air and water pollution and greenhouse gas emissions (see Table 11.1). That doesn't mean renewable energy isn't without negative environmental impacts, including damage to river habitats from hydroelectric dams, bird deaths from wind turbines, and land degradation from mining minerals for solar panels.[31]

renewable energy sources energy sources that are supplied on a continual basis, such as wind, solar, water, and biomass energy.

In one sense, renewable energy is unlimited, as supplies are continually replenished through natural processes. The total amount of energy embodied in renewable sources is also extremely abundant. The world's current electricity demands could be entirely met by installing solar panels on 0.3% of the world's land area (about the area of Norway).[32] Even more impressive, enough solar energy reaches the earth in a single day to power the planet for an entire year![33]

But solar energy and other renewable energy sources are limited in the sense that their availability varies geographically and across time. Some regions of the world are particularly well suited to wind or solar energy. For example, solar energy potential is highest in areas such as the southwestern United States and northern Africa. Geothermal energy, energy from the heat of the earth, is abundant in countries such as Iceland and the Philippines.

A further limitation of renewable energy is that its embodied energy is much less concentrated than for fossil fuels. Consider that the energy density, or the amount of energy stored within a given weight, of gasoline is about 100 times higher than the energy density of the electricity stored in a lithium-ion battery in an electric car.[34] Renewable energy sources are also intermittent—the wind isn't always blowing, and the sun isn't always shining. This suggests that either renewable energy needs to be supplemented with another source, such as natural gas, in order to provide a continuous supply of energy, or that renewable energy needs to be stored in batteries to make up for the times when the energy flow isn't sufficient to meet demand.

Perhaps renewable energy's main historical weakness compared to fossil fuels has been price. For example, in 2009 the cost of electricity from solar panels was about three times higher than for coal.[35] But the price of renewable energy has been declining dramatically, making comparisons that are even a few years old obsolete. Rather than being uncompetitive in price, renewable energy is increasingly achieving a price advantage over fossil fuels that will make an energy transition inevitable. Other limitations of renewable energy are also being addressed with improvements in technology, such as higher energy density in batteries and wind turbine designs that reduce the threat to birds.

We now consider various renewable energy sources, focusing on wind and solar power. We will discuss each source's advantages and disadvantages, along with relevant trends.

Wind Energy

For hundreds of years, humans have harnessed wind energy to perform tasks such as pumping water and grinding grain. Modern wind turbines, some more than 500 feet tall, generate electricity by spinning a geared generator. Wind energy currently provides about 3% of the world's energy total supply, and about 8% of its electric power.

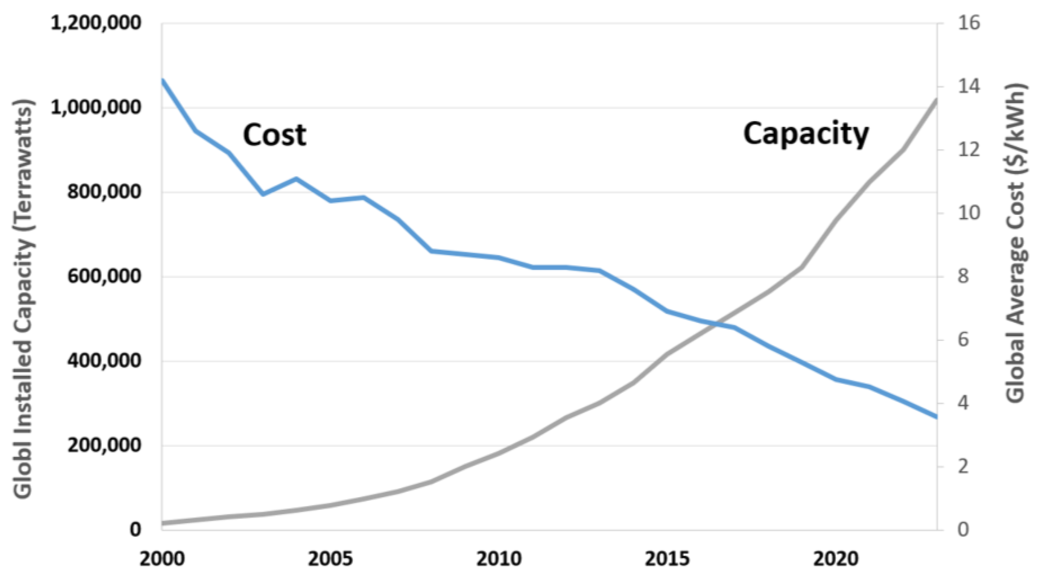
Wind energy can be harnessed from onshore and offshore turbines. Onshore wind energy is generally cheaper. Onshore turbines are easier to access for maintenance and repairs, and less subject to damage from severe storms and salt water. On the other hand, winds tend to be stronger and more consistent offshore. As some people consider onshore wind turbines unsightly, offshore turbines may be more aesthetically acceptable, especially if they are located far offshore. Offshore wind turbines are less likely to harm bird populations, although the number of birds killed by onshore wind turbines is rather low. According to a 2015 journal article, collisions with vehicles kill 350 times as many birds as wind turbines. Domestic cats are the largest source of bird mortality, killing over 4,000 times as many as wind turbines.[36]

As mentioned earlier, wind energy is more abundant in certain regions of the world, such as the central United States, northern Europe, Russia, and southern South America.[37] China has the most installed wind energy, with 38% of the world's capacity. Other top wind energy countries include the US (18%), Germany (6%), and Brazil (4%).[38]

As wind energy technologies have improved, costs have declined and installed capacity has increased, as shown in Figure 11.7. From 2000 to 2023, the global capacity of wind energy has increased by a factor of 59. During the same period, the cost of generating electricity from wind has declined by 75%.

Although wind energy currently produces a relatively small share of the world's energy, along with solar energy it is growing rapidly. About 20% of new energy capacity installed globally in 2023 was wind energy.[39] This suggests that the share of energy obtained from wind will continue to increase, as we will discuss further later in the chapter.

Figure 11.7 Global Wind Energy Installed Capacity and Average Cost, 2000–2023



Source: Capacity data from various editions of the Statistical Review of World Energy (BP and Energy Institute). Cost data from: International Renewable Energy Agency. 2019. *Global Energy Transformation: A Roadmap to 2050,* 2019 edition. Abu Dhabi; International Renewable Energy Agency. 2024. *Renewable Power Generation Costs in 2023.* Abu Dhabi.

Solar Energy

While there are several ways to convert solar energy into electricity, **photovoltaic (PV) cells** (i.e., solar panels) are the most common. PV cells transfer solar energy to electrons, creating an electrical current. Solar energy currently provides about 2% of the world's total commercial energy and 5% of the world's electric power.

photovoltaic (PV) cells devices that directly convert solar energy into electricity (i.e., solar panels).

Solar panels, like wind turbines, are often arrayed in large "farms." But unlike wind turbines, solar panels can also be employed at smaller scales, such as on household roofs. In general, larger "utility-scale" solar energy is more efficient and less costly than residential-scale solar. But household solar has become increasingly popular, appealing to many people as a way of avoiding dependence on grid electricity. Smaller-scale solar projects can also reach areas not connected to modern energy infrastructure.

