ENVIRONMENTAL AND NATURAL RESOURCE ECONOMICS:
A CONTEMPORARY APPROACH

JONATHAN M. HARRIS AND BRIAN ROACH

ADVANCE CHAPTERS FOR FOURTH EDITION (DUE 2017)

FOURTH EDITION CHAPTER 11: ENERGY - THE GREAT TRANSITION
REPLACES THIRD EDITION CHAPTER 12

(Due 2017: The final content and layout of the chapters may be subject to change.)

CHAPTER 11

Energy: The Great Transition

CHAPTER 11 FOCUS QUESTIONS

- What is the special role of energy in economic systems?
- What are current and future demands for energy?
- Is there a danger of energy shortages?
- Can we shift from fossil fuel-based energy to renewable energy systems?

solar energy the energy supplied continually by the sun, including direct solar energy as well as indirect forms such as wind energy and flowing water.
biomass an energy supply from wood, plant, and animal waste.
hydropower the generation of electricity from the energy in flowing water.
energy transition an overall shift of energy consumption away from fossil fuels toward renewable energy sources.

11.1 ENERGY AND ECONOMIC SYSTEMS

Energy is fundamental to economic systems and, indeed, to all life. On deep ocean floors, far below the reach of sunlight, giant tubeworms and other strange life forms cluster around heat vents. Energy from the earth's interior drives their metabolic processes. On the earth's surface and at shallower ocean levels, all plant life depends on sunlight, and all animal life is dependent directly or indirectly on plants. (The few plants that can live without direct sunlight make use of nutrients in the soil deposited by the decay of other plants.) Our own equally critical need for energy is partially camouflaged in a modern economy. Measured in terms of gross domestic product (GDP), energy resources represent only about 8 to 10 percent of economic output,[1] but the other 90+ percent is absolutely dependent on energy inputs.

In less developed, agrarian economies, the dependence is more evident. People's basic need for food calories is, of course, a need for energy input. Traditional agriculture is essentially a method of capturing **solar energy** for human use. Solar energy stored in firewood meets other basic needs for home heating and cooking. As economies develop and become more complex, energy needs increase greatly. Historically, as supplies of firewood and other **biomass** proved insufficient to support growing economies, people turned to **hydropower** (also a form of stored solar energy), then to coal, and then to oil and natural gas as major energy sources. In the 1950s nuclear power was introduced into the energy mix.

Each stage of economic development has been accompanied by a characteristic **energy transition** from one major fuel source to another. Today, fossil fuels—coal, oil, and natural gas—are by far the dominant energy source in industrial economies. In the twenty-first century, the next great transition in energy sources has started—from nonrenewable fossil fuels to renewable energy sources. This transition is being motivated by many factors, including concerns about environmental impacts (particularly climate change), limits on fossil fuel supplies, and prices.

Government policies will have significant influence on the nature and speed of this transition. Current energy markets bear little resemblance to the efficient unregulated markets described in Adam Smith's *Wealth of Nations*. Instead, energy markets are heavily subsidized and regulated. In particular, fossil-fuel subsidies by governments around the world total about $500 billion per year, while subsidies for renewable energy are about $120 billion.[2]

(For more on energy subsidies, see Box 11.1.)

BOX 11.1 FOSSIL FUEL SUBSIDIES

The International Energy Agency estimates that governments spent about $500 billion in 2015 to subsidize fossil fuels. According to the International Institute for Sustainable Development (IISD), global subsidies to fossil fuels may be larger, on the order of US$600 billion per year, but since there is no international framework for regularly monitoring fossil-fuel subsidies the precise figure is unknown. It is certainly much larger than total subsidies for renewable energy, which are around $120 billion per year.

The Group of 20 (G20) countries, an international forum for governments and central bank governors from 20 major economies, have agreed to phase out fossil subsidies over "the medium term" but progress has been slow and no specific target date has been set. In 2014 almost 30 countries, including Egypt, Indonesia and India, implemented some form of fossil-fuel subsidy reform (FFSR). Low oil prices made the removal of consumer fossil-fuel subsidies more politically acceptable. As a result, according to IISD, many countries that maintain subsidies to oil, gas, diesel, coal and electricity generated from such fuels will be considering or undergoing reform in the near future.

Meanwhile, many countries are ramping up their commitment toward renewable energy. Germany and other European countries use feed-in tariffs (discussed further below), a form of subsidy to solar energy. The United States spent more than any other country on renewable energy subsidies, around $15 billion in 2013. China provided about $2 billion, although this figure is likely too low as it does not include the value of low-interest loans offered for renewable energy projects by state-owned banks.

Sources: Morales, 2010; IISD, 2014; U.S. EIA, 2015.

nonrenewable stock See "nonrenewable resources."
renewable flow the continuous quantity of a renewable energy source supplied over time, such as the quantity of solar energy available each year.

Energy prices also generally fail to reflect the costs of negative externalities. As we saw in Chapter 3, economic theory suggests that a commodity be taxed according to its externality damages. In the case of energy markets, externalities are rarely fully internalized. Removing distortionary subsidies and instituting appropriate externality taxes could significantly speed the transition from fossil fuels to renewable energy sources.

While getting the prices of different energy sources "right" is critically important, we should also note a different, more ecologically oriented, perspective on energy. Theorists of the ecological economics school see energy as fundamental to economic development and focus on a crucial distinction between the **nonrenewable stock** of fossil-fuel reserves and the **renewable flow** of solar energy.[3] In this perspective, the period of intensive fossil-fuel use that began with coal in the eighteenth century was a one-time, unrepeatable bonanza—the rapid exploitation of a limited stock of high-quality resources, with increasingly negative effects on planetary ecosystems.[4]

The fossil-fuel age has obviously brought significant economic progress to much of the world, but this particular route to development cannot be followed universally. If everyone consumed fossil fuels at the rate of the average American, global greenhouse gas emissions would increase by about a factor of four. Fortunately, the earth receives enough solar energy every hour to supply all human energy needs for an entire year.[5] This figure is theoretical—the capture and use of solar energy, either directly or indirectly through such sources as wind power or biomass, involves costs and limitations. Nonetheless, renewable energy potential is very great. Operating our economies on this renewable flow, as opposed to non-renewable fossil fuels, represents a key component of any conception of sustainable development.

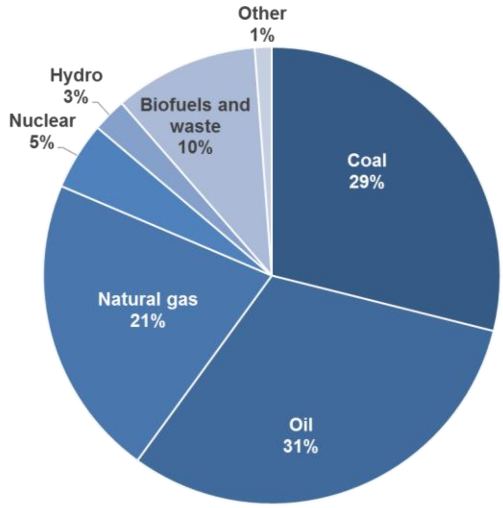
Because so much of the **capital stock** and infrastructure of modern economic systems are based on fossil-fuel energy use, any transition from fossil fuel dependence will involve massive restructuring and new investment. While private markets will play a critical role in this process, major changes in government policies are necessary to foster the transition. The considerable economic implications of this justify a special focus on energy use as a central economic and environmental issue.

capital stock the existing quantity of capital in a given region, including manufactured, human, and natural capital.

11.2 Evaluation of Energy Sources

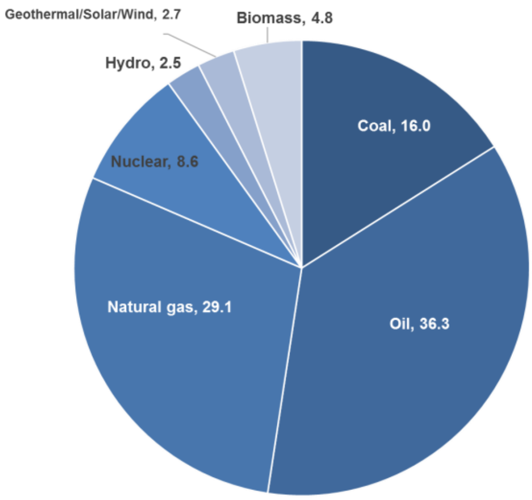
We obtain energy from numerous sources for many different purposes. Figure 11.1a shows the main energy sources consumed globally. We see that over 80 percent of the world's energy comes from fossil fuels—oil, coal, and natural gas. In most respects, the energy shares for the United States, shown in Figure 11.2, are similar to the global proportions. The United States is slightly more reliant upon natural gas and nuclear energy, and less reliant upon coal, while the world as a whole has a higher percentage of hydropower. Both the United States and the world receive only about 2-3 percent of energy from renewable wind, solar, and geothermal energy (though, as we will see, this currently small percentage is growing at a rapid rate).

Figure 11.1 Global Energy Consumption 2013, by Source



Source: International Energy Agency, 2015.

Figure 11.2 United States Energy Consumption 2014, by Source



Source: U.S. Energy Information Administration, 2016.

One objective of this chapter is to analyze how our energy supply mix will need to change in the future. But first we need to consider how we should evaluate various energy sources. This will help explain why our current energy mix is allocated as shown in Figures 11.1 and 11.2. We consider five criteria to evaluate different energy sources:

Price: This is perhaps the most obvious factor to consider. We should consider both the average price of a particular energy source and also its variability over time. As you might expect, our heavy reliance on fossil fuels has been driven largely by price considerations.

Availability: Fossil fuels are limited in supply. We consider later in the chapter whether we are in danger of running out of fossil fuels. Renewable energy sources such as wind and solar cannot be depleted but have variable geographic availability and may fluctuate daily and seasonally.

Environmental impacts: Analysis of the environmental impacts of different energy sources should consider the full life-cycle impacts. For example, for coal we should look at the impacts associated with mining coal, the air pollution generated from burning coal, the disposal of the waste from coal plants, and the eventual decommissioning of power plants.

Net energy: It takes energy to get energy. For example, the energy required to explore for, to extract, and to process crude oil should be deducted from the energy obtained to determine the net available energy. Net energy is normally expressed as a ratio of the energy available for final consumption divided by the energy required to produce it.

Suitability: Different types of energy are more useful for certain applications. For example, oil is particularly suitable for powering motor vehicles, nuclear power is primarily used to generate electricity, and geothermal energy is well suited for heating buildings.

Net Energy and Suitability of Energy Sources

We discuss price, availability, and environmental impacts of energy in more detail later in this chapter. First, we discuss the other two factors: net energy and suitability of energy sources.

If net energy is expressed as a ratio, a higher value means that we can obtain a significant amount of available energy without using much energy to obtain it. Table 11.1 shows the net energy ratios for various energy sources, based on U.S. data. Net energy ratios for fossil fuels range from 5 for shale oil (oil extracted from hydrocarbon-rich rocks) to 80 for coal. The net energy ratio for hydropower is even greater—over 100. Nuclear power, wind energy, and photovoltaic cells have moderate net energy ratios.

The lowest net energy ratios are found for some biofuels. In fact, the energy needed to produce corn ethanol is about equal to the energy obtained. This implies that without significant technological improvements, corn ethanol is not a very attractive energy option based on the net energy criterion, although other biofuels might achieve higher net energy ratios.

Table 11.1 Net Energy Ratios for Various Energy Sources

Energy source	Net energy ratio
Oil (global)	35
Natural gas	10
Coal	80
Shale oil	5
Nuclear	5–15
Hydropower	>100
Wind	18
Photovoltaic cells	6.8
Ethanol (sugarcane)	0.8–10
Ethanol (corn-based)	0.8–1.6
Biodiesel	1.3

Source: Murphy and Hall, 2010.

Energy statistics normally divide energy use among four sectors in an economy: transportation, industrial, residential and commercial (excluding electricity), and electricity (considered as a separate sector). Different energy sources are better suited for different sectors. Table 11.2 shows the three main energy sources used by each sector in the United States.

Transportation is heavily dependent upon oil, which supplies 94 percent of U.S. transportation needs. Oil is well suited for transportation because it has a high energy density and is relatively easy to store. But oil is less prevalent in the other energy sectors. The industrial sector relies about equally on natural gas and oil. Natural gas demands are highest in such industries as chemicals manufacturing, agriculture, and metal manufacturing. The residential and commercial sector relies on natural gas for about three-quarters of its non-electricity energy demands, mainly for heating.

Table 11.2 Energy Consumption by Sector in the United States, 2015

	Sector			
	Transportation	Industrial	Residential and commercial	Electricity
Percent of total U.S. energy consumption	28%	22%	11%	39%
Primary fuel source	Oil (92%)	Natural gas (44%)	Natural gas (76%)	Coal (37%)
Secondary fuel source	Renewables (5%)	Oil (39%)	Oil (15%)	Natural Gas (26%)
Tertiary fuel source	Natural gas (3%)	Renewables (11%)	Renewables (9%)	Nuclear Energy (22%)
Quaternary fuel source	N/A	Coal (7%)	Coal (1%)	Renewables (13%)
Quinary fuel source	N/A	N/A	N/A	Oil (1%)

Source: U.S. Energy Information Administration, 2016.

