PART II

BENEFITS OF FOSSIL FUELS

Introduction to Part II

Part I provided the fundamental economics and science needed to understand proposals to severely restrict the use of fossil fuels in order to slow or stop climate change. Chapter 1, addressing environmental economics, found:

> The prosperity made possible by the use of fossil fuels has made environmental protection a social value in countries around the world. The value-creating power of private property rights, prices, profits and losses, and voluntary trade can turn climate change from a possible *tragedy* of the commons into an *opportunity* of the commons. Energy freedom, not government intervention, can balance the interests and needs of today with those of tomorrow. It alone can access the local knowledge needed to find efficient win-win responses to climate change.

Chapter 2, addressing climate science, found:

> Fundamental uncertainties arising from insufficient observational evidence and disagreements over how to interpret data and set the parameters of models prevent science from determining whether human greenhouse gas emissions are having effects on Earth's atmosphere that could endanger life on the planet. There is no compelling scientific evidence of long-term trends in global mean temperatures or climate impacts that exceed the bounds of natural variability.

In the face of such economic and scientific findings, many experts recommend a "no regrets" strategy of relying on policies that generate value even if climate change turns out not to be a major problem (NCPA, 1991; Adler *et al.*, 2000; Goklany, 2001; Lomborg, 2008; Murray and Burnett, 2009; Carter, 2010; The Hartwell Group, 2010, 2011; van Kooten, 2013; Vahrenholt and Lüning, 2015; Bailey, 2015; Moore and Hartnett White, 2016). Such a strategy might include ending subsidies to development in floodplains and improving the design and construction of levees and flood walls (to reduce flood damage), improving forest management (to reduce forest fires), reducing urban traffic congestion (to reduce emissions from cars and trucks), and improving emergency response systems (to minimize the loss of life during natural disasters). A majority of voters may support policies that protect the environment and save human lives while also addressing the possibility of harmful climate change.

"No regrets" is not the strategy advocated by the IPCC and its many allies in the environmental movement. They advocate instead for immediate major reductions in the use of fossil fuels, hoping this would reduce the level of CO_2 in the atmosphere, which in turn they hope would slow or stop future climate changes, seemingly without regard to economic and scientific facts that suggest otherwise. Relying on invalidated climate models, they claim CO_2 emissions must be reduced by 80% by 2050 to avoid a climate catastrophe (Long and Greenblatt, 2012; National Research Council, 2013; World Energy Council, 2013; IPCC, 2014). If we reject the "no regrets" option, either because of genuine disagreement over economics and science or ideological fervor, we are not relieved of the obligation to weigh the cost of our decision. In particular,

- Can wind turbines, solar photovoltaic (PV) panels, and biofuels meet the world's growing need for dispatchable energy to produce electricity, heat homes, and power manufacturing and transportation?

- How much more would energy cost if fossil fuels were banned or phased out? What impact would that have on human prosperity and health?

- What would be the opportunity cost of such a transition? In other words, what other opportunities to advance human well-being would be foregone?

Answering these questions requires an accurate accounting of the benefits of our current reliance on fossil fuels. For that reason, Part II (Chapters 3, 4, and 5) surveys the three largest benefits of fossil fuels: human prosperity, human health benefits, and environmental protection. Part III (Chapters 6, 7, and 8) will survey the costs of fossil fuels and conduct cost-benefit analyses of fossil fuels, climate change, and policies proposed to prevent or delay the onset of anthropogenic climate change.

Chapter 3 reports the contribution fossil fuels make to human prosperity. The contribution is large: One study projected the "existence value" of coal production, transportation, and consumption for electric power generation in the United States at $1.275 trillion (in 2015 dollars) and estimated coal supported 6.8 million U.S. jobs (Rose and Wei, 2006). An additional benefit is the value of increased food production due to rising levels of atmospheric CO_2, a phenomenon called aerial fertilization. Its worth is estimated to have been $3.2 trillion from 1961 to 2011 and is currently approximately $170 billion annually (Idso, 2013). Chapter 3 also explains why alternatives to fossil fuels – wind turbines, solar PV panels, and biofuels –cannot sustain the prosperity made possible by fossil fuels.

Chapter 4 reports the human health benefits of fossil fuels. Fossil fuels are responsible for the prosperity that makes possible better nutrition, housing, and working conditions, and cleaner air and water, contributing to the dramatic improvements in human longevity and decline in the incidence of diseases and premature death. The marginally warmer temperatures observed in some parts of the world at the end of the twentieth and beginning of the twenty-first centuries have further contributed to human health by preventing millions of premature deaths globally from illnesses or health effects related to colder temperatures (Gasparrini *et al.*, 2015).

Chapter 5 describes the environmental protection made possible by fossil fuels. These benefits go beyond meeting human needs and providing the goods and services that contribute to human flourishing and modernity. As Nobel Laureate Amartya Sen wrote in 2015, "We can have many reasons for our conservation efforts, not all of which need to be parasitic on our own living standards (or need-fulfillment), and some of which may turn precisely on our sense of values and on our acknowledgment of our reasons for taking fiduciary responsibility for other creatures on whose lives we can have a powerful influence" (Sen, 2014). Fossil fuels make it possible to feed a growing global population without massive deforestation or air and water pollution. The aerial fertilization effect further benefits forests and terrestrial species and promotes biodiversity.

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3

Human Prosperity

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Key Findings

Key findings of this chapter include the following:

Energy Tutorial

- Some key concepts include energy, power, watts, joules, and power density.
- Advances in efficiency mean we live lives surrounded by the latest conveniences, yet we use only about 3.5 times as much energy per capita as did our ancestors in George Washington's time.
- Increased use of energy and greater energy efficiency have enabled great advances in artificial light, heat generation, and transportation.
- Fossil fuels supply 81% of the primary energy consumed globally and 78% of energy consumed in the United States.
- Due to the nature of wind and sunlight, wind turbines and solar photovoltaic (PV) cells can produce power only intermittently.

Three Industrial Revolutions

- Fossil fuels make possible such transformative technologies as nitrogen fertilizer, concrete, the steam engine and cotton gin, electrification, the internal combustion engine, and the computer and Internet revolution.
- Electricity powered by fossil fuels has made the world a healthier, safer, and more productive place.
- Access to energy is closely associated with key measures of global human development including per-capita GDP, consumption expenditure, urbanization rate, life expectancy at birth, and the adult literacy rate.

Food Production

- Fossil fuels have greatly increased farm worker productivity thanks to nitrogen fertilizer created by the Haber-Bosch process and farm machinery built with and fueled by fossil fuels.
- Higher levels of carbon dioxide (CO_2) in the atmosphere act as fertilizer for the world's plants.
- The aerial fertilization effect of rising levels of atmospheric CO_2 produced global economic benefits of $3.2 trillion from 1961 to 2011 and currently amount to approximately $170 billion annually.
- The economic value of CO_2 fertilization of crops over the period 2012–2050 is forecast to be $9.8 trillion.
- Reducing global CO_2 emissions by 28% from 2005 levels, the reduction President Barack Obama proposed in 2015 for the United States, would reduce aerial fertilization benefits by $78 billion annually.

Why Fossil Fuels?

- Fossil fuels have higher power density than all alternative energy sources except nuclear power.
- Fossil fuels are the only sources of fuel available in sufficient quantities to meet the needs of modern civilization.
- Fossil fuels provide energy in the forms needed to make electricity dispatchable (available on demand 24/7) and they can be economically transported to or stored near the places where energy is needed.
- Fossil fuels in the United States are so inexpensive that they make home heating, electricity, and transportation affordable for even low-income households.

Alternatives to Fossil Fuels

- The low power density of alternatives to fossil fuels is a crippling deficiency that prevents them from ever replacing fossil fuels in most applications.

- Wind, solar, and biofuels cannot be produced and delivered where needed in sufficient quantities to meet current and projected energy needs.

- Due to their intermittency, solar and wind power cannot power the revolving turbine generators needed to create dispatchable energy.