The potential for solar energy tends to be greatest in equatorial and arid regions, including the Middle East, most of Africa, Australia, and desert regions in the US and Central America. China is the world's leader in solar power, with over one-third of the world's capacity. Other leading solar countries include the US (15%), India (7%), Japan (6%), and Germany (4%).[40]

Solar energy is a particularly appealing option for addressing energy needs in developing countries. Low-income countries tend to have relatively abundant solar resources. A 2020 report by the World Bank found that many of the world's lowest-income countries are also those with the highest solar potential, including Namibia, Lesotho, Afghanistan, and Sudan.[41] Solar panels can be installed in remote rural areas not connected to existing energy infrastructure such as power lines and gas pipelines, providing both economic and environmental benefits and reducing the serious health issues that are caused by the use of fuelwood, charcoal, animal dung, and agricultural waste. A 2023 journal article found that China's photovoltaic poverty alleviation policy has been effective in reducing energy poverty in rural areas by "promoting the diversification of household energy sources and improving the disposable income of residents."[42]

The World Bank's Lighting Africa program has provided energy to 32 million people, primarily through the development of solar-powered "mini-grids" connecting several homes. Households then pay for the electricity they use at subsidized rates.[43] According to a recent report:

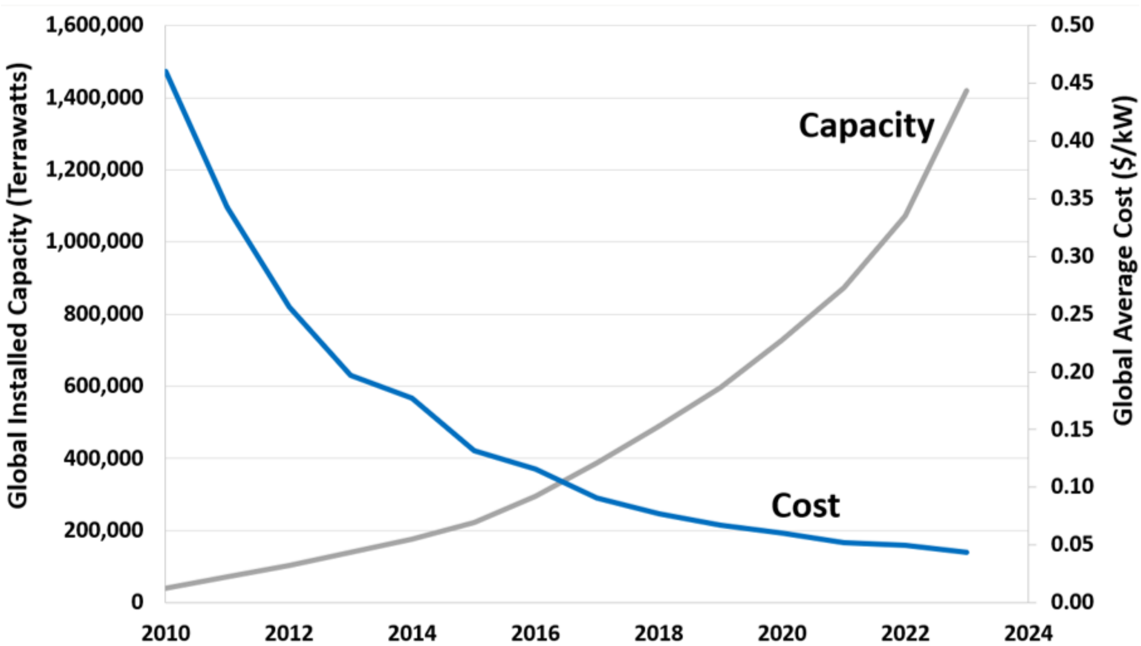
> African solar installations were projected to grow by 42 percent in 2025, according to an industry group. While South Africa and Egypt are the biggest markets for solar, West Africa is now seeing rapid growth—installations in Ghana nearly quadrupled last year. In southern Africa, locals have turned to solar to cope with recurrent blackouts after an intense drought sapped hydropower. Zambia doubled its solar capacity last year.[44]

Particularly when compared to fossil-fuel energy, the environmental impacts of solar energy are minimal. The main environmental impacts of solar power include the land used to install PV panels and the impacts of producing the panels. Although to a lesser extent than wind power, land with solar energy installations can be used for productive agricultural purposes (known as "agrivoltaics").[45]

PV panels are largely constructed of silicon, a mineral that can harm mining workers when breathed in small particles. Large-scale mining of silicon can also decrease biodiversity and create air and water pollution. Toxic materials such as hydrochloric acid are also used in the production of PV panels. Proper environmental regulation can mitigate these impacts.

No other energy source has seen such dramatic changes in prices and installed capacity in the past decade as solar. As PV technology rapidly improves, the cost of solar energy has plummeted. As shown in Figure 11.8, the cost of solar energy has decreased by more than 90% since 2010. Solar energy is the world's fastest-growing energy source, with global capacity up by a factor of 35 since 2010.

Figure 11.8 Global Solar Energy Installed Capacity and Average Cost, 2000–2023



Source: Capacity data from various editions of the Statistical Review of World Energy (BP and Energy Institute). Cost data from International Renewable Energy Agency. 2024. *Renewable Power Generation Costs in 2023.* Abu Dhabi.

As recently as 15 years ago, solar energy was widely considered a niche product that was heavily dependent on subsidies. Now, with costs rapidly declining, solar energy is poised to dominate energy markets in the coming decades. Over 70% of all new energy installed globally in 2023 was solar.[46] And while the expansion of solar energy is a critical tool in addressing climate change and air pollution, the primary driver of solar energy's growth is cost. As we will see in Section 11.4, solar energy has now become, on average, the world's cheapest energy source.

Other Renewable Energy Sources

Other sources of renewable energy include hydroelectricity, biomass, and geothermal. **Hydroelectricity (or hydropower)** involves using the energy from moving water to spin an electric turbine. Most commonly, turbines are installed inside a dam that creates a reservoir of water behind it. The passage of water through the dam and turbines is regulated, producing a relatively reliable, constant supply of electricity. Hydropower currently provides about 6% of the world's energy.

hydroelectricity (or hydropower) using the energy from moving water to spin an electric turbine and generate electricity.

Hydropower offers a number of advantages. First, it doesn't create local air pollution or direct carbon emissions. While building a hydroelectric dam entails a significant capital investment, its low operating costs make hydropower one of the lowest-cost energy sources on a lifecycle basis. Hydropower doesn't suffer from the intermittency problems of wind and solar energy; hydroelectric dams operate continuously. Dams reduce flooding and can provide a reliable supply of water for irrigation and municipal needs. Finally, reservoirs can provide recreation benefits, such as boating and swimming.

Despite these benefits, the amount of energy generated globally from hydropower is not expected to grow significantly in the future due to its drawbacks. Hydropower dams block the natural flow of rivers, which degrades aquatic habitats. Migrating fish species such as salmon are particularly affected as dams block their movement upstream to spawn. Dams also block the downstream flow of sediment, which builds up behind dams. This not only impacts aquatic species but also reduces the storage capacity of the reservoir and can affect the operation of turbines. Finally, many of the best locations for hydropower dams have already been developed, especially in the US and Europe.

Besides large dams, other types of hydropower are available with lower environmental impacts, including "run of river" installations, that store little to no water in reservoirs, and wave and tidal plants in coastal areas. While these technologies appear worthwhile in certain locations, they are not expected to provide a significant share of the world's future energy.

Biomass energy is a broad term referring to the burning of plant or animal material to generate heat or electricity. It includes burning wood or animal dung for cooking, using ethanol made from corn to power a vehicle, and burning agricultural wastes to generate electricity. Biomass currently provides about 7% of the world's energy.

biomass energy generating heat or electricity from burning plant or animal material.