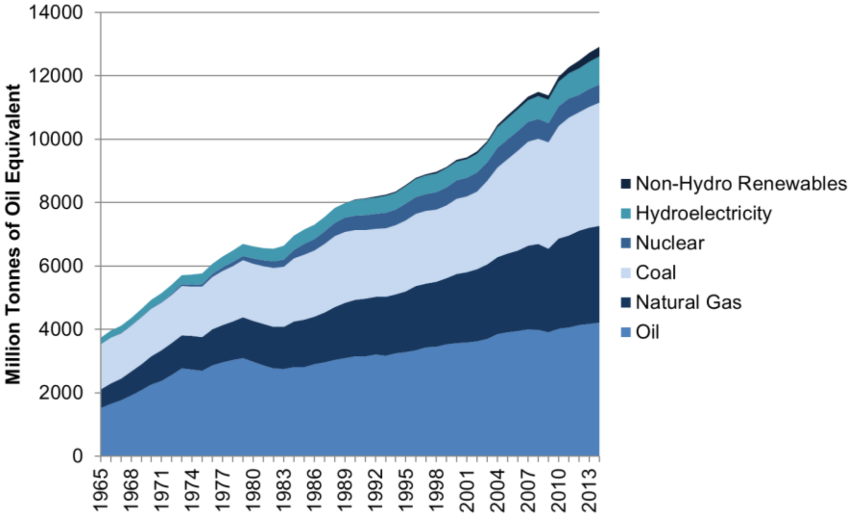
In the electricity sector, the United States gets slightly over one third of its electricity from coal (down from nearly half five years earlier), with 26 percent from natural gas and 22% from nuclear power. Renewable energy is most prevalent in electricity generation, with about 13 percent of U.S. electricity coming from renewable sources, mainly hydropower and wind. Wind energy, though starting from a small base as a percent of electric generation, has increased rapidly in recent years. Solar electric generation has also increased rapidly from a small base. We will examine the growth of renewable energy in more detail in Section 4 of this chapter.

11.3 Energy Trends and Projections

World energy demand has grown rapidly and is expected to continue to grow in the foreseeable future. As seen in Figure 11.3, world energy consumption increased by factor of more than three between 1965 and 2015. World population approximately doubled during this same period, so about half the growth in global energy demand can be attributed to a higher population and the other half can be attributed to greater demand per capita.

Higher global demand has been met by expanding the use of all forms of energy. From 1965 to 2014, energy consumption from coal increased 172 percent, from oil 178 percent, from hydropower 264 percent, and from natural gas 416 percent. The most rapid growth in recent years has occurred for non-hydro renewables. Since 1990, global consumption of non-hydro renewables has increased by a factor of more than 10. Despite such growth, solar and wind energy currently provide only a small percentage of global energy supplies—less than 2 percent in 2014. Between 2000 and 2015 over 40% of the increase in global energy demand was met by expanding coal use, mainly in new electricity plants in emerging countries such as China and India.[6]

Figure 11.3 World Energy Consumption, by Source, 1965–2014



Source: BP Statistical Review of World Energy, 2012-2015.

But in recent years renewables have become the leading source of new energy capacity, both in the U.S. and globally. About two thirds of new U.S. energy capacity in 2016 was from renewables. According to a 2015 bulletin from the International Energy Agency, "renewable energy will represent the largest single source of electricity growth over the next five years, driven by falling costs and aggressive expansion in emerging economies". [7]

Projections of future global energy demand depend on assumptions regarding prices, technology, and economic growth. Projections by the major energy agencies, including the U.S. Energy Information Administration and the International Energy Agency (IEA), typically include a baseline, or business-as-usual (BAU), scenario that assumes no significant policy changes and no dramatic shifts in prices and technology. Other scenarios consider what might be expected if, for example, oil prices are significantly higher in the future or if major policy changes are implemented.

Figure 11.4 presents one such comparison, produced by the IEA. In the baseline or "current policies" scenario, global energy consumption increases by about 45 percent from 13,559 million tonnes of oil equivalent (Mtoe) to over 19,000 Mtoe in 2040 (a tonne is one metric ton, equal to 1,000 kilograms (kg) or 2,204.6 pounds.) Compared to the energy mix shown in Figure 11.1, the percentage of global energy obtained from fossil fuels changes only slightly, from 81% to 79% (see Figure 11.5). The share of oil is expected to decline, while the share obtained from coal and nuclear is expected to remain about the same. The share from renewable energy increases, but only by about 2%.

Figure 11.4 also predicts the global energy mix under an aggressive policy scenario intended to keep global warming to no more than 2 degrees Celsius over pre-industrial levels—the target agreed on during the 2015 international meeting on climate change in Paris, corresponding to 450 parts per million of atmospheric CO_2.[8] In this scenario, global energy demand grows by only about 12 percent from 2013 to 2040.

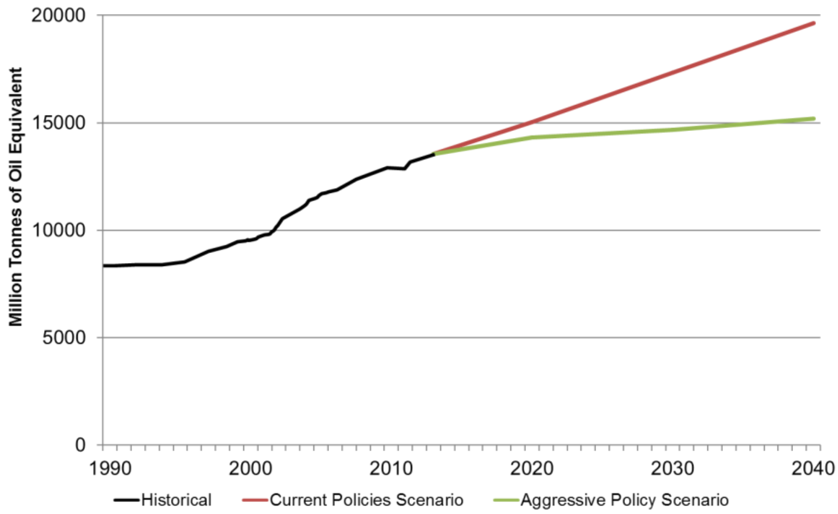
We also see significant differences in the global energy mix (Figure 11.5). Compared to the "current policies" scenario, coal use is dramatically lower, hydro and nuclear have larger shares, and non-hydro renewable energy represents a much larger proportion of global energy use at 25%. In this case, the share of global energy obtained from fossil fuels falls from 81 percent to 60 percent. Total global fossil fuel use declines about 15% below 2013 levels by

2040, as compared to an increase of 43% in the "current policies" scenario. CO_2 emissions decline even further, by nearly 40%, due to the shift away from coal.

These results demonstrate that our energy future is not predetermined, but that total energy consumption and the energy supply mix will depend on the policy choices made in the coming years. In fact, concerted policy efforts can make dramatic changes in a relatively short period of time (see Box 11.2).

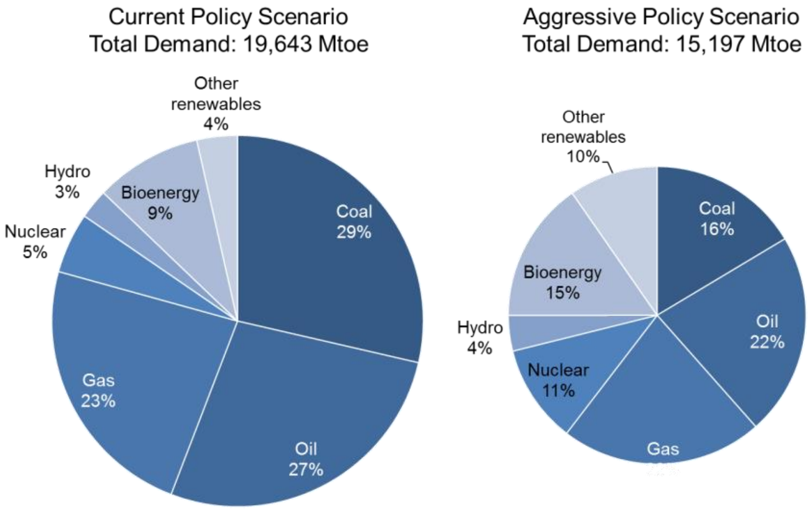
In addition to looking at energy statistics based on different energy sources, it is also instructive to analyze energy consumption across different countries and regions. As we see in Table 11.3, energy use per capita varies tremendously across countries.

Figure 11.4 Projected 2035 Global Energy Demand



Source: International Energy Agency, 2015a.

Figure 11.5 World Primary Energy Demand by Fuel and Scenario, 2040



Source: International Energy Agency, 2015a.

BOX 11.2 PORTUGAL GIVES ITSELF A CLEAN-ENERGY MAKEOVER

Back in 2005 Portugal initiated an ambitious program to increase its reliance on renewable energy. The results have been impressive—the share of Portugal's electricity coming from renewable energy increased from 17 percent in 2005 to 63 percent in 2014. Over that time period, the energy obtained from wind power increased by a factor of seven.

Portugal was able to expand its use of renewable energy rapidly because it had large supplies of untapped wind and hydroelectric power. As it previously relied heavily on costly imports of fossil fuels for its electricity, Portugal's shift toward renewable energy required no tax or debt increases. Portugal now plans to begin closing down some of its conventional power plants that are no longer needed. Portugal is also putting in place a national grid of charging stations for electric cars.

"I've seen all the smiles—you know: It's a good dream. It can't compete. It's too expensive," said Prime Minister José Sócrates. Mr. Sócrates added, "the experience of Portugal shows that it is possible to make these changes in a very short time."

Source: Rosenthal, 2010; Publico, "23% Guaranteed renewable electric consumption in Portugal in 2014" https://www.publico.pt/ecosfera/noticia/renovaveis-garantiram-63-do-consumo-electrico-em-portugal-em-2014-1681364.

Table 11.3 Energy Consumption per Capita, 2011, Selected Countries

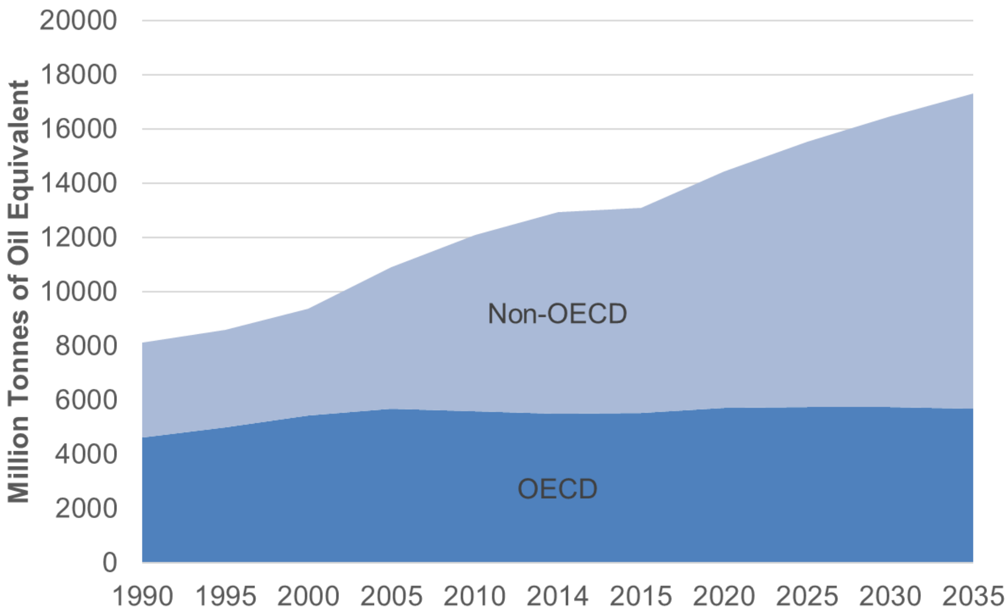
Country	Million BTUs per person
United Arab Emirates	728
Canada	394
United States	313
Sweden	236
Russia	213
France	166
Germany	165
United Kingdom	134
Italy	123
China	78
Thailand	74
Brazil	60
India	20
Nigeria	5
Ethiopia	2

Source: U.S. Energy Information Administration, International Energy Statistics online database.
Note: BTU = British thermal unit.

Countries with the highest per capita energy use tend to be either countries with a cold climate, such as Canada and Iceland, or oil-producing countries such as the United Arab Emirates and Qatar. Per capita energy use in the United States is relatively high, especially when compared with European countries such as France and Italy. Per capita energy use in China has grown rapidly in recent years, but it is still only about one-quarter of the typical energy use of a U.S. resident. Energy use per person in India is only about one-sixteenth the U.S. level, and energy use in the poorest countries is less than 1 percent of the U.S. level.

Developed (OECD) countries have historically been responsible for most of global energy demand, but this is changing. Developing (non-OECD) countries have recently surpassed developed countries in total energy consumption, as shown in Figure 11.5. Almost all future growth in global energy demand is expected to occur in developing countries, under the BAU scenario shown in Figure 11.5. Even with such rapid growth in energy consumption in developing countries, energy use per capita will still be only about one-third of the levels in developed countries. Thus global inequality in energy access will continue for the foreseeable future.

Figure 11.6 Past and Projected Energy Consumption, OECD vs. Non-OCED Nations



Source: BP Energy Outlook 2016.
Note: OECD = Organization for Economic Cooperation and Development.

Hubbert curve a bell-shaped curve showing the production quantity of a nonrenewable energy resource over time.