- Electricity from new wind capacity costs approximately 2.7 times as much as existing coal, 3 times more than combined cycle gas, and 3.7 times more than nuclear power.

- The cost of alternative energies will fall too slowly to close the gap with fossil fuels before hitting physical limits on their capacity.

Economic Value of Fossil Fuels

- Abundant and affordable energy supplies play a key role in enabling economic growth.

- Estimates of the value of fossil fuels vary but converge on very high numbers. Coal alone delivered economic benefits worth between $1.3 trillion and $1.8 trillion of U.S. GDP in 2015.

- Reducing global reliance on fossil fuels by 80% by 2050 would probably reduce global GDP by $137.5 trillion from baseline projections.

Introduction

This chapter documents the economic benefits of fossil fuels, generally measured as per-capita income or gross domestic product (GDP). Later chapters focus on the human health and environmental benefits. Parts of this chapter originally appeared in reports by Roger H. Bezdek (Bezdek, 2014) and Craig D. Idso (Idso, 2013) which have been substantially updated and revised.

Section 3.1 offers a primer on energy, similar to the tutorials on climate science in Chapter 2, fossil fuels in Chapter 5, and cost-benefit analysis in Chapter 8. Section 3.2 describes the indispensable role played by fossil fuels in creating the modern world. Billions of lives were improved and continue to be improved every day by having access to safe, reliable, and affordable energy. Electricity, overwhelmingly generated with fossil fuels, has improved human well-being in countless ways.

Section 3.3 describes how fossil fuels improved agricultural productivity thanks to nitrogen fertilizer created by the Haber-Bosch process, agricultural machinery built with and fueled by fossil fuels, and the aerial fertilization effect of rising levels of atmospheric CO_2. Section 3.4 explains why fossil fuels are uniquely suited to meeting the energy demands of modern civilization due to their density, sufficient supply, flexibility of use, and low cost.

Section 3.5 explains why alternative fuels – wind turbines, solar photovoltaic (PV) panels, and biofuels (primarily wood and ethanol) – cannot replace fossil fuels as the primary source of energy for human use. Section 3.6 surveys the economic literature estimating the economic value of fossil fuels. It finds coal alone contributed between $1.3 trillion and $1.8 trillion to the U.S. economy in 2015 and reducing global reliance on fossil fuels by 80% by 2050 would probably reduce global GDP by $2.7 trillion a year. Section 3.7 provides a brief summary and conclusion.

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3.1 An Energy Tutorial

Other sections of this chapter deal at length with the economics of energy, and especially how abundant, inexpensive energy leads to productivity, higher GDP, and other economic benefits. This first section provides useful background by reviewing the science and technology behind the engines and machines that produce and use energy. It defines key terms, explains how efficiency is measured, presents basic facts about the leading uses and sources of energy, and explains the differences between dispatchable and intermittent power and why it matters.

3.1.1 Definitions

Some key concepts include energy, power, watts, joules, and power density.

Energy is the capacity or power to do work, such as lifting or moving an object by the application of force. Energy comes in many forms, such as kinetic (energy due to motion), potential (energy due to location), electrical, mechanical, chemical, thermal, and nuclear. Energy can be converted from one form to another by such processes as combustion and letting water descend through a water turbine to drive a generator.

Power is the amount of energy converted from one form to another divided by the time interval of the conversion; in other words, the rate of conversion of energy from one form to another. Power is energy divided by time; energy is power multiplied by time. The International System of Units uses the familiar *watt* (abbreviated W) as the unit of power. One watt is one *joule* (J), the unit of energy, per one second (s), the unit of time. One joule is one watt-second. A *gigajoule* (GJ) is one billion (10^9) joules. An *exajoule* (EJ) is 10^{18} joules.

Power density is energy flow per unit of time, which can be measured in joules per second (watts) divided by a unit of space, as in watts per square meter or W/m^2.

A secondary unit of energy is the kilowatt-hour, which is 1,000 watts multiplied by 1 hour (3,600 seconds) = 3,600,000 J. In the United States, one kWh of electricity (sometimes written kWh_e or kWhe) costs about 14 cents. One thermal kWh (kWh_t or kWht) from gasoline costs about 8 cents. It is wise, when discussing energy policy, to stick to watts and joules with occasional use of watt-hours. Very simple ideas become difficult when there is a profusion of units: a ton of coal, gallon of gasoline, British Thermal Unit (BTU), million-ton-of-carbon-equivalent (MTCE), barrel of oil, cord of wood, calories, kilocalories, foot-pounds, and so forth. For example, what is the efficiency of an engine that consumes one gallon of gasoline to produce 13 horsepower-hours? Conversion factors can be found at the online [Engineering Toolbox] and in Hayden (2015).

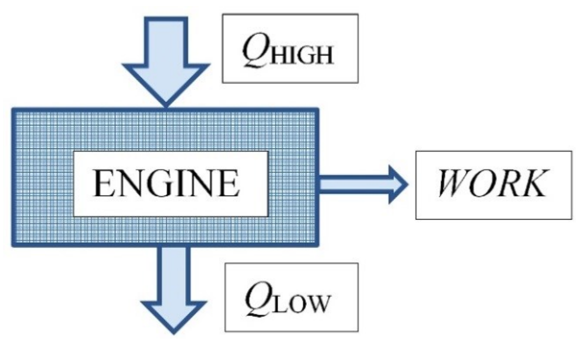
3.1.2 Efficiency

Advances in efficiency mean we live lives surrounded by the latest conveniences, yet we use only about 3.5 times as much energy per capita as did our ancestors in George Washington's time.

All conversions of energy from one form to another are characterized by an efficiency factor. When the output shaft of a car's engine is transferred to the wheels, the efficiency is very high, well above 95%; the limitation is simply friction. On the other hand, when heat is used to produce mechanical energy, the efficiency is much lower; the car's engine typically has an efficiency of around 25%.

A schematic design of a heat engine – which could be a steam engine, a gasoline engine, an aircraft's jet engine, etc. – is shown in Figure 3.1.2.1.

Figure 3.1.2.1
Energy flow in a heat engine



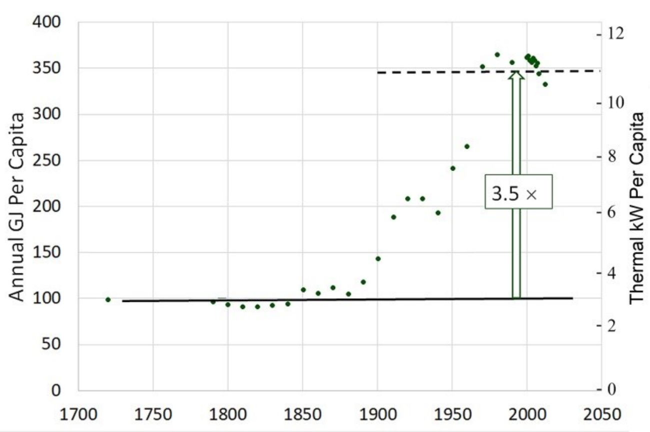
Source: Hayden, 2015, p. 41, Figure 17.

Some heat energy Q_{HIGH} flows from a hot source into an engine, which does some work *WORK*. The Second Law of Thermodynamics demands that some heat energy Q_{LOW} will flow into the lower-temperature surroundings. The efficiency of the heat-to-work engine is *WORK* divided by Q_{HIGH}. Generally speaking, the higher the temperature of the source of heat, and the lower the temperature of the surroundings (usually out of our control), the higher will be the efficiency of the engine.

The first steam engine, designed by Newcomen, was used to pump water out of a coal mine. It was huge, with a 28-inch (71 cm) diameter piston that traveled up and down a distance of 8 feet (2.4 m). It had about as much power as today's garden tractor and an efficiency of 0.05%. By way of comparison, General Electric's 9H, a 50 Hz combined-cycle gas turbine, feeds as much as 530 megawatts (MW) into the UK's electric grid with thermal efficiency of nearly 60% (Langston, 2018).