Biomass energy is a renewable resource with some advantages but also some significant disadvantages. Many low-income households in developing countries, without affordable access to electricity or fossil fuels, rely on biomass for cooking and heating. Some materials used for biomass energy, such as crop residues and animal dung, can be considered waste materials and thus a "free" energy source, but they are also highly polluting, especially when used indoors. Burning biomass emits local air pollutants such as carbon monoxide, nitrogen oxides, and particulate matter. The World Health Organization estimates that indoor air pollution is responsible for 3.2 million deaths per year, including over 230,000 children under 5 years old.[47]

Biomass energy is sometimes touted as being carbon neutral. For example, the CO_2 emissions from a wood-burning electricity plant can in theory be offset by planting new trees that will eventually absorb a similar quantity of CO_2. But numerous scientific papers have found that increasing our reliance on biomass energy will result in a significant net increase in carbon emissions.[48] One problem is that there is no assurance that enough new biomass will be created to fully offset current carbon emissions. A second problem is timing—even if current carbon emissions are fully offset by future biomass absorption, in the interim, that atmospheric carbon will contribute to climate change. When standing forests are cut, the resulting surge in carbon emissions will last for 50 years or longer, even if the forest eventually regrows.

Finally, **geothermal energy** is energy from the subsurface heat of the earth. In some locations, this heat reaches the surface as hot water or steam. In other locations, wells can be drilled to tap into geothermal reservoirs. Geothermal energy can be used directly to heat water and buildings, or used to generate electricity, normally by using steam to power an electric turbine. Geothermal energy currently provides less than 1% of the world's energy.

geothermal energy energy from the subsurface heat of the earth.

The main limitation of geothermal energy is that it is cost effective only in certain regions of the world. One country with extensive geothermal resources is Iceland, which relies on it for about half of its total energy supply, including almost all its heating needs. While the world's geothermal resources are mostly untapped, further development of geothermal is normally not the lowest-cost or least environmentally damaging energy source. Per unit of energy generated, geothermal energy tends to emit more carbon than solar or wind energy.[49] Tapping into geothermal reservoirs can also release air pollutants such as hydrogen sulfide and ammonia. Another concern with developing geothermal sites is that it may increase the risk of earthquakes.[50]

A different form of geothermal energy does not require especially hot subsurface temperatures but takes advantage of the fact that the temperature just a few feet below the earth's surface stays an average 55°−70°F year-round. It can thus be used as a basis for both heating in winter and cooling in summer. In conjunction with a heat pump—a device that works by transferring energy from colder to warmer areas or vice versa—geothermal piping can provide efficient heating and cooling, generally at lower cost than conventional heating or air-conditioning systems.

Geothermal systems have been growing in popularity, and "networked" geothermal projects can supply multiple commercial and residential buildings with significantly less carbon emissions than traditional systems. For example, New York State has initiated 13 neighborhood geothermal projects and a project in Framingham, Massachusetts includes geothermal infrastructure for 31 residential and five commercial buildings, with more projects planned throughout the state.[51]

11.4 Energy Economics: Current Analyses and Alternative Futures

The main reason that fossil fuels currently provide over 80% of the world's energy is that they have historically been cheaper than other energy sources. But the economics of energy is changing rapidly—more rapidly than most energy experts have predicted. Energy cost comparisons from just a few years ago are now obsolete. When a previous edition of this text was published in 2018, we wrote that "it is possible that fossil fuels will, in the future, lose their price advantage over renewables."[52] However, just a couple of years later, several economic analyses in 2020 reached the stunning conclusion that "the era of cheap wind and solar has arrived."[53]

Cost Comparisons of Energy Sources

Comparing the costs of different energy sources is not straightforward. Capital costs vary significantly—a new nuclear power plant can cost up to $15 billion. Some energy sources require continual fuel inputs, while other sources, such as wind and solar, require only occasional maintenance. We also need to account for the different life spans of various equipment and plants.

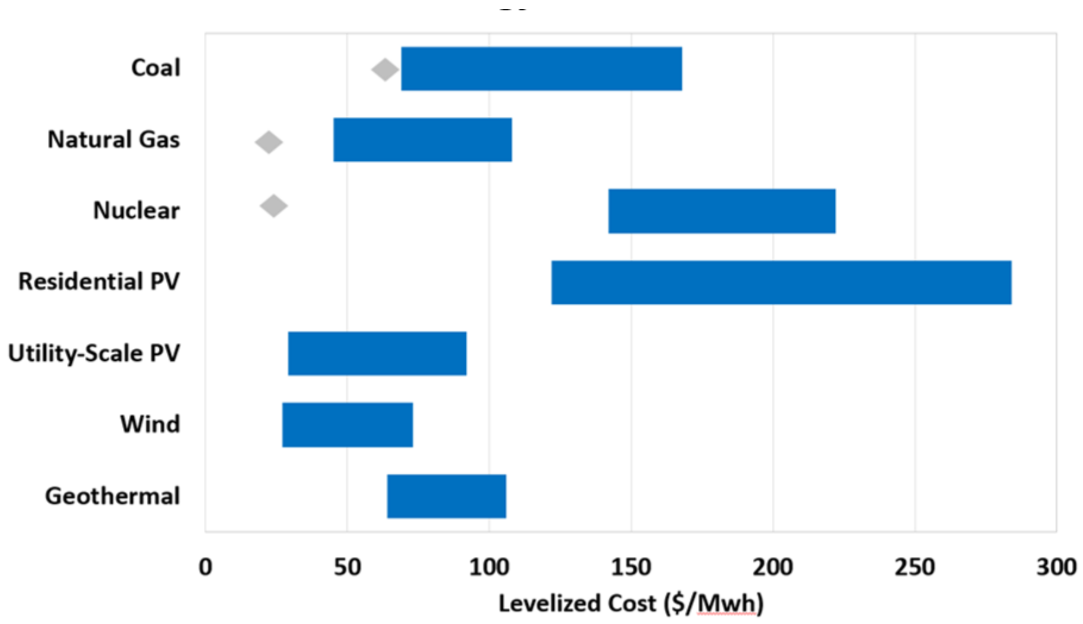
Cost comparisons between different energy sources are made by calculating the **levelized cost** of obtaining energy. Levelized costs include the present value of building and operating a plant over an assumed lifetime, expressed in real terms to remove the effect of inflation. For energy sources that require fuel, assumptions are made about future fuel costs. The levelized construction and operations costs are then divided by the total energy obtained to allow direct comparisons across different energy sources.

levelized costs the per-unit cost of energy production, accounting for all fixed and variable costs over a power source's lifetime.

Figure 11.9 presents a 2024 comparison of the levelized costs using various energy sources to generate electricity, without any subsidies. The horizontal bars show the typical range of levelized costs worldwide for new energy construction. We see that utility-scale solar and wind energy is clearly cheaper than new nuclear energy, and cheaper than new coal plants

in most cases. On average, solar and wind energy is also cheaper than constructing new natural gas plants. In other words, new solar and wind energy are now, on average across the world, the two cheapest energy sources, without any subsidies.

Figure 11.9 Unsubsidized Levelized Cost of Different Energy Sources



Source: Lazard. 2024. *Levelized Cost of Energy Analysis—Version 17.0*. June.
Note: Diamond markers indicate the midpoint of marginal operation costs for fully depreciated plants.

The gray diamond markers in Figure 11.9 indicate the marginal cost of operation of existing plants. While existing gas and nuclear plants currently remain competitive, for new construction the economics of power generation clearly favors renewable energy sources.

In addition, renewable energy is quickly becoming cheaper than the marginal operational costs of coal plants. A 2023 analysis found that it was cheaper to install new solar power than to pay just the fuel and operational costs for 99% of the coal power plants in the US.[54] With renewable energy expected to become even cheaper in the future, it may increasingly make financial sense to shut down existing coal, nuclear, and natural gas power plants and replace them with renewable energy.