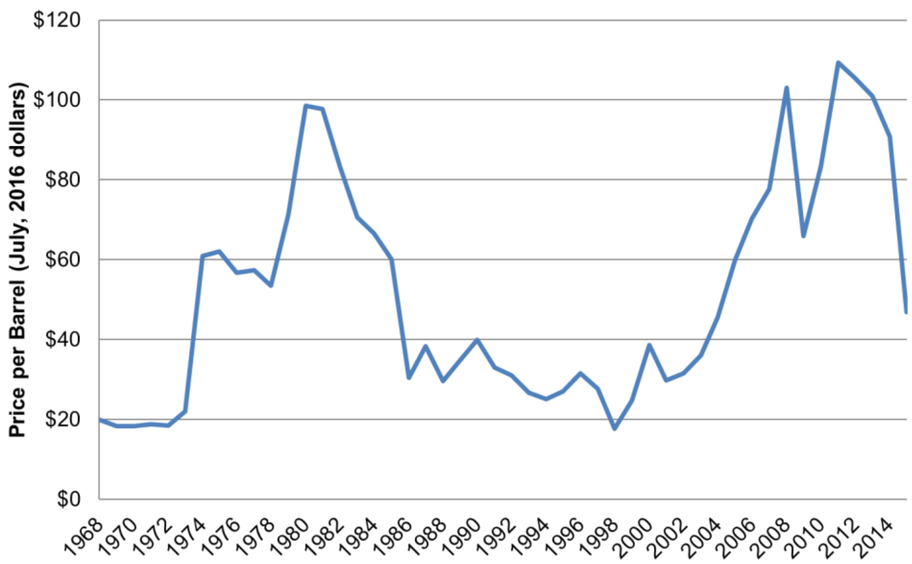
11.4 Energy Supplies: Fossil Fuels

Even with aggressive energy policies, global energy demand is projected to continue to increase in the coming decades, and we will continue to meet most of our energy needs with fossil fuels for some time. But is the supply of fossil fuel sufficient to meet future demands? And can existing supplies of fossil fuels be burned without inviting environmental disaster?

Much of the discussion about energy supplies has focused on oil. In the early years of the twenty-first century, there was a focus on the concept of “peak oil” –the idea that limited oil supplies would lead to rising prices and force a reduction in oil consumption. Prices did indeed rise from 2000 to 2012. But the introduction of “unconventional” oil sources produced by hydraulic fracturing of rock and extraction from tar sands and oil shales led to an increase in oil supply and falling prices (see Figure 11.7). Whether this trend will be maintained, or whether prices will rise again, cannot be easily predicted. How can we evaluate projections of oil supply limits?

According to a theory advanced by petroleum geologist M. King Hubbert in 1956, the typical pattern of oil production over time resembles a bell curve. In the early period of resource exploitation, discovery and production expand, leading to falling prices and exponentially rising consumption. Eventually production becomes more expensive as the most-accessible supplies are depleted. New discoveries decline, and production eventually peaks. Beyond the peak, production falls and, assuming constant or increasing demand, prices continue to increase.

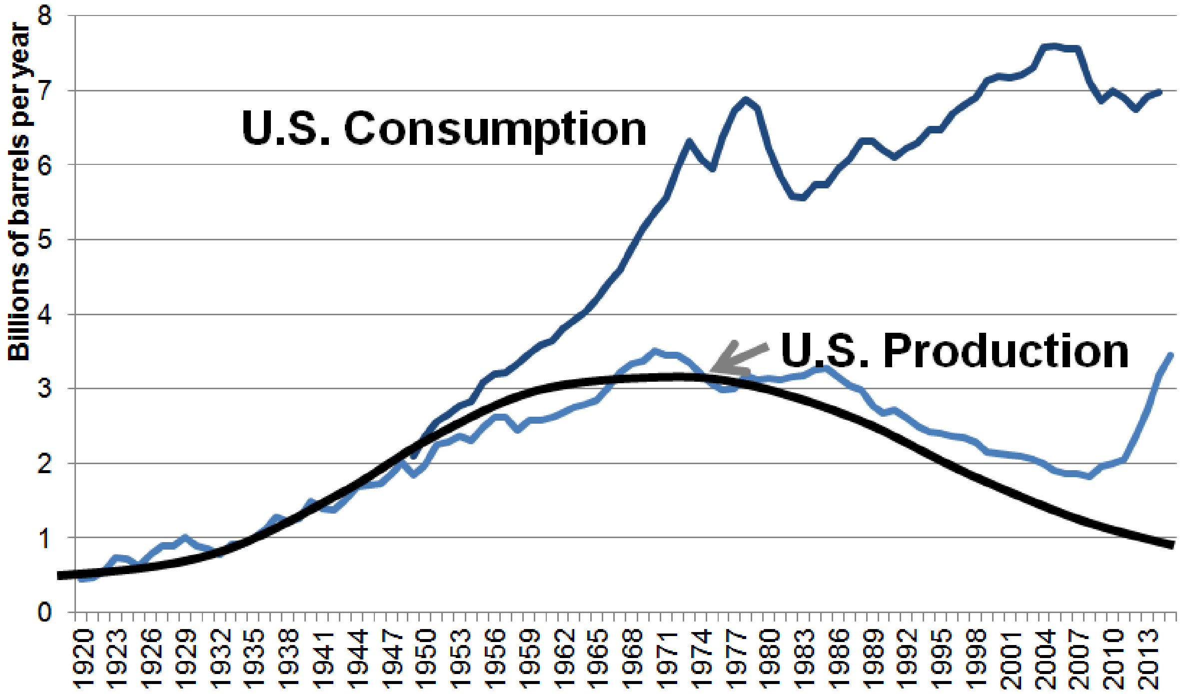
Figure 11.7 Oil Prices in Constant Dollars, 1970-2015



Sources: U.S. Energy Information Administration, www.eia.gov and http://inflationdata.com.

As Figure 11.8 shows, the **Hubbert curve** projection for U.S. crude oil production matched up rather well to the actual data through about 2010. Conventional oil output in the United States peaked in the early 1970s and has generally declined since then. But the recent increase in U.S. output, due to “unconventional” oil production, has changed this trend. Figure 11.8 also shows U.S. oil consumption. While the United States was essentially oil independent until about 1950, the share of oil demand met from imports generally increased after the 1950s. In the mid-2000s the United States obtained over 60 percent of its oil from imports. But with the rise in unconventional oil production, the proportion of imports has fallen, to about 50% in 2015.

Figure 11.8 United States Domestic Oil Production and Consumption



Source: U.S. Energy Information Administration, Annual Energy Outlook online database.
Note: The trend of declining U.S. crude oil production continued through 2008, with an increase after 2009 resulting from increased production of "unconventional" sources such as deep offshore oil and shale oil.

A common myth is that the United States obtains most of its imported oil from the Middle East. Actually, the top exporter of oil to the United States, with about 39 percent of all U.S. imports, is Canada. Other top sources of U.S. oil imports are Saudi Arabia (13 percent), Venezuela (10 percent), Mexico (9 percent), and Colombia (5 percent).

Current projections by the U.S. Energy Information Administration estimate that U.S. domestic crude oil production will hold steady or increase in the coming decades.[9] So while the Hubbert Curve may continue to be representative of conventional U.S. crude oil production, the availability of unconventional oil sources may prevent further declines in U.S. total oil production.

Global Oil Supplies

More important is the availability of oil supplies at the global level. Table 11.4 shows that in 1980 proven oil reserves would have been sufficient to meet thirty-one years of demand if demand levels stayed constant. Rather than staying constant, global demand for oil continued to increase. But did the world run out of oil in 2011, or earlier? Of course not. We see in Table 11.4 that oil reserves are now X times higher than they were in 1980 as a result of new discoveries, technological improvements, and higher oil prices, which have made more oil deposits economically viable. Even with higher global demand, proven reserves could now meet global demands for a further X years at current consumption rates.

Table 11.4 Global Oil Reserves, Consumption, and Resource Lifetime, 1980–2011

Year	Proven reserves (billion barrels)	Annual consumption (billion barrels)	Resource lifetime (years)
1980	683	22	31
1985	803	22	37
1990	1,028	24	42
1995	1,066	26	42
2000	1,258	28	45
2005	1,357	31	44
2010	1,622	32	51
2015	1,698	34	51

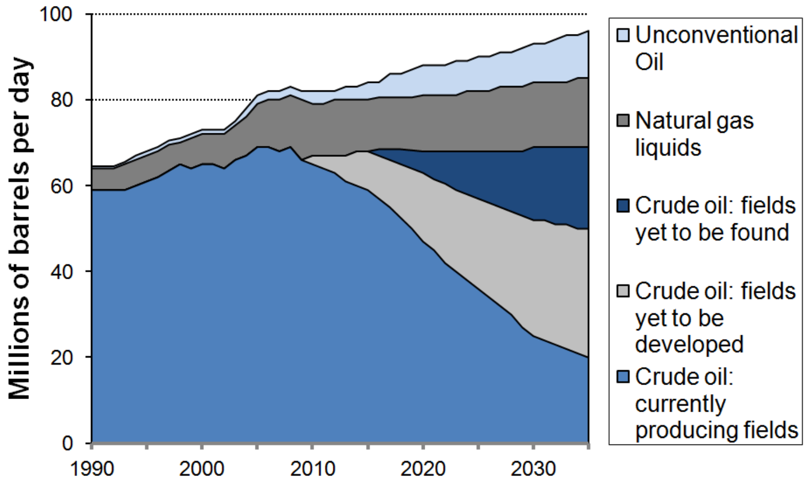
Source: British Petroleum, 2016

Figure 11.9 shows past and projected global oil production under a scenario that takes into account recent pledges by countries to reduce greenhouse gas emissions and phase out subsidies for fossil fuel. Even with new discoveries, conventional crude oil production stabilizes at around 70 million barrels per day. Global oil production is able to continue to increase through reliance on unconventional oil sources and natural gas liquids.

When global oil production peaks might depend as much upon policy as on resource availability. According to the IEA:

> Clearly, global oil production will peak one day, but that peak will be determined by factors affecting both demand and supply. . . . [I]f governments act more vigorously than currently planned to encourage more efficient use of oil and the development of alternatives, then demand for oil might begin to ease soon and, as a result, we might see a fairly early peak in oil production. That peak would not be caused by resource constraints. But if governments do nothing or little more than at present, then demand will continue to increase, supply costs will rise, the economic burden of oil use will grow, vulnerability to supply disruptions will increase and the global environment will suffer serious damage.
>
> Unconventional oil is set to play an increasingly important role in world oil supply through to 2035, regardless of what governments do to curb demand. . . . Unconventional oil resources are thought to be huge—several times larger than conventional oil resources. The rate at which they will be exploited will be determined by economic and environmental considerations, including the costs of mitigating their environmental impact. Unconventional sources of oil are among the more expensive available. Consequently, they play a key role in setting future oil prices.[10]

Figure 11.9 Past and Projected Global Oil Production, 1990–2035



Source: International Energy Agency, 2010.
Note: Estimates of ultimately recoverable global oil vary widely, and the year of projected "peak oil" production depends on these estimates. The study shown above indicates a peak in conventional production by 2010, with production from current fields falling off rapidly thereafter. Future oil production depends on discovery of new fields, natural gas liquids, and "unconventional" sources such as shale oil.

So in an absolute sense, we are unlikely to run out of oil anytime soon, especially when unconventional sources are taken into account. But sources such as tar sands and shale oil tend to have significantly higher environmental impacts than conventional oil. Currently these impacts are not reflected in market prices, but as we know economic theory suggest that the higher environmental costs should be internalized, which would make these unconventional sources more expensive.

Globally, oil demand is still rising. Given the suitability of oil for the transportation sector, there is a steady increase in demand for oil in developing countries:

> All of the net increase in oil demand comes from the transport sector in emerging economies, as economic growth pushes up demand for personal mobility and freight. Alternative vehicle technologies emerge that use oil much more efficiently or not at all, such as electric vehicles, but it takes time for them to become commercially viable and penetrate markets.[11]

Economic factors, however, may lead to substitution of other fuels for oil, and concerns about global climate change, discussed in Chapters 12 and 13, may promote policies to favor renewables over oil.

Other Fossil Fuels: Natural Gas and Coal

The other fossil fuels, coal and natural gas, are potential alternatives to oil in the transportation sector. Natural gas can be used to fuel vehicles directly; there were an estimated 5 million natural gas vehicles worldwide in 2011.[12] Coal can be used to generate electricity to fuel electric vehicles. As we saw in Table 11.1, coal and natural gas play a relatively large role in the industrial, residential, commercial, and electricity sectors. Globally, coal and natural gas provide nearly 50 percent of energy supplies. What about the availability of these resources?