Today we have cars, planes, trucks, railroad cars, electric lights, electric motors, computers, the Internet, aluminum, refrigeration, furnaces, air conditioning, and all sorts of conveniences, yet we use only about 3.5 times as much energy per capita as did our ancestors in George Washington's time, as shown in Figure 3.1.2.2. Our modern conveniences were not available to our colonial ancestors, yet they used around 3,000 (thermal) watts (100 GJ) per capita. Mostly, the energy was consumed for home heating, cooking with firewood, and lighting with candles. (Energy from horses is not considered in this brief discussion.) The vast improvement in lifestyle occurred with such a small increase in per-capita energy consumption due to vast improvements in energy efficiency.

Figure 3.1.2.2
Annual U.S. per-capita energy consumption in GJ per capita



Source: Adapted from Hayden, 2015, Figure 13, p. 21.

The process of improving efficiency will continue, but with less breathtaking results. For example, going from a Rumford fireplace at 9% efficiency to a modern furnace of 90% efficiency is a dramatic change. If it were possible to achieve 100% efficiency, the change would be less dramatic. Turning the shaft of a generator to produce electricity is already well above 98% efficiency. The friction of railroad cars is already so low that to keep the train moving straight on a level track requires a forward force equal to about 50-millionths of the weight of the train, meaning 1/10 pound keeps a ton rolling (Federal Rail Administration, 2009).

For heat engines, it has long been known that one path to higher efficiency lies in developing materials that can withstand high temperatures. Pratt and Whitney developed a method for producing single-crystal superalloys that is being used to create gas turbine blades with no grain boundaries between crystals, where cracks or corrosion develop (Langston, 2018). Steam engines and internal combustion engines will see further improvements in efficiency.

3.1.3 Energy Uses

Increased use of energy and greater energy efficiency have enabled great advances in artificial light, heat generation, and transportation.

The main uses of energy in a modern civilization are for light, heat (including home heating and heat for electricity generation and manufacturing processes), and transportation.

Light

In the novels of Jane Austen, parties were scheduled to coincide with the full moon so guests could travel at night in their horse-drawn carriages. Suffice it to say that our ancestors lived in a dark world. The common source of light early on was the candle, which produces about 0.17 lumens (a unit of the amount of visible light) per watt. By comparison, an incandescent light bulb with a filament produces about 30 lumens per watt, and a light-emitting diode produces about 200.

Candles were overtaken by whale oil in cities located near coasts or with adequate roads and infrastructure to import the oil, which burns with a very clean flame in lamps. The slaughter of whales led to a shortage that made the price soar, and kerosene, a product refined from petroleum, replaced it. According to Beckmann (1977), "sperm oil rose from 43¢ a gallon in 1823 to $2.25 a gallon, and whale oil rose from 23¢ in 1832 to $1.45 a gallon. … By 1861 [the price of kerosene] had fallen to 10¢ a barrel [*sic*, it was 10¢ a gallon], and within two years kerosene had pushed out all other lighting fuels from the market, including tallow candles (as a permanent source of light). Though not everyone had been able to afford whale oil, practically everyone was able to buy kerosene."

Kerosene was then overtaken by electric lighting made possible by fossil fuels and hydroelectric generation dams. Thomas Edison's Pearl Street Station in New York City generated direct-current electricity in 1882 and by 1884 was powering about 10,000 lamps and providing some local buildings with some heat. The rest of that story is told in Section 3.2.2 and so won't be repeated here.

Heat

In the late 1700s, houses were heated by fireplaces that were very smoky and very inefficient. Count Rumford (Benjamin Thompson), who was the first scientist to prove that heat and mechanical energy were related, invented a way to improve fireplaces on both counts (Brown, 1981). The efficiency of a Rumford fireplace was about 9%. At about the same time, Benjamin Franklin invented the cast-iron stove, for which the efficiency was probably 15% to 20%. Modern home furnaces have efficiencies of roughly 90%. Of course, people in those early days were not measuring efficiency. They simply had to cut, split, and stack lots of firewood for cooking and home-heating requirements.

The British denuded their forests, using the best timber for building the ships that made the kingdom powerful at sea, and much of the rest for the manufacture of glass windows for mansions. Part of the reason for the rebellion against King George was that he claimed the best trees on American lands owned by people in the colonies.

Transportation

Until the advent of steam locomotives in the early 1800s, all transportation was by foot, animals, or ships with sails. The vast majority of people never traveled more than a few tens of kilometers (a few dozen miles) from where they were born. Even in the early decades of the 1900s, two major problems in big cities were the removal of horse manure and disposal of dead horses.

The first primitive locomotive was built in 1812, and the first practical one was Stephenson's 8-ton "LOCOMOTION No. 1" built in 1825 for the Stockton & Darlington Railroad. It was capable of pulling 90 tons of coal at 15 mph. Today's coal trains move 10,000 tons at more than 60 mph. It was not until about 1850 that train travel became common. The trains were powered mostly by coal for the next century. City trains (streetcars and trolleybuses) were powered by overhead power lines, but only after electricity became widespread.

Trains, streetcars, and trolleybuses can take you to a station near where you want to go, but that station may be a long walk from your final destination. There will be stops along the way to allow other passengers to board or leave, and the trains operate on schedules that may not coincide with yours. For reasons of convenience, cars and trucks became the default means of transportation except in a few cities with high population densities. Cars and trucks delivered unprecedented mobility, opening up innumerable opportunities for commerce, recreation, and individual freedom. O'Toole (2009) writes,

> No matter where you are in the United States, you owe almost everything you see around you to mobility. If you live in a major city, your access to food, clothing, and other goods imported from outside the city depends on mobility. If you live in a rural area, your access to the services enjoyed by urban dwellers, such as electrical power and communications lines that are installed and served by trucks, depends on mobility. If you spend your vacations hiking in the most remote wilderness areas, your ability to reach the trailheads depends on your mobility (p. 6).

3.1.4 Energy Sources

> *Fossil fuels supply 81% of the primary energy consumed globally and 78% of energy consumed in the United States.*

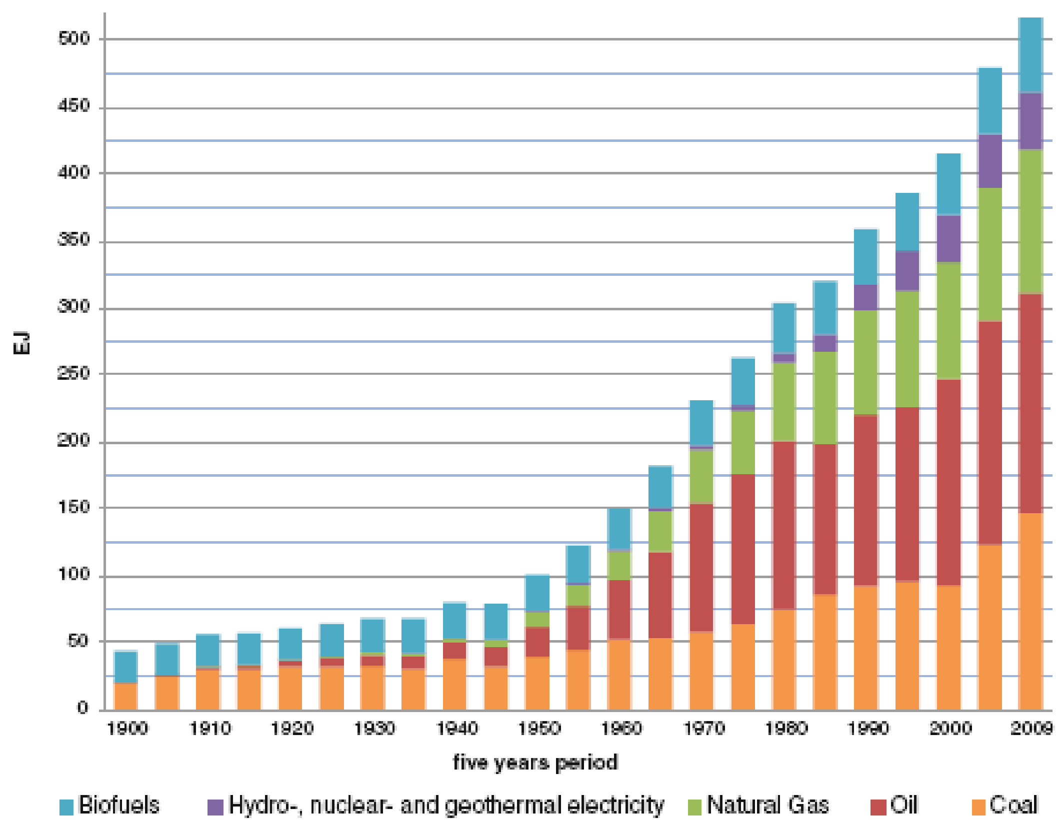
Already during the second half of the seventeenth century, a shortage of wood was leading to rising prices and restrictions on the harvesting of forest trees in England and elsewhere in Europe. The abundance of trees in the Americas assured wood's prominence longer, but by around 1900 coal had overtaken wood as the world's primary energy supply, and fossil fuels have dominated ever since, as shown in Figure 3.1.4.1.