Other recent economic studies of the costs of different energy sources reach the same conclusion—renewables cost about the same or less, on average, than traditional energy sources. The International Renewable Energy Agency estimated that 81% of new renewable energy installations in 2024 produce energy at lower cost than fossil fuels.[55] A 2022 paper found that a rapid global transition away from fossil fuels toward renewables, as compared to a slow transition, will reduce the present value of future energy costs by about $8 trillion.[56] The authors conclude:

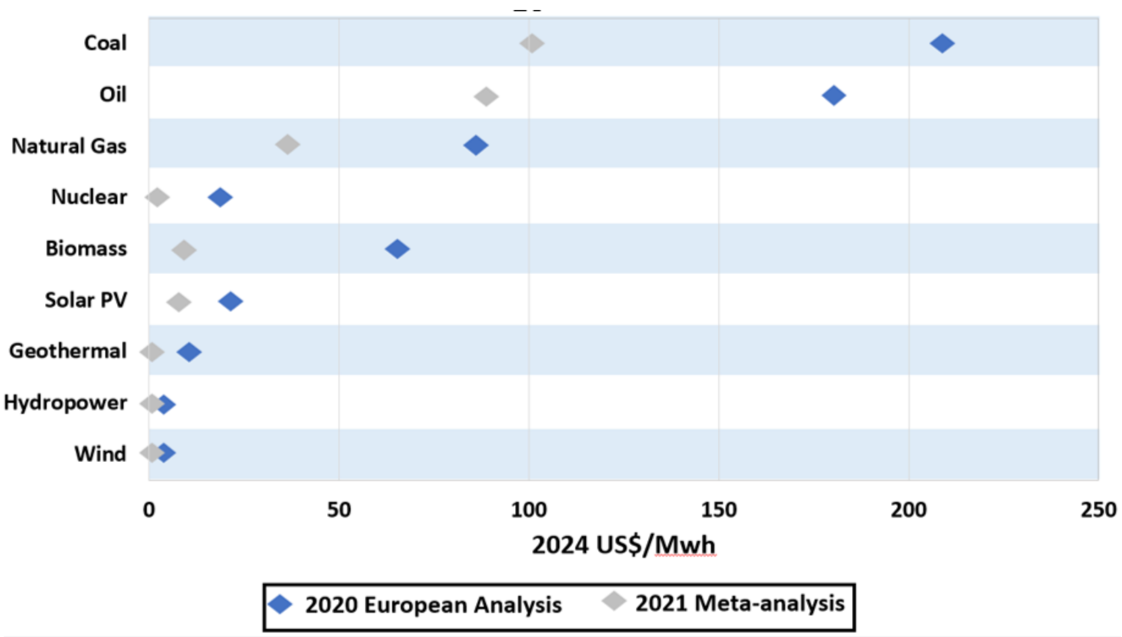
> The belief that the green energy transition will be expensive has been a major driver of the ineffective response to climate change for the past 40 years. This pessimism is at odds with past technological cost improvement trends and risks locking humanity into an expensive and dangerous energy future. … While arguments for a rapid green transition cite benefits such as the avoidance of climate damages, reduced air pollution, and lower energy price volatility, these benefits are often contrasted against discussions about the associated costs of the transition. Our analysis suggests that such trade-offs are unlikely to exist: *a greener, healthier, and safer global energy system is also likely to be cheaper*.

Externality Costs of Different Energy Sources

Our comparison of the costs of various energy sources is incomplete without inclusion of externality costs. The external costs of energy production include land degradation, water use, climate change damages, and human health effects from air pollution. Several studies have estimated the external costs of various energy sources.

Figure 11.10 presents the results of two studies of the externality costs of electricity generation from different energy sources: a comprehensive 2020 European study and a 2021 meta-analysis based on 83 studies from various countries. The European study indicates generally higher external costs, but the pattern is the same: coal and oil clearly have the highest externalities per unit of electricity, primarily damage from local air pollution and carbon emissions. External costs are lowest for hydropower and wind energy. While the external costs of nuclear and solar energy are about the same, the external costs from the long-term storage of nuclear wastes were not estimated.

Figure 11.10 External Costs of Electricity Generation, by Energy Source



Source: European estimates: Trinomics. 2020. *Final Report, External Costs: Energy Costs, Taxes and the Impact of Government Interventions on Investments*. European Commission, October. Meta-analysis: Sovacool, Benjamin K., Jinsoo Kim, and Minyoung Yang. 2021. "The Hidden Costs of Energy and Mobility: A Global Meta-analysis and Research Synthesis of Electricity and Transport Externalities." Energy Research & Social Science, 72:101885.
Note: European values are for the EU–27; values in euros were converted to 2024 dollars. Meta-analysis values are median values, converted to 2024 dollars.

Note that the units in Figure 11.10 are the same as in Figure 11.9. Thus, the levelized costs can be added to the external costs to obtain an estimate of the total economic cost of each energy source. For example, the levelized cost of new natural gas electricity from Figure 11.9 is $45–$108/MWh. Adding the external costs of $37–$86/MWh from Figure 11.10 increases the "true" cost of natural gas by 34–191%. While natural gas is currently reasonably cost competitive with wind and solar energy based solely on levelized costs, especially when only the marginal costs of gas are considered, inclusion of external costs would make natural gas more costly than wind and solar energy in nearly all cases. The authors of the meta-analysis conclude:

> If [external costs] were included in the price of energy … it would become clear not only that we need to fundamentally change our systems and markets, but that it would actually be profitable to do so. … Although the services provided by energy and

transport systems generate unprecedented opportunities for those who have access to them, the externalities that result from these same systems limit opportunities for many others, frequently to the extent of making it difficult to live a meaningful and healthy human life, and sometimes to the extent of making it impossible to live.[57]

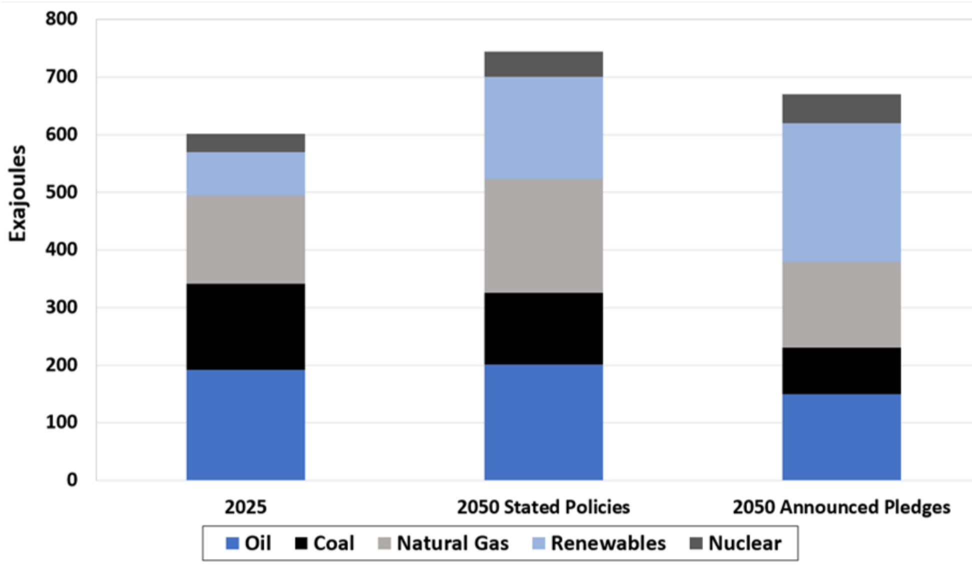
Energy Projections

With renewable energy now as cheap as or cheaper than traditional energy sources, even without subsidies and inclusion of external costs, the share of global energy from fossil fuels will decrease in the future. But, as we mentioned at the start of the chapter, the critical question is whether the transition to renewable energy will occur soon enough to prevent unacceptable climate change and other environmental impacts.