Both coal and natural gas are more abundant than oil in the United States and globally. While the United States has only 3 percent of global oil reserves, it has 5 percent of the world's natural gas reserves and 27 percent of coal reserves. In recent years, the United States has experienced a natural gas boom, with an increase in production of 50 percent between 2005 and 2015. According to the U.S. Energy Information Administration, U.S. production of natural gas is expected to grow by about 1 percent per year over the next couple of decades.[13]

Natural gas is generally viewed as the cleanest fossil fuel, producing comparatively low amounts of air pollutants and greenhouse gases. Yet environmentalists have expressed concerns in recent years over the process of hydraulic fracturing, or "fracking," to obtain natural gas (see Box 11.3). Some analysts have suggested that leakages of methane, a powerful greenhouse gas, can make fracked natural gas as bad as or worse than coal in terms of greenhouse gas emissions.[14] Globally, natural gas reserves are sufficient for more than fifty years of supply at current demand levels.[15]

Coal is the most environmentally damaging fossil fuel. It is estimated that particulate-matter pollution from coal power plants leads to the deaths of more than 13,000 people in the United States every year.[16] Coal also emits more carbon dioxide, the primary greenhouse gas, per unit of energy. Coal is, however, the most abundant fossil fuel. The United States is the world leader in coal reserves—its reserves alone could satisfy current world demand for thirty-one years. Global reserves are sufficient for 114 years of world consumption at current demand levels.[17] But burning this much coal would be likely to create disastrous climate change effects, as we will discuss in Chapters 12 and 13, as well as considerably increased ground-level pollution especially in countries such as China where air pollution is already severe.

BOX 11.3 TAINTED WATER AND EARTHQUAKES LINKED TO HYDRAULIC FRACTURING FOR NATURAL GAS

In 2011 a report published by the U.S. Environmental Protection Agency (EPA) found that the hydraulic fracturing of rocks in the process of drilling for natural gas, commonly known as fracking, is the likely cause of contaminated water supplies in Wyoming. The report raises questions about the environmental safety of fracking, which is being used to extract previously unrecoverable natural gas in dozens of places around the United States. However, the energy industry claims that water contamination from fracking has not been conclusively proven.

The report is based on a three-year study initiated when local residents complained about the smell and taste of their water. The study site, known as the Pavillion field, is a natural gas well that is unusually shallow. The shallow depth means that natural gas can seep upward into underground aquifers, contaminating water supplies.

Another potential threat from fracking is the chemicals companies use to extract natural gas, which can also contaminate water supplies. While Wyoming now requires companies to disclose the ingredients in their fracking fluids, in other states disclosure is not required. The EPA has begun a national study of the effects of fracking on drinking water supplies.

In Oklahoma, a new Federal hazard maps shows that parts of the state are now as earthquake-prone as California, due to the effects of widespread fracking. Scientists say Oklahoma's increase in quakes results from the injection of billions of barrels of salty wastewater from oil and natural gas exploration. Wastewater injection has put pressure on the state's fault lines, leading to quakes that have damaged homes, schools and other structures.

Sources: Johnson, 2011; Josh Sanburn, "Oklahoma is Now as Much of an Earthquake Risk as California," *Time* March 28, 2016, http://time.com/4273258/usgs-earthquake-map-oklahoma/.

Renewable Energy Sources

In one sense, renewable energy is unlimited, as supplies are continually replenished through natural processes. As noted earlier, the daily supply of solar energy is theoretically sufficient to meet all human energy needs for an entire year. 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 for wind or solar energy. For example, solar energy potential is highest in the southwestern United States, northern Africa, the Middle East, and parts of Australia and South America. Some of the best regions for wind energy include northern Europe, the southern tip of South America, and the Great Lakes region of the United States. Geothermal energy is abundant in countries such as Iceland and the Philippines.

One important question is whether renewable energy is available in sufficient quantities to replace our dependence on fossil fuels while also being comparably reliable and suitable for different purposes (we consider the issue of cost in the next section). A recent study concluded that renewable energy sources, based on wind, water, and sunlight (WWS), could provide all new energy globally by 2030 and replace all current nonrenewable energy sources by 2050.[18] Table 11.5 shows estimates of the potential energy from various renewable energy sources, converted into trillions of watts.

Table 11.5 Availability of Global Renewable Energy

Energy source	Total global availability (trillion watts)	Availability in likely developable locations (trillion watts)
Wind	1700	40–85
Wave	> 2.7	0.5
Geothermal	45	0.07–0.14
Hydroelectric	1.9	1.6
Tidal	3.7	0.02
Solar photovoltaic	6500	340
Concentrated solar power	4600	240

Source: Jacobson and Delucchi, 2011a.

Projected global energy demand in 2030 is 17 trillion watts. Thus we see in Table 11.5 that the availability of energy from wind and solar in likely developable locations is more than sufficient to meet all the world's energy needs. The report authors' analysis envisions:

> a world powered entirely by WWS, with zero fossil-fuel and biomass combustion. We have assumed that all end uses that feasibly can be electrified use WWS power directly, and that the remaining end uses use WWS power indirectly in the form of

electrolytic hydrogen (hydrogen produced by splitting water with WWS power). The hydrogen would be produced using WWS power to split water; thus, directly or indirectly, WWS powers the world.[19]

The authors then estimate the infrastructure that would be necessary to supply all energy worldwide from WWS in 2030. Table 11.6 presents their results, based on the assumption that 90 percent of global energy is supplied by wind and solar and 10 percent by other renewables. They also consider the land requirements for renewable **energy infrastructure**, including the land for appropriate spacing between wind turbines. Land requirements total about 2 percent of global land area, with most of this the space between wind turbines that could be used for agriculture, grazing land, or open space. Also, wind turbines could be located offshore to reduce the land requirements.

energy infrastructure a system that supports the use of a particular energy source, such as the supply of gas stations and roads that support the use of automobiles.

Table 11.6 Infrastructure Requirements for Supplying All Global Energy in 2030 from Renewable Sources

Energy source	Percent of 2030 global power supply	Number of plants/devices needed worldwide
Wind turbines	50	3,800,000
Wave power plants	1	720,000
Geothermal plants	4	5,350
Hydroelectric plants	4	900
Tidal turbines	1	490,000
Rooftop solar photovoltaic systems	6	1.7 billion
Solar photovoltaic power plants	14	40,000
Concentrated solar power plants	20	49,000
Total	100	

Source: Jacobson and Delucchi, 2011a.

The technology already exists to implement these renewable energy sources. Effective deployment of greatly increased renewable energy supply will require upgrading the electric grid as well as new capacity to store and transfer power (see Box 11.4). While construction of this renewable energy infrastructure will require significant investment, the authors conclude that the primary hurdles are not economic. “Barriers to the plan are primarily social and political, not technological or economic. The energy cost in a WWS world should be similar to that today."[20]

The issue of cost is central to the question of whether an energy transition will occur and, if so, how rapidly. The availability of energy supplies, whether fossil fuels or renewables, is not the determining factor. Rather, it is the relative costs, including the cost of energy infrastructure investment and the cost of day-to-day energy supply. In analyzing costs, we should consider both the market cost of supply and the environmental costs of various energy sources. It is to this analysis that we now turn.

BOX 11.4: INTERMITTENCY AND CAPACITY ISSUES WITH RENEWABLES

While renewable energy supplies have huge potential, their availability varies by time and location. They therefore cannot be matched to demand as easily as fossil fuels. Wind power depends on the speed of the wind at any given time. The availability of sunshine for solar power is greatest at certain times of day, and can be limited by cloudy weather. Also, most renewable energy sources have relatively low capacity factors compared to fossil fuels.

The supply-demand matching problem is most significant in the electricity market, where supply must continually match demand. While fossil fuel plants can be scheduled to start and stop at times of anticipated demand change, the output of solar and wind facilities cannot be increased on demand. As power systems move to a higher percentage of renewable sources, supply management policies must be developed to deal with energy-source **intermittency**.

Energy diversity is one response to intermittency. For example, solar energy is strongest in the summer, while in most places wind energy is strongest in the winter. A combination of the two can provide more consistent year-round electricity generation than either one individually.

Power storage is another option. Solar houses can store electricity in batteries. Battery storage must be at least sufficient for nights, ideally with some additional storage for cloudy days and/or periods of high electricity use. This same technology could be deployed on a broader scale, with individual buildings having on-premise battery storage. Renewable energy could be taken from the grid as it was available, and used as needed. The cost of delivered energy would then be the cost of production plus the cost of battery storage.

On a grid scale, electricity storage is more frequently accomplished with pumped water storage. When excess electricity is available from the grid, water is pumped from a lower reservoir to a higher reservoir. When electricity is needed, the water is allowed to flow back down and generate electricity. This is the same technology used in hydroelectric plants, but with water and energy able to move in both directions.

In combination with excess capacity, a robust national (and possibly international) electric grid is another approach to intermittency. Though the wind may not blow in a particular place at a particular time, wind is likely blowing somewhere all the time. An electric grid can be used to move energy from where it is being produced to where it is needed. But moving large amounts of electricity over long distance requires a substantial electricity grid. Policies that support modernized grid development will be needed to facilitate increased renewable energy utilization.

Source: Timmons et al., 2016.

intermittency a characteristic of energy sources such as wind and solar, which are available in different amounts at different times.

11.5 THE ECONOMICS OF ALTERNATIVE ENERGY FUTURES

The world currently gets about 80 percent of its energy supplies from fossil fuels because these sources generally provide energy at the lowest cost. However, the cost advantage of fossil fuels over renewable energy sources has been decreasing in recent years, and certain renewables can already compete with fossil fuels on solely financial terms. The price of fossil fuels, especially for oil, in the future is difficult to predict, while the costs of renewable energy are expected to decline further. Thus even without policies to promote a transition toward renewables, economic factors are currently moving us in that direction.

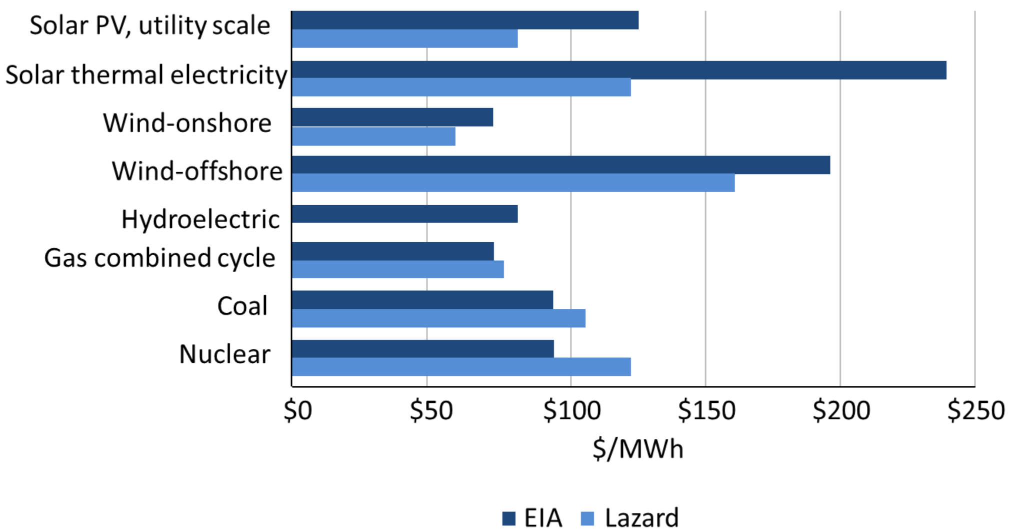
levelized costs the per-unit cost of energy production, accounting for all fixed and variable costs over a power source's lifetime.
present value the current value of a steam of future costs or benefits; a discount rate is used to convert future costs or benefits to present values.

Comparing the costs of different energy sources is not straightforward. Capital costs vary significantly—a new nuclear power plant can cost $5 billion to $8 billion. Some energy sources require continual fuel inputs, while other sources, such as wind and solar, only require occasional maintenance. We also need to account for the different lifespans of various equipment and plants.

Cost comparisons between different energy sources are made by calculating the **levelized cost** of obtaining energy. Levelized costs represent 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.

Different studies have produced different estimates of the costs of various energy sources. Some of these differences are attributed to cost variations in different regions of the world. Figure 11.10 provides a comparison of the projected levelized costs of generating electricity in the United States, from two different sources providing a range of estimates.

Figure 11.10 Levelized Cost of Different Energy Sources, United States



Sources: Lazard, 2014; U.S. EIA, 2016c.
Note: Lazard values are midpoints of estimated ranges.

Though there is some variation in estimates, it appears that onshore wind power is fully competitive with coal, natural gas, and nuclear. (Natural gas is currently the cheapest fossil fuel, displacing coal.) Hydroelectric power is also competitive. Solar photovoltaic at utility scale is cheaper than coal according to one set of estimates, while a bit more expensive based on the EIA estimate. Solar thermal electricity and offshore wind are more expensive, though solar thermal approaches competitiveness according to the lower estimate.

Oil does not appear in Figure11.10 because it is rarely used to generate electricity. In the United States, only about 0.5 percent of electricity is generated using petroleum products. But as we saw in Table 11.2, oil dominates the transportation sector. Various alternative options are available for road vehicles, including fully-electric vehicles, plug-in hybrids which use fossil fuels only for long-distance trips, and potentially hydrogen fuel cells. The electricity to charge vehicles or generate hydrogen could be generated by wind power, solar energy, geothermal power, or other renewable sources.

Cost comparisons between traditional internal combustion vehicles and renewable energy alternatives depend on such factors as the price of gasoline, the price of electricity, and the availability of tax credits or rebates for clean vehicles. A recent review of studies comparing the costs of different vehicle energy options finds that renewable alternatives, particularly using wind energy to power batteries of electric vehicles, may already be cost competitive with traditional vehicles, even in the United States, where gasoline is relatively cheap.[21] (See Box 11.5.)