Fossil Fuels

The world's energy supply increased dramatically from 1900 to 2009, with nearly all the increase supplied by coal, oil, and natural gas, as shown by Figure 3.1.4.1. According to the International Energy Agency (IEA, n.d.), 81% of total world energy consumption was supplied by fossil fuels in 2016. Biofuels and waste supplied about 9.8%, nuclear provided 4.9%, hydroelectric provides 2.5%, and wind, solar and other renewables combined contributed only 1.6%. See Figure 3.1.4.2. It is important to note these are stylized facts, a simplified presentation summarizing data that are incomplete, derived from models, and known to have inaccuracies. The presentation illustrates the ability of coal, oil, and natural gas to increase rapidly in supply relative to renewables – primarily wind turbines and solar PV cells – which contribute very little to global energy supplies.

The history of U.S. energy consumption from 1635 to the present is shown in Figure 3.1.4.3. Until 1850, virtually all energy came from firewood. Now our energy comes also from petroleum, coal, natural gas, nuclear power stations, hydro, wind, geothermal, solar thermal, and solar photovoltaics. The vast

Figure 3.1.4.1
The world's total primary energy supply for 1900–2009

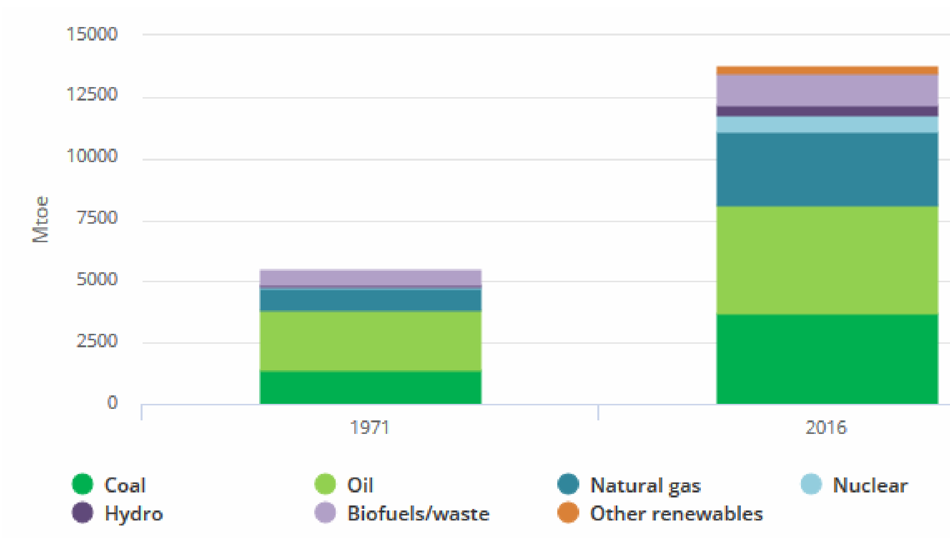


Source: Bithas and Kalimeris, 2016, Figure 2.1, p. 8.

majority of the increase in energy demand is due to the increase in population, which has increased by a factor of 100 since the founding of the nation. In 2017, fossil fuels accounted for 78% of primary energy production in the United States; nuclear and nonhydroelectric renewables each contributed about 9.5%, and hydroelectric produced 3% (EIA, 2018, Table 1.2, p. 5).

Figure 3.1.4.4 shows the complex energy flow in the United States, with sources on the left. The widths of the lines are proportional to the amounts of energy flowing in the directions indicated. The light gray areas represent "rejected energy," which is primarily the Q_{LOW} from heat engines explained in Section 3.1.1. By far the main sources of energy for producing electricity are coal, natural gas, and nuclear. Petroleum is not used much for electricity

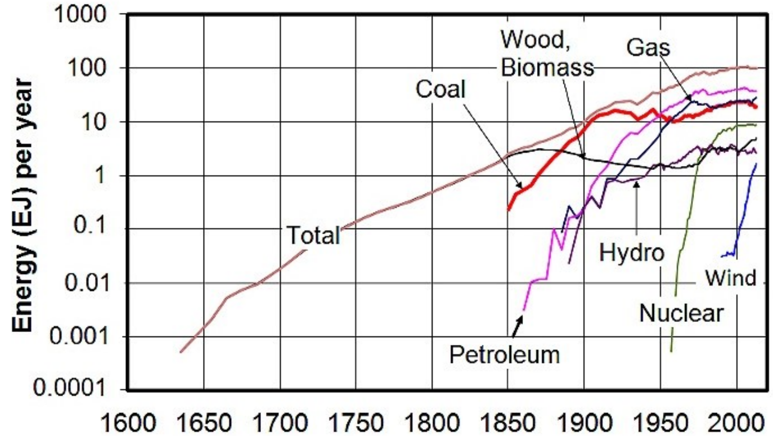
Figure 3.1.4.2
Global primary energy supply by fuel, 1971 and 2016



2016 global primary energy supply by fuel			
Source	**Mtoe**	**EJ**	**Percentage**
Oil	4,390	184	31.9%
Coal	3,731	156	27.1%
Natural gas	3,035	127	22.1%
Fossil fuels subtotal	11,156	467	81.1%
Biofuels and waste	1,349	56	9.8%
Nuclear	680	28	4.9%
Hydroelectric	349	15	2.5%
Other renewables	226	9	1.6%
Total	**13,760**	**575**	**100.0%**