Various government agencies and private companies project the global energy mix into the future. One of the most referenced projections is developed by the IEA. The IEA produces energy projections for two main scenarios: a “stated policies” scenario in which countries pursue policies currently in place or already planned, and an “announced pledges” scenario where all countries meet their current “net zero” carbon emissions targets on time.

Figure 11.11 presents the IEA’s global energy mix projections to 2050 under these two scenarios. While the projections for the stated policies scenario show coal production declining relative to 2025 and production of renewables such as wind and solar increasing, it shows little overall change in the global energy mix. The world’s total energy share from fossil fuels declines slightly, from 82% in 2025 to 70% in 2050. In the announced pledges scenario, we see coal production decreasing more significantly and renewable production increasing more. While the stated policies scenario sees global energy demand increasing by 6% from 2025 to 2050, the announced pledges scenario projects a 23% decline in global demand, as a result of increased energy efficiency. Even in this scenario, however, fossil fuels still provide 57% of global energy supplies in 2050.

Figure 11.11 IEA Global Energy Mix: 2025 and Projections to 2050



Source: International Energy Agency. 2021. *Net Zero by 2050: A Roadmap for the Global Energy Sector*. October.

The US Energy Information Administration (EIA) projects the global energy mix to 2050 under a "reference case" scenario based on current policies and moderate assumptions about economic growth, energy prices, and technological changes.[58] Under this scenario, the EIA projects that the share of global energy from renewables (including wind, solar, hydropower, and biomass) will increase from 17% in 2025 to 26% in 2050. But in 2050, fossil fuels combined still provide 70% of the global energy supply—clearly not sufficient to meet climate targets.

Another source of global energy projections is from the consulting firm McKinsey & Company. In a 2024 report, they estimate the global energy mix in 2050 under three different scenarios, with fossil fuels providing between 39% and 61% of energy in 2050.[59]

Considering these projections, along with other data we've presented in this chapter, you may notice an apparent inconsistency. Wind and solar are currently the world's two cheapest energy sources, on average. These two sources also made up over 90% of the world's new electricity generation capacity in 2024.[60] With the cost advantage of wind and solar relative to other energy sources expected to only increase in the future, it may be surprising that fossil fuels are projected to still dominate global energy supplies in 2050 under most of the scenarios discussed above.

One factor limiting the expansion of wind and solar energy is that existing fossil-fuel and nuclear plants will phase out slowly due to their relatively long life spans, typically 30–50 years. But remember that the costs of wind and solar are declining so rapidly that they are increasingly cheaper than even the marginal operational costs of traditional power plants, suggesting it would make economic sense to shut down such plants early and replace them with new wind and solar energy.

Another factor to consider is that large-scale adoption of renewable energy requires electrification of the world's energy systems—one of the challenges mentioned at the start of the chapter. The widespread distribution of renewable energy will require significant private and public investment, as we'll discuss later in the chapter.

But perhaps the most important factor to consider is that energy projections, particularly those developed by the EIA and the IEA, have historically underestimated the expansion of renewable energy—see Box 11.3 for more on this issue. Consider the EIA's current forecast for renewable energy production in the US. The EIA projects that renewable energy generation will grow at an annual rate of only 3% through 2050.[61] But from 2020 to 2023, wind energy production in the US increased by 8% per year, while solar energy increased by 20% annually![62] Further, about 90% of new electricity generation capacity in the US in 2024 came from wind and solar energy.[63] Thus the EIA's forecast for only modest growth in wind and solar energy seems inconsistent with actual experience.

Box 11.3 Consistent Inaccuracies in Renewable Energy Forecasts

The US Energy Information Administration and the International Energy Agency produce annual energy forecasts that are widely quoted. Many people, from academics to politicians, rely upon these forecasts. But, in recent years, an increasing number of energy experts have been pointing out that the EIA and IEA forecasts have consistently underestimated the growth of renewable energy. Consider just a few examples:

- In 2000, the EIA forecast that under a "high renewables case," wind generation capacity in the US would reach nearly 20 gigawatts in 2020. Actual wind capacity in 2020 exceeded 100 gigawatts.
- In 2010, the EIA forecast that under a favorable "low renewables cost" scenario, non

-hydropower renewable energy capacity in the US could nearly double from 2015 to 2035. In less than half this time, from 2015 to 2023, solar energy capacity in the US increased by a factor 4.5 and wind energy increased by a factor of 2.2.

- In 2010, the IEA forecast that global energy production from wind and solar could grow by nearly a factor of 10 from 2008 to 2035 under a "new policies scenario" to encourage a transition to renewable energy. From 2008 to 2023 alone, global wind capacity increased by a factor of 9 and solar capacity increased by a factor of 95!
- In 2015, the IEA predicted that by 2040 the price of solar energy would decline by about 40%. From 2015 to 2024 alone, the price of solar energy fell by 56%.

Many other examples could be presented to show that the growth of wind and solar generation capacity, and the decline in renewable prices, has consistently exceeded the EIA's and IEA's most optimistic forecasts. Part of the problem is that the agencies' models are built to favor the status quo. But, as one energy expert explains regarding the EIA's forecasts, "They have constraints that tie their hands a bit, but that doesn't explain why they're so consistently wrong in the same direction. They're not just conservative about change. They're ignoring the evidence of what's actually happening in the market."

A 2016 journal article suggests several improvements to the EIA's energy projection methodology, concluding that unless "projections of renewable energy are greatly improved, the reliability of [the EIA's] electricity projections is inherently low."

Source: US Energy Information Administration. 2000. *Annual Energy Outlook 2000*. Washington, DC; US Energy Information Administration. 2010. *Annual Energy Outlook 2010*. Washington, DC; US Energy Information Administration. 2025. *Monthly Energy Review.* Washington, DC. January; International Energy Agency. 2010. *World Energy Outlook 2010*. Paris; Our World in Data. 2024. "Total Wind Capacity" and "Total Solar Capacity"; International Energy Agency. 2015. *World Energy Outlook 2015*. Paris; Our World in Data. 2024. "Solar Photovoltaic Module Price."; Grunwald, Michael. 2015. "Why Are the Government's Energy Forecasts So Bad?" *Politico*, June 24; Gilbert, Alexander Q., and Benjamin K. Sovacool. 2016. "Looking the Wrong Way: Bias, Renewable Electricity, and Energy Modelling in the United States." *Energy*, 94:533–541.

Carbon-Neutral Energy Systems

Rather than fossil fuels continuing to dominate global energy supplies for decades, what would it take for a comprehensive global transition to renewables? Numerous studies have analyzed the potential and cost for a carbon-neutral global energy supply system. A 2022 journal article reviewing these studies concludes:

> The main conclusion of the vast majority of 100% renewable energy systems studies is that such systems can power all energy in all regions of the world at low cost. As such, we do not need to rely on fossil fuels in the future. In the early 2020s, the consensus has increasingly become that solar PV and wind power will dominate the future energy system and new research increasingly shows that 100% renewable energy systems are not only feasible but also cost effective.[64]

The IEA presents a roadmap for a carbon-neutral global energy system by 2050.[65] Some of the main findings of this roadmap include:

- Solar and wind become the leading sources of electricity globally before 2030 and together they provide nearly 70% of global generation in 2050.
- By 2050, global coal demand declines by 90%, oil declines by 75%, and natural gas declines by 55%. Remaining fossil fuel use in 2050 is used for non-energy goods such as plastics.
- Annual global costs for the transition are about $4 trillion per year.