BOX 11.5: ELECTRIC VEHICLES BECOMING COST COMPETIVE

Electric Vehicles (EVs) are starting to penetrate the automobile market. A step beyond hybrids and plug-in hybrids, which use both gasoline and electric power, fully-electric vehicles use electricity only. According to a 2015 analysis by the Union of Concerned Scientists, over a vehicle's lifetime EVs produce less than half the greenhouse gas emissions of a typical vehicle. 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 fuel costs. According to the U.S. Department of Energy, a Nissan Leaf (a fully electric vehicle) owner will save over $3,700 in fuel costs over five years compared to an average gas vehicle.

EVs are generally more expensive to purchase than comparable gas vehicles, primarily due to the high cost of the batteries. However, the cost savings from reduced maintenance and fuel costs means that total vehicle ownership costs tend to be less for EVs. For example, a 2013 analysis finds that for most drivers the total 5-year ownership costs of an EV is lower than the cost of a traditional gas car or hybrid. Also, EV battery costs are rapidly declining – dropping by 65% between 2010 and 2015. With expected further declines in battery prices, EVs may soon become cost-competitive with gas vehicle based on purchase price alone. Once this occurs, "electric vehicles will probably move beyond niche applications and begin to penetrate the market widely, leading to a potential paradigm shift in vehicle technology."

EVs still comprise only about 1% of all new vehicle sales globally. But global EV sales increased by 80% in 2015, with much of that growth in China and Western Europe. Depending on such factors as the decline in battery costs, the expansion of charging infrastructure, and government incentives, EVs could comprise a much larger share of vehicle sales in the future – 35% by 2040 according to one analysis.

Norway is an example of how government incentives can dramatically boost the sales of EVs. EV owners in Norway are exempt from purchase taxes, including a 25% value-added tax, as well as paying road tolls and parking fees. EV drivers can use bus lanes and have access to an extensive network of free charging stations. As a result, EV registrations in Norway increased by a factor of five between 2012 and 2015. In 2015 EVs comprised about 25% of all new vehicle registrations in Norway, far exceeding EV sales rates in other countries.

Sources: Nealer et al., 2015; EPRI, 2013; Frankfurt School-UNEP Collaborating Centre and Bloomberg New Energy Finance, 2016; Nykvist and Nilsson, 2015, quote from p. 330; Edelstein, 2016; Bloomberg New Energy Finance, 2016; Bjerkan et al., 2016; Barnato, 2016. Lifetime emissions estimate for 2016 Nissan Leaf from https://www.fueleconomy.gov/

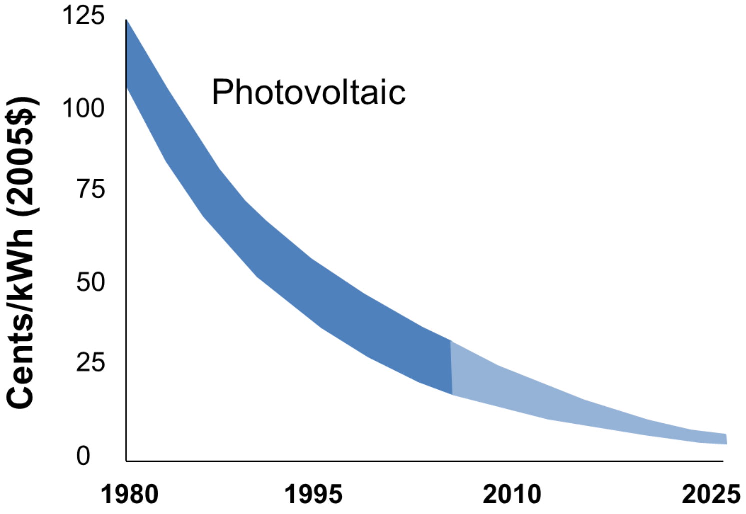
Looking to the future, it is reasonable to expect that the cost of renewables will continue to decline, while the future price of fossil fuels is highly uncertain. Consider the past and projected cost trends for wind and solar energy in Figures 11.11 and 11.12. Particularly with solar PV, we can be confident that its cost will continue to decline. Note the more rapid recent decrease in solar costs since 2009 shown in Figure 11.13. As technologies improve and prices decline, the utilization of these energy sources is increasing rapidly. (See Figure 11.14)

Not only are the costs of renewable energy sources expected to decline in the future, but Figures 11.11 and 11.12 also indicate that cost range will decrease for wind and solar energy. Thus the future prices for renewable energy are expected to be predictable within a relatively narrow band. This is not the case for fossil fuels, particularly oil. The price of oil depends on technology and future discoveries, and it is also highly dependent on political factors and other world events. The price of coal and natural gas normally does not vary as much as that of oil, but the future costs of these are also highly unpredictable.

Given the declining costs of renewables, it is possible that fossil fuels will in the future lose their price advantage over renewables. According to a report by Bloomberg New Energy Finance, solar will "emerge as the least-cost generation technology in most countries by 2030." The report foresees wind and solar accounting for 64% of new generating capacity to be installed over the next 25 years. [22]

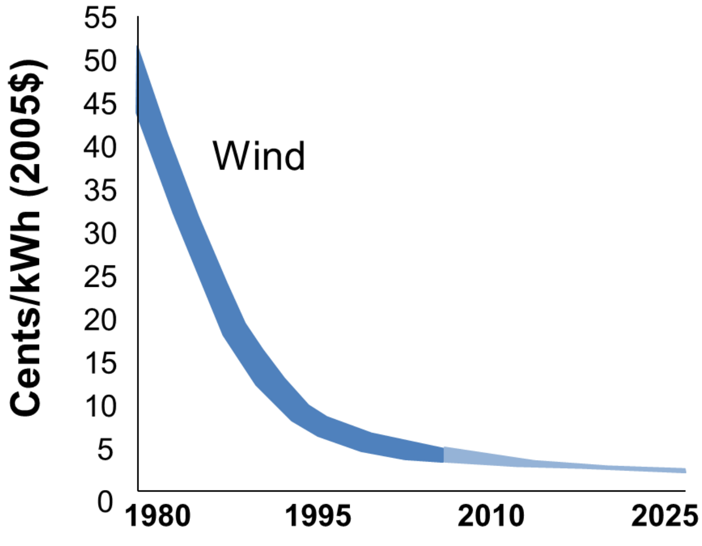
Whether this forecast of an increasing shift to renewables comes true depends largely on market cost competitiveness. So far, however, we have been comparing the costs of different energy sources based on current market prices. But we also need to consider two other factors that affect current and future energy prices: energy subsidies and environmental externalities.

Figure 11.11 Declining Past and Future Price Range for Solar Energy



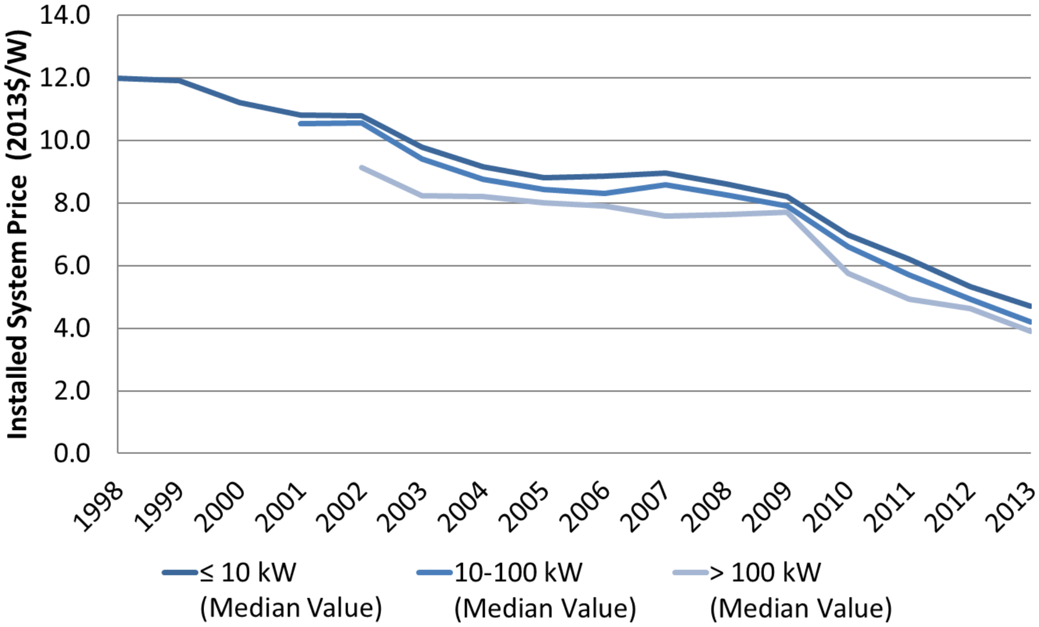
Source: National Renewable Energy Laboratory, Renewable Energy Cost Trends, www.geni.org/globalenergy/library/energytrends/renewableenergy-cost-trends/renewable-energy-cost_curves_2005.pdf.

Figure 11.12 Declining Past and Future Price Range for Wind Energy



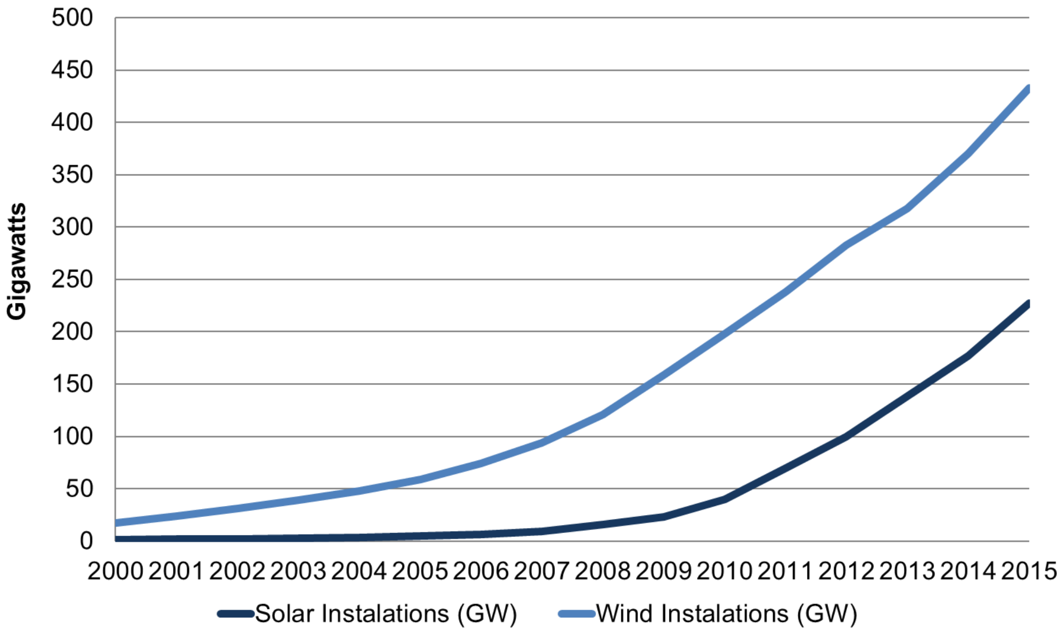
Source: National Renewable Energy Laboratory, Renewable Energy Cost Trends, www.geni.org/globalenergy/library/energytrends/renewableenergy-cost-trends/renewable-energy-cost_curves_2005.pdf.
Note: kWh = kilowatt hours.

Figure 11.13 Recent Trends in Solar Prices



Source: Barbose et al. 2014.

Figure 11.14 Growth in Solar and Wind Power, 2003-2012



Source: Renewables 2016 Global Status Report http://www.ren21.net/wp-content/uploads/2016/06/GSR_2016_KeyFindings1.pdf. For data before 2005, Renewables 2013 Global Status Report.

depletion allowances a tax deduction for capital investments used to extract natural resources, typically oil and gas.
feed-in tariffs a policy to provide renewable energy producers long-term contracts to purchase energy at a set price, normally based on the costs of production (but higher than the cost of production).

Energy Subsidies

Energy subsidies can take various forms, including:

- *Direct payments or favorable loans*: A government can pay a company a per-unit subsidy for producing particular products or provide them with a loan at below-market interest rates.
- *Tax credits and deductions*: A government can allow individuals and businesses to claim tax credits for actions such as installing insulation or purchasing a fuel-efficient vehicle. **Depletion allowances** are a form of tax credit widely used for oil production.
- *Price supports*: For example, the price that producers of renewable energy receive may be guaranteed to be at or above a certain level. **Feed-in tariffs**, commonly used in Europe, guarantee producers of solar and wind power a certain rate for sales of power to the national grid.
- *Mandated purchase quotas*: These include laws requiring that gasoline contain a certain percentage of ethanol or that governments buy a certain percentage of their energy from renewable sources.

As we saw in Chapter 3, subsidies can be justified to the extent that they support goods and services that generate positive externalities. All energy sources currently receive a degree of subsidy support, but, as discussed in Box 11.1, subsidies heavily favor fossil fuels. Given that fossil-fuel use tends to generate negative, rather than positive, externalities, it is difficult to justify large current fossil fuel subsidies on the basis of economic theory. Directing the bulk of energy subsidies to fossil fuels tilts the playing field in their favor relative to renewables.