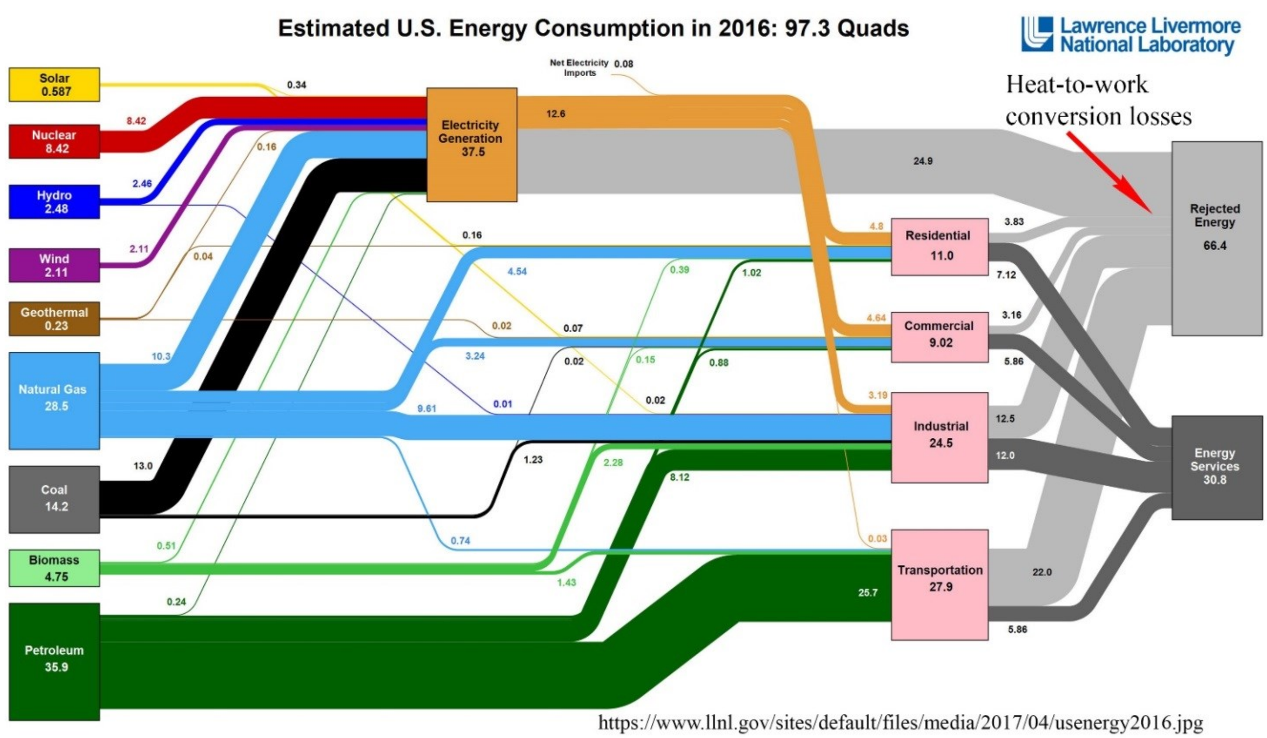
Primary energy sources for the world in millions of tons of oil equivalent. Mtoe = megatonnes (million tons) oil equivalent, EJ = exajoules. *Source:* IEA, n.d.

Figure 3.1.4.3
U.S. energy consumption from 1635–2013 by energy source



Note the vertical axis is a logarithmic scale, equal differences in order of magnitude are represented by equal distances from the value of 1. *Source:* Hayden, 2015, Figure 9, p. 18.

Figure 3.1.4.4
Sources and uses of energy in the United States in 2016



A quad is a quadrillion BTU, or 1.055×10^{18} J = 1.055 EJ. *Source:* Lawrence Livermore National Laboratory (LLNL), 2017.

production, but is the source for almost all of our transportation needs. Natural gas is the most versatile fuel, providing energy for electricity production and heating, cooking, and process heat for homes, commercial establishments, and industries. The world as a whole consumes 576 EJ, about 5.8 times as much energy as the 100 EJ consumed by the United States. Coal supplies 162 EJ, 28% of the world's total energy, versus coal's 37% share in the United States.

Bioenergy

Biofuels (mainly wood) supply about 10% of the global energy supply. Ethanol and biodiesel are often proposed as "climate friendly" alternatives to gasoline and diesel fuel, which are derived from petroleum. Biofuels are severely limited by their lack of power density, a matter discussed at some length in Section 3.4.1 below and again in Chapter 5, Section 5.2.2. Here in a nutshell is the engineering science behind that problem.

Chlorophyll absorbs about 6.6% of the sunlight falling on it. Of that amount, some energy is used to combine carbon (stolen from CO_2), hydrogen (stolen from H_2O), nitrogen and various minerals into green leaves. All in all, 90% of that absorbed solar energy is used up in the plant itself. The best plants that can be grown in large areas of the United States produce about 10 tons of drymatter per acre per year, which when converted into biofuel translates into 1.2 thermal watts per square meter of land (Bomgardner, 2013). This yield diminishes to only 0.069 and 0.315 W/m^2 for biofuels produced from soy and corn, respectively, when energy is deducted to account for farming and processing (Kiefer, 2013). Full accounts of the ethanol production process generally find more energy (produced by using fossil fuels) is consumed than is produced, meaning ethanol may produce more greenhouse gas emissions than the oil it replaces (Searchinger *et al.*, 2008; Melillo *et al.,* 2009; Mosnier *et al.,* 2013).

Solar Energy

There are three main uses of solar energy: home and workplace heating, conversion of solar heat to electricity, and direct conversion of sunlight to electricity by using photovoltaic (PV) cells. Most of the emphasis has been on PV cells, so we focus on them here. Higher PV efficiency means less collection area is needed to produce the same energy output. Less obvious, perhaps, is that higher efficiency sometimes comes at a dramatically higher cost.

Figure 3.1.4.5 shows progress in improving module efficiencies for PV cells from 1975 to 2016. (A module is better known as a panel, a collection of cells pre-wired and packaged for modular installation.) These modules often are on the cutting edge of research and not yet ready for commercial applications. Some, for example, are the size of your fingernail. Efficiencies as high as 46% have been obtained but only for very small, very expensive cells. For large-scale photovoltaics, efficiencies tend to be around 15% and have not been improving much over time.

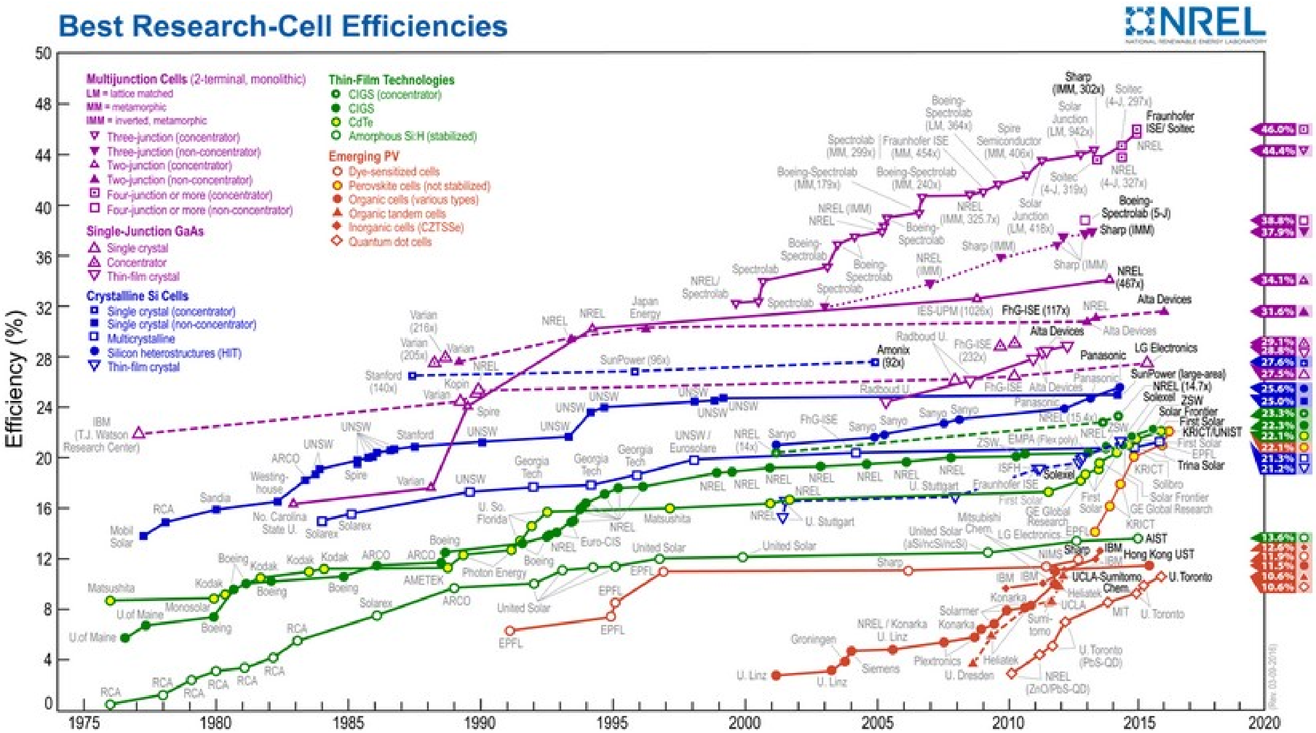
The electricity generated by PV cells must be converted from direct current (DC) to alternating current (AC) before sale on wholesale electricity markets or for direct use in an AC household system, resulting in a loss of energy reported as "system efficiency." The U.S. Energy Information Administration (2010) made the following forecasts of improvements in module and system efficiencies:

- *Module Efficiency*. Module efficiencies for crystalline technologies operating in the field are estimated to range from 14% in 2008 to 20% in 2035. For thin-film technologies, module efficiencies are anticipated to range from 10% to 14% over this same time span (2008 to 2035).