A 2024 article summarizes various studies that have analyzed a global transition to renewable energy.[66] The authors find that the average additional investment requirements for such a transition are about $2.8 trillion annually, or about 2.4% of global GDP. However, a carbon-neutral world is expected to have about 2% higher GDP in the long run, relative to a reference case scenario. The authors conclude:

> When one contrasts the costs and benefits, the scales undoubtedly tip in favor of the transition. The advantages … far overshadow the policy costs. … For nations navigating this transition, it is a testament to the fact that the long-term economic, environmental, and societal dividends of embracing renewable energy and low-carbon solutions outweigh the initial investments and transitional challenges.[67]

What is a possible timeline for a transition to a global renewable energy economy? In a 2023 overview, energy systems expert Mark Jacobson outlines the possibility of a 100% WWS (wind, water, and sunlight) energy economy by 2050, with an earlier date possible. Jacobson argues that most of the technologies needed for a complete conversion to a WWS-powered world are already available. He concludes that the main barriers to conversion to WWS energy are a lack of awareness and political will.[68]

The Importance of Energy Efficiency

As mentioned at the start of the chapter, one of the global energy challenges is to promote energy demand-side management, limiting or even reversing the projected growth in global energy demand. Meeting the world's energy demands primarily, or fully, from renewable energy becomes more feasible if energy demand growth is restrained. Investments in energy efficiency are normally more cost effective than investments in new energy supplies. In other words, it is normally cheaper to not use energy in the first place, say by increasing insulation in buildings or installing more efficient appliances, than to build new power plants.

The IEA finds that more than 40% of the carbon emissions reduction needed by 2040 can come from energy efficiency gains. The EIA refers to energy efficiency as the "first fuel" of a clean energy transition, one that "can reduce the overall costs of mitigating carbon emissions while advancing social and economic development, enhancing energy security and quality of life, and creating jobs."[69]

A 2023 report by the World Bank also emphasizes the untapped potential of energy efficiency.[70] The report estimates that the rate of improvements in energy efficiency needs to increase by a factor 2–3 to meet climate goals. The Bank also notes that the greatest focus for energy efficiency improvements should be in low- and middle-income countries, which lack sufficient resources and tend to be more inefficient in energy use than high-income countries.

11.5 Policies for the Great Energy Transition

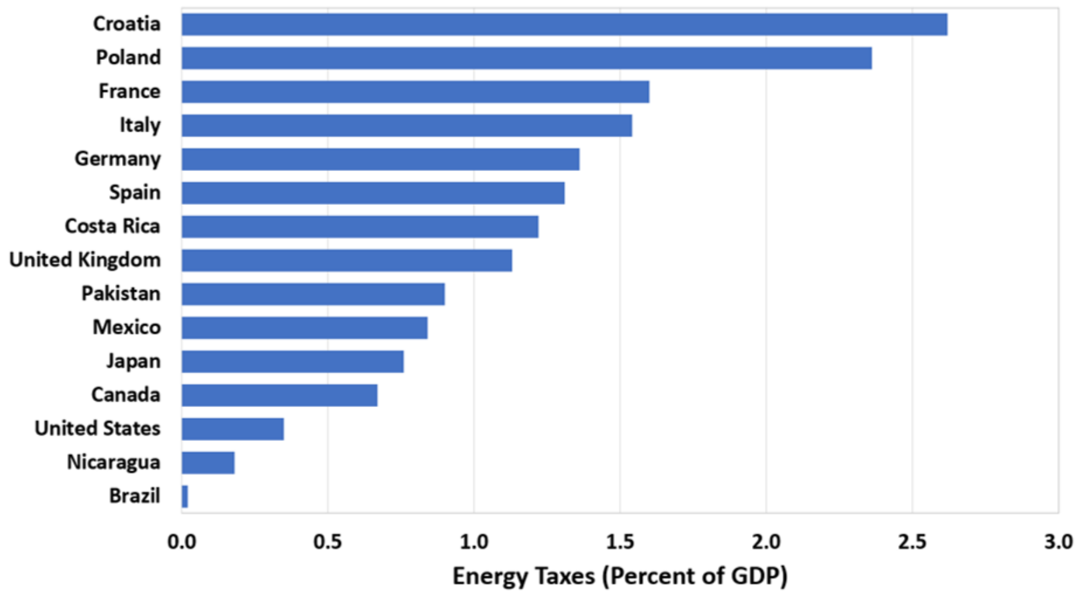
In this final section, we consider what policies could be implemented to meet the world's energy challenges. We've seen that economic forces are increasingly favoring renewables over fossil fuels, but the transition is not occurring quickly enough to meet climate targets. Government policies can fill the gap by promoting electrification, focusing on demand-side energy management, and addressing global energy disparities.

Internalizing Externalities

Recalling our discussion from Chapters 3 and 8, fossil-fuel energy is associated with significant negative externalities, suggesting that taxation or tradable permits could be used to motivate a transition to renewables. In principle, economic policies that internalize the negative externalities of various energy sources (including fossil fuels and renewables) would create a "level playing field" that can produce economically efficient, and potentially environmentally sustainable, outcomes. As we saw in Figure 11.10, internalizing the externalities associated with different forms of energy would significantly raise the prices of fossil fuels, particularly coal, relative to renewables.

Countries implement energy taxes on electricity, transportation fuels, and other energy use. Figure 11.12 shows that energy taxes typically amount to about 0.5% to 1.5% of GDP across countries. Energy taxes are particularly high, as a percentage of GDP, in Croatia, Poland, and France, and particularly low in the US, Nicaragua, and Brazil.

Figure 11.12 Energy Taxes, 2022, Selected Countries



Source: OECD. OECD Data Explorer. "Environmentally Related Tax Revenue."
Note: Tax data for Canada and Mexico are for 2021.

The energy taxes illustrated in Figure 11.12 do not necessarily reflect full internalization of negative externalities. In the US, the federal gasoline tax of 18 cents per gallon is justified exclusively to fund highway maintenance and other transportation projects. Even in the European Union, with its relatively high fuel taxes, energy externalities are not fully internalized. The European Environment Agency notes that "to date fuel taxation is not generally used to internalise the environmental externalities of transport, possibly because high fuel tax is often politically unviable."[71]

All countries could thus do much more to internalize the externalities of energy use. As we discussed in Chapter 3, a system of upstream Pigovian taxes could be placed on fossil fuels, resulting in higher prices on products such as gasoline, electricity from coal, and natural gas heat. These taxes would motivate both a supply-side and a demand-side response. Producers such as utility companies would have an incentive to shift their energy sources from fossil fuels to renewables to lower their taxes. Consumers would reduce their demand for products whose prices rise significantly from taxation, such as gasoline. But overall economic impacts on consumers could be reduced by returning tax revenues to households or using them to lower other taxes. The extent to which economically efficient energy taxes would speed the transition to renewables depends on the price elasticity of demand for various energy sources, which we'll discuss later in the chapter.

Energy Subsidy Reform

Subsidies can also be used to promote economically efficient outcomes. As we learned in Chapter 3, a subsidy is economically justified when a market creates a positive externality, such as when a homeowner installs solar panels that benefit society as a whole. Subsidies favoring renewable energy can be used as an alternative to Pigovian taxes on fossil fuels. Subsidies can take the form of direct payments or rebates to households and businesses that install solar panels, purchase EVs, or install energy-efficient heating or cooling systems. Subsidies can also take the form of low-cost loans or tax credits. In the US, as of 2025, households or businesses that install solar panels received 30% back as a tax credit.