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."[23] The International Energy Agency notes:

> Energy subsidies—government measures that artificially lower the price of energy paid by consumers, raise the price received by producers or lower the cost of production—are large and pervasive. When they are well-designed, subsidies to renewables and low-carbon energy technologies can bring long-term economic and environmental benefits. However, when they are directed at fossil fuels, the costs generally outweigh the benefits. [Fossil-fuel subsidies] encourage wasteful consumption, exacerbate energy-price volatility by blurring market signals, incentivize fuel adulteration and smuggling, and undermine the competitiveness of renewables and other low-emission energy technologies.[24]

Global subsidies to fossil fuels in the electricity sector total about $100 billion annually.[25] Data on subsidies to nuclear power are difficult to obtain, but the limited information available suggests global nuclear subsidies of at least $10 billion. In addition, there are implicit subsidies to the nuclear industry related to limiting accident liability. The Price-

Anderson Act in the United States limits nuclear operator liability to less than half a billion dollars, although the potential costs of a major accident could be much greater. Global subsidies to renewable forms of electricity total about $30 billion annually but are growing faster than other subsidies.

While the majority of electricity-sector subsidies go to fossil fuels and nuclear, on a per-kilowatt-hour basis the current subsidy structure favors renewables. Since renewables currently represent a small percentage of electricity generation, the per-unit subsidy for renewables is significantly greater than for fossil fuels. . Subsidies effectively lower the price of electricity provided by fossil fuels by about one cent per kilowatt-hour. But according to one estimate, subsidies in 2007 lowered the per-kilowatt-hour price of wind energy by 7 cents, of concentrated solar energy by 29 cents, and of solar PV by 64 cents.[26] Thus electricity-sector subsidies are generally encouraging a shift to renewables.

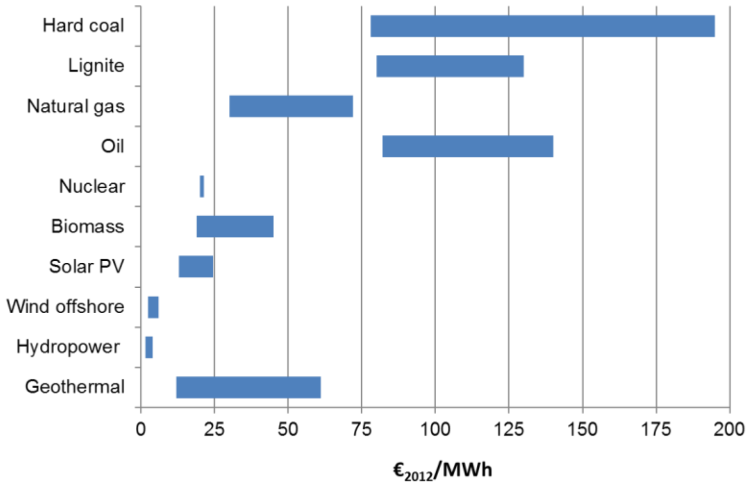
In the transportation sector, global oil subsidies averaged about $212 billion annually in 2011.[27] With annual global oil consumption around 1.3 trillion gallons, this amounts to a subsidy of about $0.15 per gallon. If we assume that this value is applicable for the United States, oil subsidies approximately cancel out the federal gasoline tax of 18 cents per gallon. The other major recipient of subsidies in the transportation sector is biofuels. Global subsidies to biofuels are estimated at about $20 billion and growing rapidly.

Environmental Externalities

In addition to subsidy reform, economic theory also supports internalizing externalities. The price of each energy source should reflect its full social costs. Various studies of energy externalities suggest that if the price of all energy sources included externality costs, a transition toward renewables would already be much further along.

Figure 11.15 provides a summary of the range of external costs associated with different electricity sources, based on European analyses. The externality cost of coal is particularly high, ranging between 2 and 15 eurocents per kilowatt-hour. This is consistent with other research that estimates the external cost of coal electricity in the United States at about 6 cents per kilowatt-hour.[28]The externalities associated with natural gas are lower, but still range between 1 and 4 eurocents per kilowatt-hour, a result that is also consistent with U.S. estimates.

Figure 11.15 Externality Cost of Various Electricity Generating Methods, European Union



Source: European Commission, 2014.

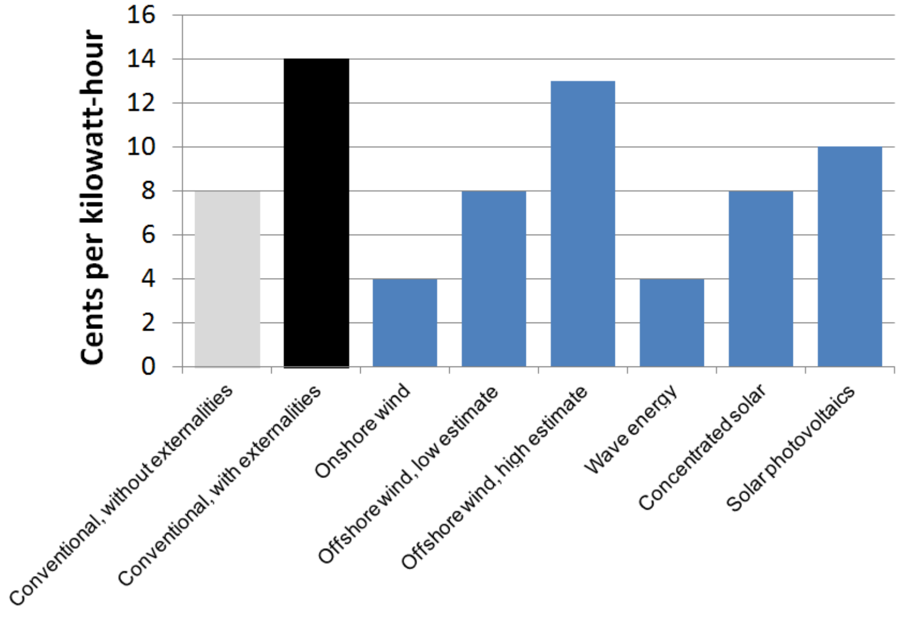
The externality costs associated with renewable energy are much lower, less than one eurocent per kilowatt-hour. So while fossil fuels may currently have a cost advantage over renewables based solely on market prices, if externalities were included, several renewables would likely become the most affordable energy sources—in particular, onshore wind, geothermal, and biomass energy. Similarly, the cost advantage of oil in transportation would likely disappear if externalities were fully included in the price.[29]

The operating externalities of nuclear energy are relatively low, as the life cycle of nuclear power generates low levels of air pollution and greenhouse gas emissions. But the potentially most significant externalities from nuclear power are the risks of a major accident and the long-term storage of nuclear wastes. These impacts are difficult to estimate in monetary terms (remember the analysis in Chapter 7 of the assessment of risk and uncertainty). Whether nuclear power will play an increased or decreased role in future energy supplies remains a controversial topic (for more on the debate over nuclear energy, see Box 11.6).

Our discussion suggests that the biggest factor currently preventing a transition to renewable energy is the failure to account for externalities. Getting the prices "right" would send a clear signal to businesses and consumers that continued reliance on fossil fuels is bad economics. According to a 2015 study by the International Monetary Fund, while global pre-tax subsides to fossil fuels amount to about $333 billion, this figure rises to as much as $5 *trillion* when externality costs are included.[30] But even without full internalization of externalities, the declining cost of renewable means that a transition from fossil fuels will occur in the future.

Figure 11.16 shows a projected comparison of the cost of electricity generation in 2020 using traditional fossil-fuel methods and various renewable alternatives, with and without externality costs included

Figure 11.16 Projected Cost of Electricity Generating Approaches, 2020



Source: Jacobson and Delucchi, 2011b.

Based solely on production costs without externalities, the renewable sources of onshore wind, wave energy, concentrated solar, and potentially offshore wind are all expected to be cost competitive with fossil fuels. When the impacts of externalities are fully included, all renewable sources become less expensive than fossil fuels. These results imply that there are good economic reasons for promoting a transition to renewables. In the final section of this chapter, we turn to policy proposals to encourage a more rapid transition.

BOX 11.6 NUCLEAR POWER: COMING OR GOING?

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 (Miller, 1998).

Currently, nuclear power provides only about 4.4 percent of the world's primary energy consumption and about 11 percent of the world's electricity. Most of the world's capacity to produce nuclear power predates 1990. The decommissioning of older plants, which had an expected lifespan of thirty to forty years, has already begun. However, some people have called for a "nuclear renaissance", mainly because carbon emissions from the nuclear power lifecycle are much lower than with fossil fuels.

The catastrophic 2011 Fukushima accident in Japan has caused many countries to reevaluate their nuclear power plans. As Japan reevaluates its use of nuclear power, Germany has decided to phase out the use of nuclear power entirely by 2022. In Italy, the debate over nuclear power was put to voters, with 94 percent 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. Currently 20 nuclear plants are under construction in China. Other countries moving ahead with expanded use of nuclear power are India, Russia, and South Korea.

Thus the role of nuclear power in the future global energy mix remains uncertain. The Fukushima accident has slightly 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 like wind and solar, others worry that a decline in nuclear power will result in "higher energy costs, more carbon emissions and greater supply uncertainty"

Sources: Macalister, 2011; World Nuclear Association, "Nuclear Power in China," http://world-nuclear.org/information-library/country-profiles/countries-a-f/china-nuclear-power.aspx; Nuclear Energy Institute, "World Statistics" http://www.nei.org/Knowledge-Center/Nuclear-Statistics/World-Statistics .

11.6 POLICIES FOR THE GREAT ENERGY TRANSITION

What kinds of government policies are most important to foster a timely and efficient transition to a shift to renewable energy sources? As discussed, one policy goal agreed on by many of the world's largest countries is to phase out inefficient fossil-fuel subsidies. One concern is that in the short term this could lead to higher energy prices and a decrease in economic growth. But the money that governments save could be invested in ways that would reduce the cost of renewable alternatives and encourage a more rapid transition from fossil fuels. According to a study by the International Institute for Sustainable Development:

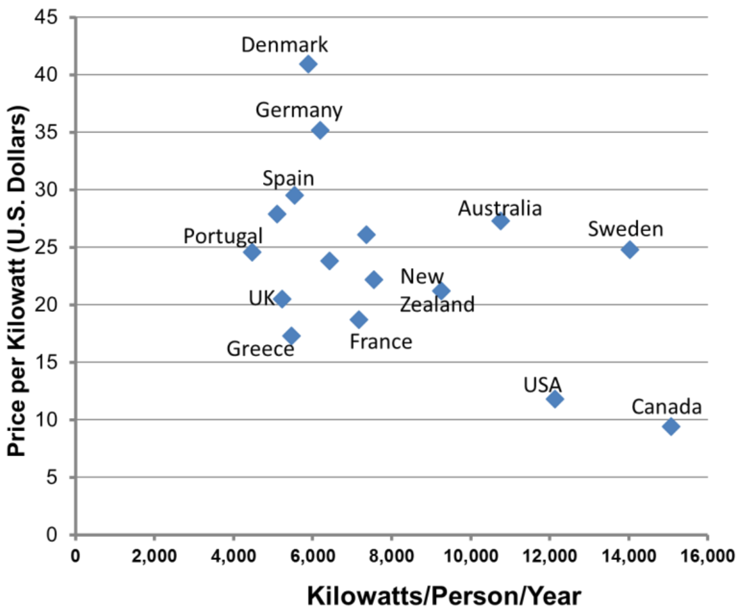
… fossil fuel subsidy reform would result in aggregate increases in gross domestic product (GDP) in both OECD and non-OECD countries. The expected [increase is as high as] 0.7 per cent per year to 2050. . . . Results from a wide variety of global and single-country economic modeling studies of subsidy reform suggest that on an aggregate level, changes to GDP are likely to be positive, due to the incentives resulting from price changes leading to more efficient resource allocation.[31]

One major issue is the need to internalize the negative externalities of different energy sources. A common form of Pigovian tax is a tax on gasoline. Even though governments use this tax primarily to raise revenue, it also serves the function of internalizing externalities. While the price of crude oil is determined in a global market, the retail price of gasoline varies widely across countries due to differences in gasoline taxes. In 2016 the price of gasoline ranged from less than $1/gallon in countries such as Venezuela, Saudi Arabia, and Kuwait, where gas is subsidized rather than taxed, to as much as $6/gallon in France, Norway, the United Kingdom, and other countries where gas is heavily taxed.[32]

Economic theory suggests that the "correct" tax on gas should fully account for the negative externalities. In the United States, the current federal gas tax is 18.4 cents per gallon, in addition to state taxes that range from 8 to 50 cents per gallon. Virtually all economists agree that these taxes are too low, although there is disagreement about how much higher the tax should be. While some economists suggest it should be only about 60 cents higher, others suggest that gas taxes should be over $10 per gallon to fully reflect all external costs.[33]

Pigovian taxes can also be applied to the electricity sector. As we see in Figure 11.17, electricity prices vary across countries, primarily due to variations in tax rates. In general, higher electricity prices are associated with lower per capita consumption rates. For example, the United States has relatively low electricity prices and relatively high consumption rates. Electricity prices in Germany, Spain, and Denmark are much higher, and per capita consumption rates are about half the rate of the United States.

Figure 11.17 Electricity Prices and Consumption Rates



Sources: U.S. Energy Information Administration, International Energy Statistics database; International Energy Agency, Energy Prices and Statistics online database.

Although there is a general correlation between higher electricity prices and lower consumption, we need to be careful about drawing conclusions based on a simple comparison like this because it fails to account for many other variables that could influence electricity demand other than prices, such as income levels, climate, and the availability of different heating options. For example, Sweden has both higher electricity prices and higher consumption rates than the United States. Explaining this difference would require additional information not presented in Figure 11.17.