- *System Efficiency*. System efficiencies (DC to AC power) for crystalline technologies are expected to increase from levels in the range of 78% to 82% in 2008, to levels in the range of 86% to 90% in 2035. For thin-film technologies, system efficiencies are forecast to increase from a range of 77% to 81% in 2008, to a range of 86% to 90% in 2035.

Six years later, in 2016, EIA still assumed average system efficiency was 80% for new installations (EIA, 2016, p. 18, fn 26). In fact, PV cell efficiency in 2016 was probably about 15% and conversion to grid voltage was about 80%, making an overall efficiency of only 12%. There is every reason to expect efficiency to improve, but despite billions of dollars spent on research and development and decades of subsidies and tax breaks, so far the rate of increase has not been rapid.

Figure 3.1.4.5
Progress in improving best research-cell efficiencies from 1975 to 2016



Source: National Renewable Energy Laboratory, 2018.

Wind

Wind turbines extract kinetic energy from the wind. Wind turbines rotate slowly, measured in rotations per minute (RPM), but the tips of the blades move very rapidly. As an example, the Vestas V80-2.0 MW turbine turns at 16.7 revolutions per minute, doing a full rotation in 3.6 seconds. But the tips of the 80-meter-diameter turbine move at about 70 meters per second (about 155 miles per hour) and can reach up to 80 m/s (about 180 mph).

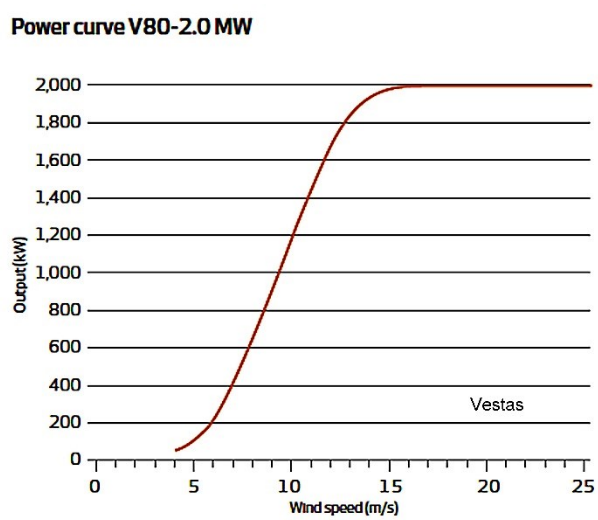
Because wind turbines are designed around the properties of the wind, the tip speed is a multiple of the wind speed, regardless of the rotor diameter. Accordingly, the RPM decreases with rotor diameter. Generators, on the other hand, work best at high rotation rate, typically hundreds to thousands of RPM. Gearboxes are required to convert the ponderous rotation of the wind turbine rotor into the high RPM of the generator. To date, gearboxes have been the main cause of wind turbine failures.

The annual capacity factor (CF) of wind – the average annual power divided by the nameplate power of the generator – is a matter of engineering design. A small generator on a large-diameter turbine will have a high CF. A large generator turned by a small-diameter turbine will have a small CF. The current best engineering compromise is a 35% CF. Wind turbines cause the air to slow down. This coupled with the need to avoid turbulence means wind turbines have to be spaced some distance apart, typically about 10 rotor diameters. The power produced by the wind turbine is proportional to the area swept by the rotors: If you double the diameter, you quadruple the power. But the distance between adjacent turbines must double in both directions, thereby quadrupling the land area. Consequently, the power produced per unit area of land is independent of the size of the wind turbines.

For arrays of industrial wind turbines there are two useful numbers to know: the CF is 35% by design, and the year-round average power per unit area, or power density, is about 1.2 W/m^2 (12 kW/ha, 5 kW/acre).

The wind energy arriving at the wind turbine per unit of time is proportional to the *cube* – the third power – of the wind speed. As a consequence, the power generated by a wind turbine varies dramatically with wind speed. Figure 3.1.4.6 shows the power curve for the Vestas unit discussed above; the curves for any model of industrial wind turbine by any manufacturer is similar in shape. The only significant difference is the peak power. At wind speeds below about 4.5 m/s (10 mph), no power is produced. At 6 m/s (13.4 mph), the power is 200 kW. At 12 m/s (27 mph), the power is 1600 kW. When the wind speed doubles from 6 m/s to 12 m/s, the power output increases by a factor of 8. Above about 14 m/s (31.3 mph), the generated power is 2 MW until the speed reaches 25 m/s (56 mph), after which the system must be shut down to avoid tearing itself apart.

Figure 3.1.4.6
Power produced by the Vestas V80-2.0 MW versus wind speed



Source: Hayden, 2015, Figure 36, p. 72.

3.1.5 Intermittency

Due to the nature of wind and sunlight, wind turbines and solar photovoltaic (PV) cells can produce power only intermittently.

Wind turbines and solar photovoltaic (PV) cells are unable to produce a steady stream of energy into an electric grid and sometimes produce no power at all for hours, days, or even weeks. Both are unable to produce *dispatchable* energy, defined as energy available to an electric grid on demand. PV cell output drops when clouds, rain, or dust reduce the amount of sunlight reaching the panel, during seasons that tend to be cloudy or rainy, and of course every day from nightfall until sunrise. Figure 3.1.5.1 records actual solar energy production in southeastern Australia on a typical day, June 19, 2018. Evident from the figure are high levels of variability during daylight hours and, as expected, zero power production at night.

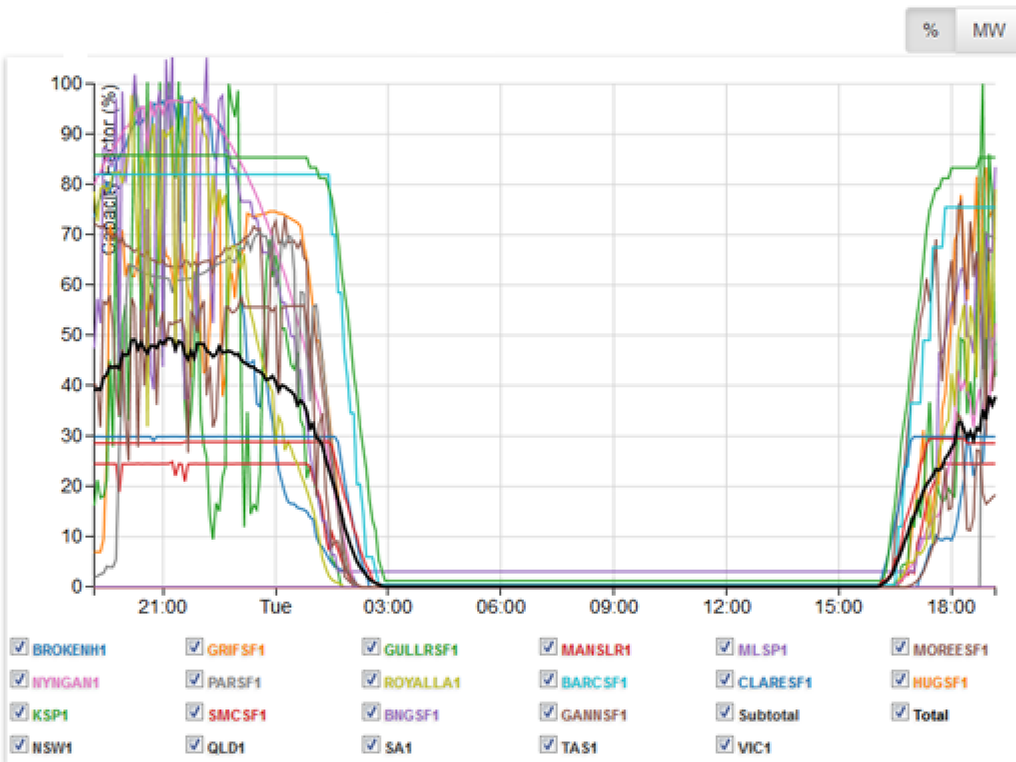
Figure 3.1.5.2 illustrates the dramatic volatility of wind power on a typical day (June 19, 2018) in southeastern Australia. Wind turbines were constantly ramping up and down, from 100% to 0% often in just minutes.