Another form of subsidy is a **feed-in tariff**, which guarantees renewable energy producers access to electricity grids and long-term price contracts. For example, homeowners or businesses that install PV panels can sell excess energy back to their utility at a set price.

Feed-in tariff policies have been instituted by dozens of countries and several US states. The most ambitious has been in Germany, which has become a leading country in installed solar PV capacity. Feed-in tariffs are intended to be reduced over time as renewables become cost competitive with traditional energy sources. A reduction in feed-in tariff rates has already begun in Germany. An analysis by the European Union of different approaches for expanding the share of renewables in electricity supplies found that "well-adapted feed-in tariff regimes are generally the most efficient and effective support schemes for promoting renewable electricity."[72]

feed-in tariffs a policy to provide renewable energy producers long-term contracts to purchase energy at a set price.

While policies such as fossil-fuel taxes and renewable energy subsidies are increasingly implemented at national and sub-national levels, fossil fuels unfortunately remain heavily subsidized. According to the International Monetary Fund, global fossil-fuel subsidies amount to about $7 trillion annually—equivalent to over 7% of the world economy.[73] The International Renewable Energy Agency found that global subsidies supporting fossil fuels are 20 times higher than subsidies for renewable energy.[74] So rather than encouraging an energy transition, government policy overall seems to be slowing the necessary changes. (For more on energy subsidies, see Box 11.4.)

Box 11.4 Fossil-Fuel Subsidies

Fossil fuels are subsidized by governments in many ways. The most direct, or explicit, subsidies include cash payments, tax breaks, and other financial incentives. According to a 2023 analysis of fossil-fuel subsidies by the International Monetary Fund (IMF), explicit subsidies amounted to about $1.3 trillion in 2022. About half of this amount benefits the natural gas industry, while 26% accrues to the oil industry and 25% to the electricity industry.

Implicit fossil-fuel subsidies include unpriced environmental externalities such as local air pollution and carbon emissions. According to the IMF, global fossil fuel implicit subsidies were about $5.7 trillion in 2022. Thus, global fossil-fuel subsidies, including explicit and implicit subsidies, totaled $7 trillion in 2022, or 7.1% of global GDP. China received the largest fossil fuel subsidy of any country ($2.2 trillion), followed by the US ($760 billion) and Russia ($420 billion).

The authors note that eliminating fossil-fuel subsidies and properly pricing energy sources would:

- Reduced global carbon dioxide emissions by 43% below 'business as usual' levels in 2030, which would be in line with limiting global warming to below 2°C.
- Generate revenues of 3.6% of global GDP. The revenue gains from these reforms would exceed the cost of achieving the UN's 2030 Sustainable Development Goals.
- Prevent 1.6 million premature deaths from local air pollution.

Source: Black, Simon, Antung A. Liu, Ian Parry, and Nate Vernon. 2023. "IMF Fossil Fuel Subsidies Data: 2023 Update." IMF Working Paper WP/23/169. August.

Fossil-fuel subsidies are often justified as making energy more affordable to low-income consumers, especially in developing countries. Economic analyses have found, however, that fossil-fuel subsidies primarily benefit higher-income groups. For example, a study by the International Monetary Fund found that:

> Fuel subsidies are a costly approach to protecting the poor due to substantial benefit leakage to higher income groups. In absolute terms, the top income quintile captures six times more in subsidies than the bottom.[75]

The money governments save by reducing fossil-fuel subsidies can benefit the poor more efficiently in other ways, such as spending on education or health programs.

In 2009, the members of the G20, a group of major economies including both developed and developing countries, agreed to "rationalize and phase out over the medium term inefficient fossil-fuel subsidies that encourage wasteful consumption" and "adopt policies that will phase out such subsidies worldwide."[76] But total fossil-fuel subsidies as of 2024 had actually increased over 2009 levels. Most countries have not set a timeline for phasing out fossil-fuel subsidies or even report subsidies on a regular basis. Considering the need to transition away from fossil fuels to meet climate targets, these issues highlight "the urgent need to accelerate progress in phasing out fossil-fuel subsidies."[77]

Promoting Electrification

The recent dramatic decline in the cost of renewable energy production has removed a major barrier to a global transition to renewable energy. But renewable energy production, mainly in the form of electricity, must be accompanied by a system to distribute, store, and utilize it. Currently, only about 25% of the world's energy is provided through electricity. The International Renewable Energy Agency suggests that the global production of electricity will need to at least double by 2050 in order to limit warming to no more than 2°C. This not only requires investment in renewable energy generation, but expansion of electric infrastructure and energy efficiency improvements.[78]

Electrification increasingly makes financial sense for businesses and households. One example is the use of electric heat pump systems for space and water heating. Particularly in moderate climates, heat pumps can provide space and water heating at a lower lifecycle cost than fossil-fuel alternatives. Another example is electric vehicles. As we saw in Box 11.1, the lifecycle cost of an EV is typically many thousands of dollars less than a comparable gas-powered vehicle. But the higher up-front cost of these efficient alternatives often prevents consumers from choosing them. For more on this issue, see Box 11.5.

Box 11.5 Implicit Discount Rates and Energy Efficiency

Many consumers purchase cheaper but inefficient appliances and vehicles, rather than more expensive and efficient options, yet end up paying more in the long run due to high operating costs. Suppose that a consumer can purchase a standard refrigerator for \$500 and an energy-efficient model for \$800. Assume the energy-efficient model will save the consumer \$15 per month in energy costs. From an economic point of view, we can say that the return on the extra \$300 invested in the efficient model is \$15 × 12 = \$180/year, or 60%. In less than two years, the consumer will actually come out ahead by buying the more efficient refrigerator.

Anyone offered a market investment that would have a guaranteed 60% annual rate of return would consider this a tremendous opportunity. But it is likely that the refrigerator buyer will turn down the chance to make this fantastic return. The reason is that he or she will weigh more heavily the immediate decision to spend \$500 versus \$800 and therefore choose the cheaper model. We could say that the consumer is implicitly using a discount rate of greater than 60% to make this purchase—a consumer behavior that is difficult to justify economically, yet very common.

Electric battery storage is another key component of an energy system that relies heavily on intermittent electricity production from wind and solar energy. Fortunately, the cost of battery storage is declining as steeply as the cost of renewable energy production. The cost of lithium-ion battery storage declined by 85% over 2014–2024, with further cost declines anticipated in the future.[79] Further investment in battery storage can be incentivized or directly funded publicly. As of 2024, 11 US states have mandated targets for battery storage by electric utilities, including California, Nevada New York, and Virginia.[80]

Electrification can be promoted by government phaseouts of fossil-fuel products. Numerous countries have announced target dates for banning the sale of new gas-powered vehicles. In 2020, the UK announced a plan to prohibit the sale of gas-powered vehicles by 2030 and hybrids by 2035, along with public funding for EV charging and battery research. Norway aims to become to the first country to ban the sale of gas-powered vehicles, with a target date of 2025. Other policies ban or restrict the use of fossil fuels in construction. For example, the city of Seattle has mandated that all large commercial and residential buildings must reach net zero emissions by 2050, effectively requiring owners to replace fossil-fuel infrastructure with efficient electric alternatives.[81]

Government targets also set dates for the conversion of electricity power to renewable sources. In 2024, Spain updated its renewable energy target to 81% of electricity generation by 2030, up from the previous target of 74%.[82] Sweden has set a target of eliminating fossil fuels from electricity production by 2040.[83] China had set a target of installing 1,200 gigawatts of renewable capacity by 2030—a goal it reached in July 2024.[84]

Demand-Side Energy Management

Demand-side energy management is generally considered the most cost-effective and environmentally beneficial approach to energy policy. As we've seen, shifting a kilowatt of energy supply from coal to solar or wind is desirable, but eliminating that kilowatt of demand entirely is even better. Economists often focus on pricing to induce a demand-side response, either implementing Pigovian taxes or increasing government-regulated rates for products such as electricity.