Beyond reducing fossil-fuel subsidies and implementing externality taxes, other policy options to encourage a transition to renewable energy include:

1. Energy research and development
2. Feed-in tariffs
3. Subsidies for renewable sources, including favorable tax provisions and loan terms
4. Renewable energy targets
5. Efficiency improvements and standards

Increasing research and development (R&D) expenditures will speed the maturation of renewable energy technologies. Public energy R&D expenditures have been increasing in recent years, from $10 billion in 2000 to $17 billion in 2014.[34] Countries that invest heavily in energy R&D will likely gain a competitive advantage in this area in the future.

> Those nations—such as China, Brazil, the United Kingdom, Germany and Spain—with strong, national policies aimed at reducing global warming pollution and incentivizing the use of renewable energy are establishing stronger competitive positions in the clean energy economy. Nations seeking to compete effectively for clean energy jobs and manufacturing would do well to evaluate the array of policy mechanisms that can be employed to stimulate clean energy investment. China, for example, has set ambitious targets for wind, biomass and solar energy and, for the first time, took the top spot within the G-20 and globally for overall clean energy finance and investment in 2009. The United States slipped to second place. Relative to the size of its economy, the United States' clean energy finance and investments lag behind many of its G-20 partners. For example, in relative terms, Spain invested five times more than the United States last year, and China, Brazil and the United Kingdom invested three times more.[35]

Feed-in tariffs guarantee renewable energy producers access to electricity grids and long-term price contracts. For example, homeowners who install solar 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 U.S. states. The most ambitious is in Germany, which has become the world's leader in installed solar PV capacity.

Feed-in tariffs are intended to be reduced over time as renewables become more cost competitive with traditional energy sources. A reduction in feed-in tariff rates has already begun in Germany. A 2008 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."[36]

Subsidies can take the form of direct payments or other favorable provisions, such as tax credits or low-interest loans. As mentioned earlier, the bulk of current subsidies go to fossil fuels. Yet subsidies make more sense for developing, rather than mature, technologies. Subsidies for renewable energy can promote economies of scale that lower production costs.

Like feed-in tariffs, output subsidies can be gradually reduced as renewables become more competitive.

renewable energy targets regulations that set targets for the percentage of energy obtained from renewable energy sources.
energy demand-side management an energy policy approach that seeks to reduce energy consumption, through policies such as information campaigns or higher energy prices.

Renewable energy targets set goals for the percentage of total energy or electricity obtained from renewables. More than sixty countries have set renewable energy targets. The European Union has set a goal of 20 percent of total energy from renewables by 2020, with different goals for each member country. The 2020 targets include goals of 18 percent for Germany, 23 percent for France, 31 percent for Portugal, and 49 percent for Sweden. All EU countries have adopted national renewable energy action plans showing what actions they intend to take to meet their renewables targets. EU countries have also agreed on a new renewable energy target of at least 27% of final energy consumption in the EU as a whole by 2030.[37]

While the United States does not have a national renewable goal, most states have set goals. Some of the most ambitious goals include California and New York (50 percent by 2030), Hawaii (100% by 2045), and Vermont (75% by 2032).).[38]

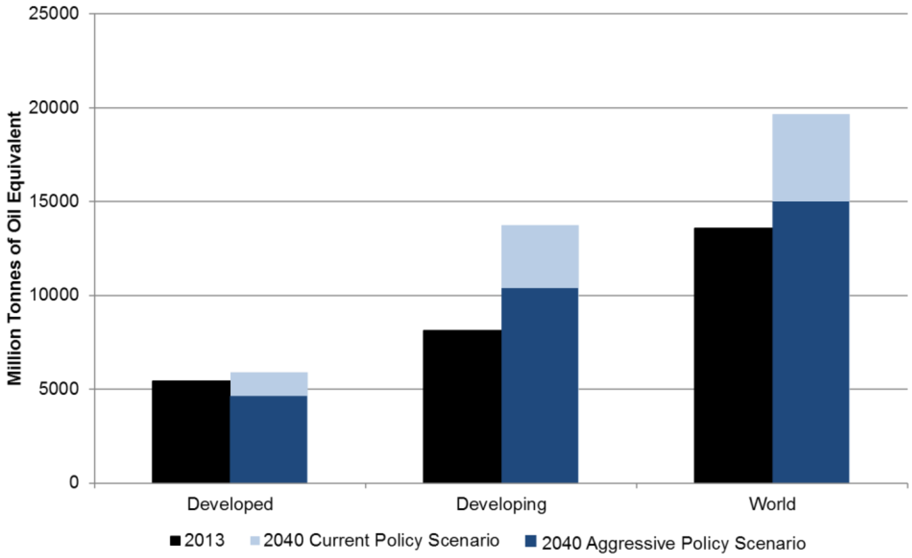
Most of the discussion in this chapter has focused on energy supply-side management—adjusting the energy supply mix to include a greater share of renewable sources. However, **energy demand-side management** is generally considered the most cost effective and environmentally beneficial approach to energy policy. In other words, while shifting a kilowatt of energy supply from coal to solar or wind is desirable, eliminating that kilowatt of demand entirely is even better. As the U.S. Environmental Protection Agency has noted:

> Improving energy efficiency in our homes, businesses, schools, governments, and industries—which consume more than 70 percent of the natural gas and electricity used in the country—is one of the most constructive, cost-effective ways to address the challenges of high energy prices, energy security and independence, air pollution, and global climate change.[39]

In some cases energy efficiency improvements can be obtained by technological changes, such as reducing fossil fuel use by driving a hybrid car or fully electric vehicle. Improving energy efficiency in machinery, appliances, and buildings has the potential to reduce energy use by 40-60%.[32] In other cases, energy efficiency means changing behavior, such as washing clothes in cold water, drying clothes on a clothesline instead of a clothes dryer, or switching off lights and appliances when not in use. The potential for demand-side management to reduce the projected growth of energy consumption is particularly important in reducing fossil fuel use, since the lower total demand for energy becomes, the larger the proportion of the remaining needed energy that can be supplied by renewables.

Under a "business as usual" (BAU) scenario, the International Energy Agency (IEA) has projected that global energy demand will increase by 44% over 2013 levels by 2040. But with greater energy efficiency, the IEA projects only a 12% increase in global energy demand by 2040.In developed countries, energy demand could actually decrease relative to current levels. In developing countries, energy consumption would still increase, but only by about 28 percent, instead of by 69 percent under a BAU scenario. (See Figure 11.18 – this is consistent with the scenarios shown earlier in Figure 11.4 and Table 11.3)

Figure 11.18 Global Potential for Energy Efficiency



Source: Based on Blok et al., 2008; updated data from IEA 2015a.

Realizing such gains from energy efficiency will require substantial investment, estimated at about 0.2 percent of global GDP.[40] However, investments in energy efficiency are typically much cheaper than meeting demand growth through developing new energy supplies. Well-designed energy efficiency programs cost, on average, only about half the cost of providing new energy supplies.[41] Another analysis estimates the cost of energy efficiency at 0 to 5 cents per kilowatt-hour.[42] Comparing this estimate to the cost of energy sources in Figure 11.9, we see that improving energy efficiency is the most economical option for addressing energy demand.

economic efficiency standards an environmental regulation approach that sets minimum standards for efficiency such as electricity or fuel consumption.
efficiency labeling labels on goods that indicate energy efficiency, such as a label on a refrigerator indicating annual energy use.

In addition to expanding R&D, two other policies can be effective at promoting energy efficiency. One is to set energy **efficiency standards**. Fuel-economy standards are one example. After about twenty years in which fuel-economy standards were little changed, in 2011 the Obama administration announced new standards that would raise the average fuel efficiency of new vehicles to 54.5 mpg in 2025. Compared to 2010 model year vehicles, total fuel savings for 2025 vehicles would total more than $8,000 over the lifetime of the vehicle. Tighter standards have also been proposed for heavy trucks. Fuel efficiency for automobiles improved by about 5 miles per gallon between 2005 and 2015, from 19.5 to 24.5 mpg.[43] Other energy efficiency standards exist for buildings, appliances, electronics, and light bulbs.

Efficiency labeling informs consumers about the energy efficiency of various products. For example, in the United States the U.S. Environmental Protection Agency and U.S. 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 75 percent of consumers who purchased an Energy Star product indicated that the label was an important factor in their purchase decision. In 2014 the energy savings from Energy Star products totaled about $34 billion.[44]

Even with informative labels, many consumers do not purchase high-efficiency products because the upfront costs may be higher. For example, light-emitting diode (LED) and compact fluorescent light bulbs cost more than traditional incandescent light bulbs. However, the energy savings from efficient bulbs means that the additional cost will be recovered in a relatively short period, normally less than one year. While people may resist buying efficient bulbs for other reasons, one problem is that people often have high implicit discount rates, focusing on the upfront cost while discounting the long-term savings (see Box 11.7).

BOX 11.7 IMPLICIT DISCOUNT RATES AND ENERGY EFFICIENCY

A major problem in increasing energy efficiency of appliances arises from high implicit discount rates. Suppose that a consumer can purchase a standard refrigerator for $500 and an energy-efficient model for $800. 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 x 12 = $180/year, or 60 percent. Thus 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 percent annual 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 percent to make this judgment—a consumer behavior that is difficult to justify economically, yet very common.

As we have seen, numerous effective policies exist to promote a faster transition to renewables. Many of these policies simply implement principles that we introduced early in this text – internalizing externalities through subsidizing positive externalities and taxing negative externalities. At a minimum, it makes economic sense to avoid perverse subsidies that increase external costs. In the next two chapters, we focus more specifically on the most pervasive and urgent externality associated with energy use – global climate change.

SUMMARY

Energy is a fundamental input for economic systems. Current economic activity depends overwhelmingly on fossil fuels, including oil, coal, and natural gas. These fuels are nonrenewable. Renewable sources such as hydroelectric, wind, and solar power currently provide less than 10 percent of global energy.

World energy use has expanded rapidly and is projected to continue growing, with an increase in energy demand of 44 percent by 2040 in a "business as usual" scenario. While a continued heavy reliance on fossil fuels is projected under a business-as-usual scenario, the potential exists to reduce demand growth through energy efficiency, and to obtain a much larger proportion of global energy from renewables, over the next several decades.

Considering only market costs, fossil fuels tend to be cheaper than renewables. But this is misleading, since fossil fuels receive a disproportionate share of energy subsidies and current energy costs fail to account for negative externalities. If the price of different energy sources reflected their full social costs, then several renewables would gain a competitive advantage over fossil fuels. Also, the price of renewables is declining and relatively predictable, while the projected prices of fossil fuels are expected to rise and are highly uncertain. Thus even without internalizing externalities, renewables re becoming cost competitive with fossil fuels, and the largest proportion of new energy capacity is projected to be provided by renewables over the next 25 years.

The speed of the transition to renewable energy will be highly influenced by policy choices. Reforming fossil-fuel subsidies and instituting Pigovian taxes are two policies that can yield more economically efficient outcomes. Other potential policies include increasing energy research and development expenditures, feed-in tariffs, and renewable energy targets. Finally, the most cost-effective approach to address energy demand is to promote energy efficiency, which can limit demand growth in the developing world and reduce total energy demand in currently developed countries.

KEY TERMS AND CONCEPTS

biomass
capital stock
depletion allowances
economic efficiency standards
efficiency labeling
energy demand-side management
energy infrastructure
energy subsidies
energy transition
feed-in tariffs
Hubbert curve
hydropower
levelized costs
nonrenewable stock
present value
renewable energy targets
renewable flow
solar energy

Discussion Questions

1. Since energy production represents only about 8-10 percent of economic output, why should any special importance be placed on this sector? Is there any significant difference between an economic system that relies on nonrenewable energy supplies and one that uses primarily renewable sources? Should policy decisions about energy use be implemented by governments, or should the patterns of energy use be determined solely by market allocation and pricing?
2. How will the world's energy needs change over the coming decades? What are the different possibilities for energy development paths, and what are the advantages and drawbacks of different possible paths? Are we likely to run out of fossil fuels, or to shift away from fossil fuels for other reason?
3. What policies are most relevant to promoting a transition to renewables? Is this likely to occur through the market, or are aggressive government polices required? What are the justifications for such policies from the point of view of environmental economics?

References

American Council for an Energy-Efficient Economy. 2015. "Energy Efficiency in the United States: 35 Years and Counting." http://aceee.org/research-report/e1502.

Badcock, Jeremy, and Manfred Lenzen. 2010. "Subsidies for Electricity-Generating Technologies: A Review." *Energy Policy* 38: 5038–5047.

Barbose et al. 2014. "Tracking the Sun VII: an historical summary of the installed price of photovoltaics from 1998 to 2013." Lawrence Berkeley National Laboratory and U.S. Department of Energy SunShot Initiative: http://emp.lbl.gov/sites/all/files/lbnl-6858e.pdf

Barnato, Katy. 2016. "This Country Has Hit a Major Milestone for Electric Cars – Here's How," CNBC, May 24, 2016.

Bjerkan, Kristin Ystmark, Tom E. Nørbech, and Marianne Elvaas Nordtømme. 2016. "Incentives for Promoting Battery Electric Vehicle (BEV) Adoption in Norway." *Transportation Research Part D* 43:169-180.