Data plotted in Figures 3.1.5.1 (solar) and 3.1.5.2 (wind) are from the energy markets and systems in southeastern Australia operated by the Australian Energy Market Operator (AEMO). AEMO also documents the very small amounts of energy generated by wind and solar relative to total energy consumption in southeastern Australia, shown in Figure 3.1.5.3. Fossil fuels, the only dispatchable energy source available in sufficient amounts to meet demand, makes up for the shortfalls when the sun doesn't shine and the wind doesn't blow. Similar patterns are apparent in all industrialized countries of the world.

In many countries, calm periods sometimes last longer than a week. It is probably reasonable to assume that the installed capacity of wind power needs to be something like twice the system maximum demand and the storage system needs to be able to receive this surplus energy at a rate greater than the system demand. So if the system demand is 1,000 MW, 3,000 – 4,000 MW of generating capacity is needed supported by about 2,500 MW of storage. So a 1,000 MW system needs to have a connected generating capacity of about 6,000 MW. This will be extremely expensive.

Energy can be stored primarily in three ways: as chemical energy in batteries, as gravitational potential energy behind dams, and as heat, typically heated water. While each method is widely used and has valuable applications, all have limitations making them unable to store more than a small fraction of the energy used on an hourly or daily basis. Without back-up power produced by fossil fuels, a renewables-

Figure 3.1.5.1
Solar energy production in southeastern Australia on June 19, 2018



The default, capacity factor graph shows the output as a percentage of registered capacity. Alternatively, you may view the actual output in megawatts.

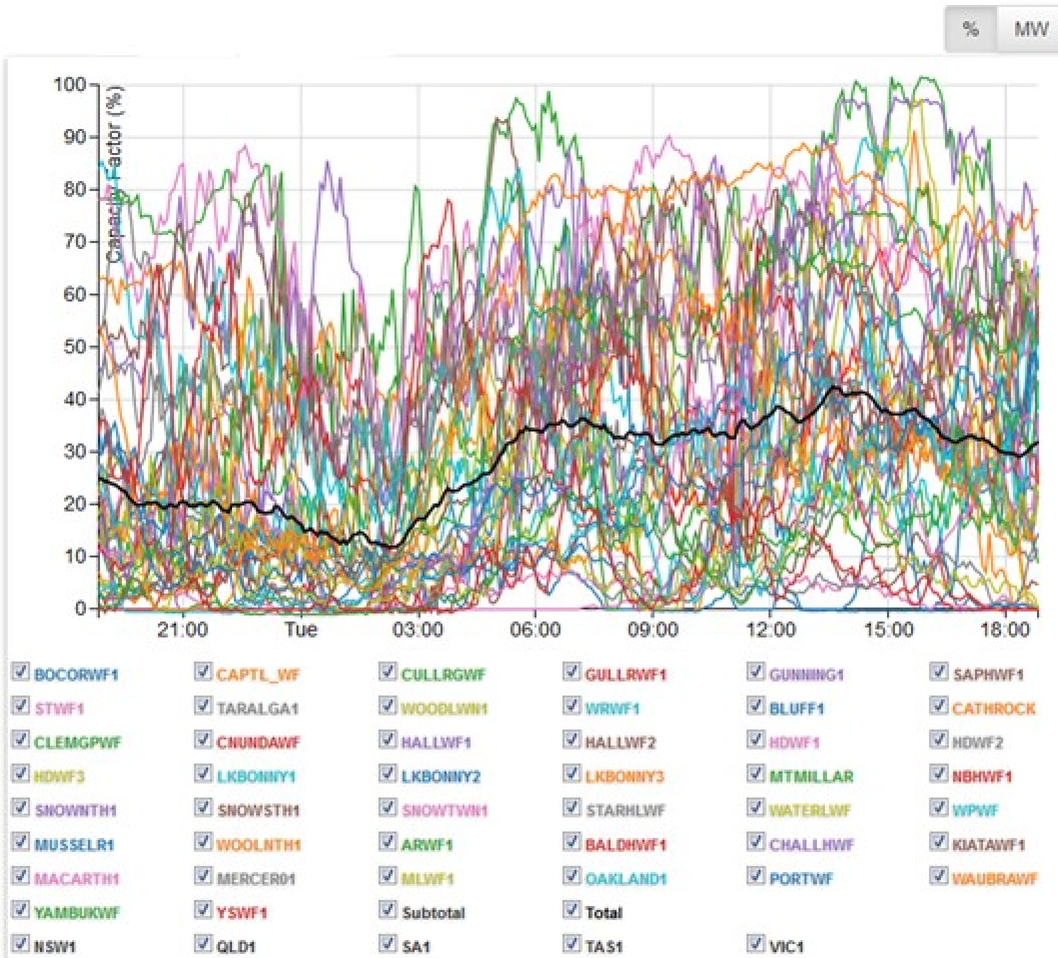
Source: AEMO, 2018.

only energy system would require a vast amount of storage. The only technology available at the moment that can provide this is pumped storage hydropower. An installation consists of a lower lake and an upper lake 300 to 800 m above the lower lake. The two lakes are connected by a pipeline with a power station at the lower lake that can either generate from water from the upper lake or pump water from the lower lake to the upper lake.

Conventional pumped hydro power stations store water for between 6 and 10 hours and normally generate during the morning and evening peak demand periods and pump the early hours of the morning and the middle of the day. There might be six storage schemes in the world that can provide storage for longer than a few days. In order to support solar and wind generation a pumped storage scheme would need to have far more capacity than any pumped hydro system operating today, enough to power a grid for days or weeks at a time. It would be extremely difficult to find a site for such a station because it needs huge basins less than about 10 miles apart, one of which is hundreds of metres higher than the other. It is also necessary to find a source of make-up water because the evaporation from two lakes is likely to be quite large.

The economics of such a scheme will be dubious because it likely involves submerging thousands of acres of land plus an investment of thousands or millions of tons of concrete and steel to build the dam, hydroelectric turbines, power lines, etc. A very large quantity of water has to be pumped up to the upper lake using expensive wind and solar power, held there for days, weeks or months, and then used to generate electricity with an overall loss of about 20%. The reality is that there are few suitable sites available and those that exist are likely to be remote from solar and wind power sources, thus incurring