The effectiveness of price increases in reducing energy demand depends on the price elasticity. A 2018 meta-analysis reviewed 103 studies of residential electricity demand from developing and developed countries and found that the average elasticity of demand was −0.23 in the short term and −0.58 in the long term.[85]

In the transportation area, while most older studies find that the demand for gasoline is highly inelastic (with elasticities below −0.10), a 2020 analysis concluded that newer studies using better estimation methods find a short-term elasticity of around −0.40.[86] As alternatives to gasoline-powered vehicles become more widely available and affordable, one would expect that gasoline demand will become more elastic, especially in the long run.

Numerous demand-side energy policy tools are available besides pricing. Reductions in energy demand can be achieved by promoting efficient technologies such as EVs and LED lighting using rebates, tax credits, and other economic incentives. Government policies can mandate the phaseout of older, inefficient technologies. For example, numerous countries have been phasing out incandescent lightbulbs, which tend to be highly inefficient and short-lived. Efficiency standards, such as fuel economy standards or new home construction standards, are another demand-side energy policy tool.

Efficiency labeling informs consumers about the energy efficiency of various products. For example, in the US, the US Environmental Protection Agency and US Department of Energy manage the Energy Star program. Products that meet high-efficiency standards, above the minimum requirements, are entitled to receive the Energy Star label. About half of American households intentionally purchase an Energy Star product each year, with the typical household saving $50 in energy costs annually.[87]

efficiency labeling labels on goods that indicate energy efficiency, such as a label on a refrigerator indicating annual energy use.

Information campaigns can advocate for behavioral changes such as washing clothes using cold water or switching off lights and appliances when not in use. A meta-analysis found that providing people with information about the ways they could reduce their energy use resulted in an average energy use reduction of 10–14%.[88]

A similar approach is to use social comparisons to motivate energy-efficient behavior. A common example is to provide electricity customers with information about how they rank in usage compared to their neighbors, with rankings such as "below average" or "most efficient." A 2018 meta-analysis indicated that 18 of 20 studies concluded that social comparisons significantly reduce household energy use, with declines ranging from 1% to 30%.[89] These results suggest that nonprice interventions can be at least as effective as raising prices in reducing energy demand, while also being more politically acceptable.

Addressing Global Energy Disparities

Energy poverty is defined as lacking access to modern, affordable, and reliable energy. As mentioned earlier in the chapter, the World Bank estimates that 1.3 billion people globally suffer from energy poverty, including 750 million people who lack access to an electrical grid.[90] Even if a household is connected to an electrical grid, their energy may not be affordable or reliable.

Electricity is expensive in many countries, especially relative to income. While the average price of electricity in the US is about 18 cents per kWh, electric rates are higher in many low-income countries including as Burkina Faso, Kenya, and Rwanda.[91] Blackouts have been common in South Africa in recent years, with electricity typically unavailable for several hours per day.[92] When the electricity is not working, people must either do without or rely upon diesel generators which emit toxic pollutants and are expensive to operate.

energy poverty lacking access to modern, affordable, and reliable energy.

While small-scale, decentralized renewable energy can clearly help reduce energy poverty in rural areas, low-income countries need access to sufficient levels of energy to foster widespread economic growth and competitiveness in international markets. Also, larger-scale energy generation tends to reduce per-unit costs. A 2020 report by the Global Commission to End Energy Poverty (GCEEP) calls for a flexible approach to address energy poverty that includes:[93]

- Annual funding of $40 billion per year to provide universal access to electricity, utilizing private and public funding.

- A mixture of on-grid and off-grid energy solutions, emphasizing but not limited to renewable sources, tailored to individual circumstances.
- A focus on energy transmission, which is often the weak link in energy supply systems in lower-income countries.
- Building the capacity for effective government regulation of energy markets to prevent corruption and inefficiency.

While fossil-fuel subsidies are sometimes promoted as a means to reduce energy poverty, a 2024 journal article concludes that they actually do the opposite—impeding energy access by directing investment away from renewables and grid expansion, with the benefits primarily accruing to higher-income households. Instead, the authors suggest that governments in lower-income countries:

> should implement subsidy reforms that encourage energy efficiency and the adoption of renewable energy sources. By making subsidies more conditional and focused on promoting renewable technologies, such as solar and wind energy, not only can dependence on petroleum be reduced, but also a more sustainable and resilient energy system can be fostered.[94]

It thus appears possible to combine a global transition to renewable energy with greater equity in energy access—provided that governments implement appropriate policies.

Summary

The world faces four major energy challenges: transitioning from fossil fuels to renewable energy, electrification of much of the world's energy systems, constraining the growth of energy demand through energy efficiency improvements and other approaches, and addressing global energy disparities.

Fossil fuels currently provide about 80% of the world's energy. Despite past concerns about supplies, fossil fuels are generally abundant. The disadvantages of fossil fuels include price volatility, emissions of carbon dioxide and local air pollutants, and the environmental impacts of mining. Nuclear energy results in low emissions, but the main concerns are high costs and the possibility of accidents.

Renewable energy sources, particularly wind and solar energy, were limited in the past due to high costs. But the price of wind and solar energy has declined dramatically in recent years due to technological improvements, such that they are now the two cheapest energy sources in the world, on average, even without subsidies. With the internalization of externalities, the economic advantage of renewable energy over fossil fuels becomes even larger.

The global transition to renewable energy is clearly underway, but it needs to be accelerated to meet climate goals. Energy taxes and subsidy reform are two main economic policy tools to speed the transition. A focus on demand-side energy management is also important, using pricing, informational, and behavioral approaches. Finally, additional investment is needed to address energy poverty in low-income countries.

Key Terms

biomass energy
demand-side energy management
efficiency labeling
energy poverty
feed-in tariffs
geothermal energy
hydroelectricity (or hydropower)
levelized costs
nonrenewable energy sources
photovoltaic (PV) cells
renewable energy sources
supply-side energy management

Discussion Questions

1. Would you add any other global energy challenges to the four listed at the start of the chapter? What do you see as the most effective policies to meet the challenges?
2. How do you see the world's energy systems changing over the next few decades? What will it take to accelerate the pace of change? What are the primary barriers to an effective energy transition?
3. Do you think market forces will motivate most of the transition to renewable energy, or are aggressive government policies required? Which policies are most important, and what are the justifications for such policies from the point of view of environmental economics?

Websites

1. **www.eia.gov** Website of the Energy Information Administration, a division of the US Department of Energy that provides a wealth of information about energy demand, supply, trends, and prices.
2. **www.nrel.gov** The website of the National Renewable Energy Laboratory in Colorado. The NREL conducts research on renewable energy technologies including solar, wind, biomass, and fuel cell energy.
3. **www.rmi.org** Homepage of the Rocky Mountain Institute, a nonprofit organization that "fosters the efficient and restorative use of resources to create a more secure, prosperous, and life-sustaining world." The RMI's main focus has been promoting increased energy efficiency in industry and households.
4. **www.iea.org** Website of the International Energy Agency, which maintains an extensive database of energy statistics and publishes numerous reports. While some data are

available only to subscribers, other data are available for free, as well as access to informative publications such as the "Key World Energy Statistics" annual report.

5. **www.energystar.gov** Website of the Energy Star program, including information about which products meet guidelines for energy efficiency.

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