Blok, Kornelis, Pieter van Breevoort, Lex Roes, Rogier Coenraads, and Nicolas Müller. 2008. *Global Status Report on Energy Efficiency 2008*. Renewable Energy and Energy Efficiency Partnership, www.reeep.org.

Bloomberg New Energy Finance. 2016. "New Energy Outlook 2016: Long-Term Projections of the Global Energy Sector." #NEO2016. http://www.bloomberg.com/company/new-energy-outlook/

British Petroleum. 2016. *Statistical Review of World Energy 2016*. http://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html———. 2013. BP Energy Outlook 2030, http://www.bp.com/content/dam/bp/pdf/energy-economics/energy-outlook-2015/bp-energy-outlook-booklet_2013.pdf

Charles, Chris, and Peter Wooders. 2011. "Subsidies to Liquid Transport Fuels: A Comparative Review of Estimates." International Institute for Sustainable Development, September.

Clean Air Task Force. 2010. *The Toll from Coal*. www.catf.us/resources/publications/.

Cleveland, Cutler. 1991. "Natural Resource Scarcity and Economic Growth Revisited: Economic and Biophysical Perspectives." In *Ecological Economics*, ed. Robert Costanza. New York: Columbia University Press.

Commission of the European Communities. 2008. "The Support of Electricity from Renewable Energy Sources." SEC(2008) 57, Brussels, January 23.
Department of Energy and Climate Change. 2011. "Review of the Generation Costs and Deployment Potential of Renewable Electricity Technologies in the UK," Study Report REP001, October.
Edelstein, Stephen. 2016. "Global Electric Car Sales on the Rise." Christian Science Monitor, April 17, 2016.
Electric Power Research Institute (EPRI). 2013. "Total Cost of Ownership Model for Current Plug-in Electric Vehicles." Report 3002001728, Palo Alto, CA. June 2013.
Ellis, Jennifer. 2010. "The Effects of Fossil-Fuel Subsidy Reform: A Review of Modelling and Empirical Studies." International Institute for Sustainable Development, March.
European Commission. 2016. "Renewable Energy: Moving Towards a Low-Carbon Economy," https://ec.europa.eu/energy/en/topics/renewable-energy
———. 2014. "Subsides and costs of EU Energy," https://ec.europa.eu/energy/sites/ener/files/documents/ECOFYS%202014%20Subsidies%20and%20costs%20of%20EU%20energy_11_Nov.pdf
Frankfurt School-UNEP Collaborating Centre and Bloomberg New Energy Finance. 2016. "Global Trends in Renewable Energy Investment 2016."
Georgescu-Roegen, Nicholas. 1971. *The Entropy Law and the Economic Process*. Cambridge, MA: Harvard University Press.
Hall, Charles A.S., and Kent A. Klitgaard. 2012. *Energy and the Wealth of Nations: Understanding the Biophysical Economy*. New York: Springer.
Howarth, Robert W., Renee Santoro, and Anthony Ingraffea. 2011. "Methane and the Greenhouse Gas Footprint of Natural Gas from Shale Formations," *Climatic Change* 106 (4): 679–690.
Institute for Energy Research. 2010. "A Primer on Energy and the Economy," http://instituteforenergyresearch.org/
International Center for Technology Assessment (CTA). 1998. "The Real Price of Gasoline." Report No. 3: An Analysis of the Hidden External Costs Consumers Pay to Fuel Their Automobiles.
International Energy Agency (IEA). 2010. *World Energy Outlook 2010*. Paris.
———. 2011. *World Energy Outlook 2011*. Paris.
———. 2015a. *World Energy Outlook 2015*. Paris.
———. 2015b. *Key World Energy Statistics*. Paris.
———. 2015c. "Renewables to Lead World Power Market Growth to 2020", https://www.iea.org/newsroomandevents/pressreleases/2015/october/renewables-to-lead-world-power-market-growth-to-2020.html
———. 2011c. *World Energy Outlook 2011 Factsheet*. Paris.
International Energy Agency, Nuclear Energy Agency, and Organization for Economic Cooperation and Development. 2010. Projected Costs of Generating Electricity.
International Energy Agency, Organization for Economic Cooperation and Development, Organization of the Petroleum Exporting Countries, and World Bank. 2011. "Joint Report by IEA, OPEC, OECD and World Bank on Fossil-Fuel and Other Energy Subsidies: An Update of the G20 Pittsburgh and Toronto Commitments." Report prepared for the G20 Meeting of Finance Ministers and Central Bank Governors (Paris, 14–15 October 2011) and the G20 Summit (Cannes, November 3–4).
International Institute for Sustainable Development (IISD). 2014. "The Impact of Fossil Fuel Subsidies on Renewable Energy Generation." https://www.iisd.org/gsi/impact-fossil-fuel-subsidies-renewable-energy
International Monetary Fund. 2015. "IMF Survey: Counting the Cost of Energy Subsidies",

http://www.imf.org/external/pubs/ft/survey/so/2015/NEW070215A.htm
Jacobson, Mark Z., and Mark A. Delucchi. 2011a. "Providing All Global Energy with Wind, Water, and Solar Power, Part I: Technologies, Energy Resources, Quantities and Areas of Infrastructure, and Materials." *Energy Policy* 39: 1154–1169.
———. 2011b. "Providing All Global Energy with Wind, Water, and Solar Power, Part II: Reliability, System and Transmission Costs, and Policies." *Energy Policy* 39: 1170–1190.
Johnson, Kirk. 2011. "E.P.A. Links Tainted Water in Wyoming to Hydraulic Fracturing for Natural Gas." *New York Times*, December 9.
Kitson, Lucy, Peter Wooders, and Tom Moerenhout. 2011. "Subsidies and External Costs in Electric Power Generation: A Comparative Review of Estimates." International Institute for Sustainable Development, September.
Krishnan, Rajaram, Jonathan M. Harris, and Neva Goodwin, eds. 1995. *A Survey of Ecological Economics*. Washington, DC: Island Press.
Lazard. 2014. "Levelized Cost of Energy Analysis—Version 8.0," September https://www.lazard.com/media/1777/levelized_cost_of_energy_-_version_80.pdf
Macalister, Terry. 2011. "IEA Says Shift from Nuclear Will Be Costly and Raise Emissions." *The Guardian*, June 17.
Miller, G. Tyler, Jr. 1998. *Living in the Environment*, 10th ed. Belmont, CA: Wadsworth.
Morales, Alex. 2010. "Fossil Fuel Subsidies Are Twelve Times Renewables Support." Bloomberg, July 29.
Morton, Oliver. 2006. "Solar Energy: A New Day Dawning? Silicon Valley Sunrise." *Nature* 443: 19–22.
Murphy, David J., and Charles A.S. Hall. 2010. "Year in Review—EROI or Energy Return on (Energy) Invested." *Annals of the New York Academy of Science* 1185: 102–118.
Nealer, Rachael, David Reichmuth, and Don Anair. 2015. "Cleaner Cars from Cradle to Grave." Union of Concerned Scientists. November 2015.
Nykvist, Björn, and Måns Nilsson. 2015. "Rapidly Falling Costs of Battery Packs for Electric Vehicles," Nature Climate Change 5 (April 2015): 329-332.
Odgen, Joan M., Robert H. Williams, and Eric D. Larson. 2004. "Societal Lifecycle Costs of Cars with Alternative Fuels/Engines." *Energy Policy* 32: 7–27.
Owen, Anthony D. 2006. "Renewable Energy: Externality Costs as Market Barriers." *Energy Policy* 34: 632–642.
Parry, Ian W.H., and Kenneth A. Small. 2005. "Does Britain or the United States Have the Right Gasoline Tax?" *American Economic Review*, 95(4): 1276–1289.
Pew Charitable Trusts. 2010. "Who's Winning the Clean Energy Race? Growth, Competition, and Opportunity in the World's Largest Economies." Washington, DC.
Rosenthal, Elisabeth. 2010. "Portugal Gives Itself a Clean-Energy Makeover." *New York Times*, August 9.
Timmons, David, Jonathan M. Harris, and Brian Roach. 2016. *The Economics of Renewable Energy*. Tufts University Global Development and Environment Institute, http://www.ase.tufts.edu/gdae/education_materials/modules.html#energy
U.S. Energy Information Administration (EIA). 2011a. Annual Energy Review. U.S. Department of Energy.
———. 2011b. International Energy Outlook. U.S. Department of Energy.
———. 2011c. "Levelized Cost of New Generation Resources in the Annual Energy Outlook 2011." U.S. Department of Energy.
———. 2015a. "U.S. Crude Oil Production to 2025: Updated Projection," http://www.eia.gov/analysis/petroleum/crudetypes/
———. 2015b. "Direct Federal Financial Interventions and Subsidies in Energy in Fiscal Year 2013."

———. 2016a. *Monthly Energy Review* U.S. Department of Energy.
———. 2016b, "Fossil fuels still dominate U.S. energy consumption despite recent market share decline," http://www.eia.gov/todayinenergy/detail.cfm?id=26912.
———.2016c. *Annual Energy Outlook 2016,* http://www.eia.gov/forecasts/aeo/electricity_generation.cfm
U.S. Environmental Protection Agency (EPA). 2006. National Action Plan for Energy Efficiency. "National Action Plan for Energy Efficiency." July.
———. 2008. "Understanding Cost-Effectiveness of Energy Efficiency Programs: Best Practices, Technical Methods, and Emerging Issues for Policy-Makers." Energy and Environmental Economics and Regulatory Assistance Project.
———.2014. "Energy Star Overview of 2014 Achievements."
Wigley, Tom M. 2011. "Coal to Gas: The Influence of Methane Leakage," *Climatic Change* 108 (3): 601–608.

WEB SITES

1. **www.eia.gov**. Web site of the Energy Information Administration, a division of the U.S. Department of Energy that provides a wealth of information about energy demand, supply, trends, and prices.
2. **www.cnie.org/nle/crsreports/energy/**. Access to energy reports and issue briefs published by the Congressional Research Service.
3. **www.nrel.gov**. The Web site of the National Renewable Energy Laboratory in Colorado. The NREL conducts research on renewable energy technologies including solar, wind, biomass, and fuel cell energy.
4. **www.rmi.org**. Home page 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.
5. **www.eren.doe.gov**. Web site of the Energy Efficiency and Renewable Energy Network in the U.S. Department of Energy. The site includes a large amount of information on energy efficiency and renewable energy sources as well as hundreds of publications.
6. **www.iea.org**. Web site of the International Energy Agency, an "autonomous organisation which works to ensure reliable, affordable and clean energy for its 28 member countries and beyond." 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.
7. **www.energystar.gov**. Web site of the Energy Star program, including information about which products meet guidelines for energy efficiency.

NOTES

[1] Institute for Energy Research, 2010.
[2] IEA, 2016; IISD, 2014.
[3] For the classic assertion of energy's critical role in the economy, see Georgescu-Roegen, 1971. For an overview of differing analytical perspectives on energy see Krishnan et al., 1995.
[4] See, e.g., Hall and Klitgaard, 2012.
[5] Morton, 2006.

[6] International Energy Agency, 2015b.
[7] BP Statistical Review of World Energy, 2012-2016; International Energy Agency, 2015c; U.S. Energy Information Administration, 2016b.
[8] For detailed discussion of global climate analysis and policy, see Chapters 12 and 13.
[9] U.S EIA, 2015a.
[10] IEA, 2010, Executive Summary, 6–7.
[11] IEA, 2011, Executive Summary, 3.
[12] Natural Gas Supply Association, naturalgas.org.
[13] U.S. Energy Information Administration (EIA). 2011a.
[14] See Howarth et al., 2011, and Wigley, 2011.
[15] British Petroleum, 2016.
[16] Clean Air Task Force, 2010.
[17] British Petroleum, 2016.
[18] Jacobson and Delucchi, 2011a, p. 1154.
[19] Ibid.
[20] Ibid.
[21] Jacobson and Delucchi, 2011b.
[22] Bloomberg New Energy Finance, 2016.
[23] IEA et al., 2011.
[24] IEA, 2011.
[25] Kitson et al., 2011.
[26] Badcock and Lenzen, 2010.
[27] Charles and Wooders, 2011; IMF, 2015.
[28] Jacobson and Delucchi, 2011b.
[29] See, e.g., Odgen et al., 2004.
[30] IMF, 2015
[31] Ellis, 2010, p.7, p.26.
[32] http://www.statista.com/statistics/221368/gas-prices-around-the-world/
[33] Parry and Small, 2005.
[34] International Energy Agency, "RD&D statistics", 2016, http://www.iea.org/statistics/topics/rdd/.
[35] Pew Charitable Trusts, 2010, pp. 4–5
[36] Commission of the European Communities, 2008, p. 3.
[37] European Commission, 2016.
[38] PV Magazine, August 2016, "New York Regulators Issue 50% by 2030 Renewable Energy Mandate" http://www.pv-magazine.com/news/details/beitrag/new-york-regulators-issue-50-by-2030-renewable-energy-mandate_100025634/#axzz4G7jkZUBX; California Energy Commission, 2016 http://www.energy.ca.gov/renewables/
[39] U.S. EPA, 2008, p. ES-1.
[40] Blok et al., 2006.
[41] U.S. EPA, 2006.
[42] Lazard, 2014.
[43] U.S. EPA, "Fuel Economy Trends Report" https://www3.epa.gov/fueleconomy/fetrends/1975-2015/420r15016.pdf
[44] U.S. Environmental Protection Agency, 2014.