Figure 3.1.5.2
Wind energy production in southeastern Australia on June 19, 2018

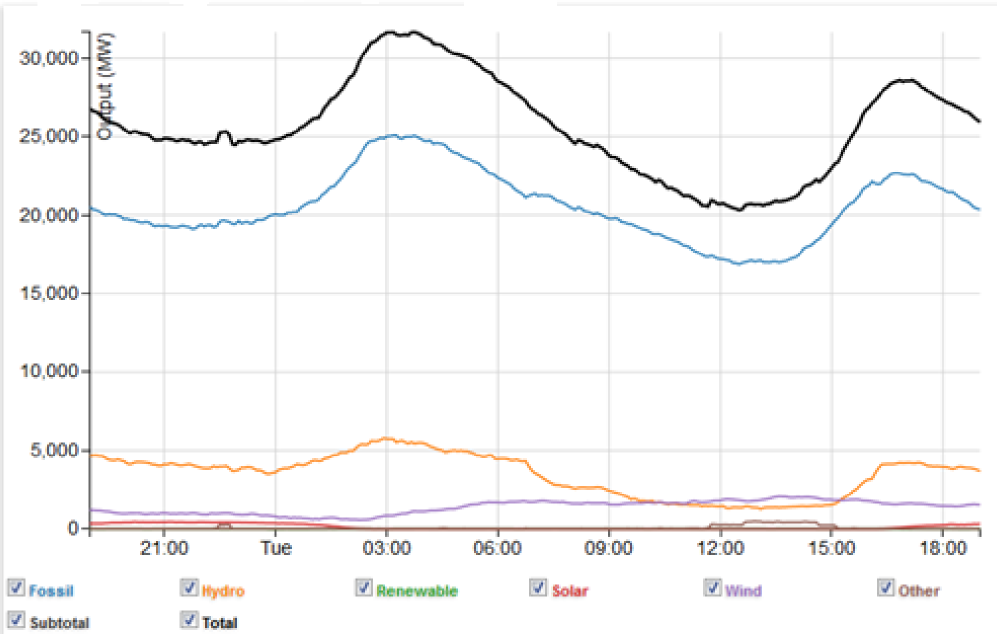


This graph depicts performance of wind farms connected to the electricity grid in south-eastern Australia over a 24-hour period.

The default, capacity factor graph shows the output as a percentage of registered capacity. On average wind farms in south-east Australia operate at a capacity factor of around 30-35%.

Source: AEMO, 2018.

Figure 3.1.5.3
Energy production by source in southeastern Australia on June 19, 2018



This graph shows the amount of energy being contributed into the grid by each type of generator. It also shows the total which essentially amounts to energy being demanded of the grid at any given time.

Source: AEMO, 2018.

very large transmission losses.

In addition to the storage problem, the variability of wind and solar power creates problems for electrical grid operators that may be unsolvable at high penetration rates. This topic is addressed in Section 3.5.3.

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3.2 Three Industrial Revolutions

The primary reason humans burn fossil fuels is to produce the goods and services that make human prosperity possible. Put another way, we burn fossil fuels to live more comfortable, safer, and higher-quality lives. The close connection between fossil fuels and human prosperity is revealed by the history of the Industrial Revolution and analysis of more recent technological innovations.

3.2.1 Creating Modernity

Fossil fuels make possible such transformative technologies as nitrogen fertilizer, concrete, the steam engine and cotton gin, electrification, the internal combustion engine, and the computer and Internet revolution.

Prior to the widespread use of fossil fuels, humans expended nearly as much energy (calories) producing food and finding fuel (primarily wood and dung) to warm their dwellings as their primitive technologies were able to produce. Back-breaking work to provide bare necessities was required from sun-up to sun-down, by children as well as adults, leaving little time for any other activity. The result was a vicious cycle in which the demands of the immediate present prevented investing the time and capital needed to think about and discover ways to improve productivity and therefore the future (Simon, 1981; Bradley and Fulmer, 2004; Epstein, 2014).

According to Goklany (2012), "For most of its existence, mankind's well-being was dictated by disease, the elements and other natural factors, and the occasional conflict. Virtually everything required – food, fuel, clothing, medicine, transport, mechanical power – was the direct or indirect product of living nature" (p. 2). Generations of farmers and craftsmen used the same tools and worked the same land as their ancestors. Progress, whether measured by lifespan, population, or per-capita income, was almost nonexistent. The main sources of non-labor power in that era were windmills, waterwheels, and grass-fed horses, none of which could be easily scaled up. Prosperity came slowly to humanity. According to Maddison (2006):

- "Over the past millennium, world population rose 22–fold. Per capita income increased 13–fold, world GDP nearly 300–fold. This contrasts sharply with the preceding millennium, when world population grew by only a sixth, and there was no advance in per capita income.

- "From the year 1000 to 1820 the advance in per capita income was a slow crawl – the world average rose about 50 per cent. Most of the growth went to accommodate a fourfold increase in population.

- "Since 1820, world development has been much more dynamic. Per capita income rose more than eightfold, population more than fivefold.

- "Per capita income growth is not the only indicator of welfare. Over the long run, there has been a dramatic increase in life expectation. In the year 1000, the average infant could expect to live about 24 years. A third would die in the first year of life, hunger and epidemic disease would ravage the survivors.

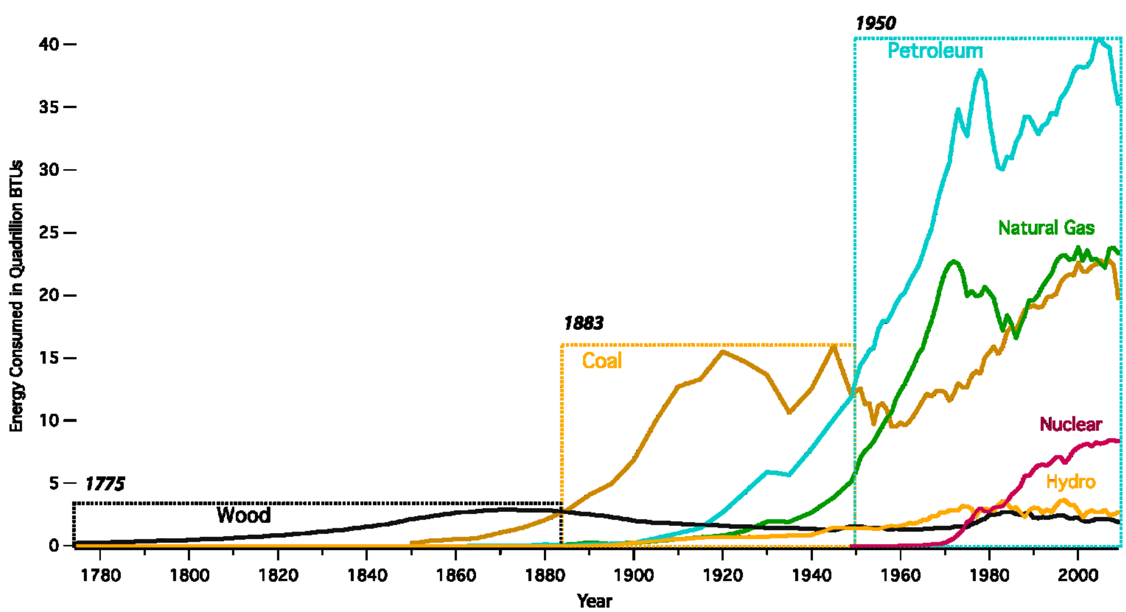
- "There was an almost imperceptible rise [in life expectancy] up to 1820, mainly in Western Europe. Most of the improvement has occurred since then. Now the average infant can expect to survive 66 years" (p. 19).

The increasing use of fossil fuels was responsible for the astonishing change in human well-being starting around 1800. Gordon (2012, 2016) analyzed economic growth in the United States over the past several hundred years and identified fossil fuels as the power source that drove not one but *three* Industrial Revolutions. The first (1750 to 1830) resulted from the invention of the steam engine and cotton gin and proceeded through the development of the early railroads and steamships, although much of the impact of railroads on the American economy came later, between 1850 and 1900. The *Second Industrial Revolution* (1870 to 1900) was the most important, with the invention of electricity generation, lights, motors, and the internal combustion engine, and widespread access to running water with indoor plumbing. Both of the first two revolutions required about 100 years for their full effects to percolate through the economy.

During the two decades 1950–70 the benefits of the Second Industrial Revolution were still transforming the economy, including air conditioning, home appliances, and the interstate highway system. After 1970, productivity growth from this second revolution slowed markedly as the new inventions had reached every corner of the country. The *Third Industrial Revolution* (1970 to present) is marked by the computer and Internet revolution. Its beginnings can be traced back to around 1960, but it really took off and reached a climax during the dot-com era of the late 1990s. It continues to revolutionize science, medicine, manufacturing, and transportation.

As documented in Section 3.1, fossil fuels provided the energy required by nearly all of the revolutionary technologies Gordon identified, from the steam engine and cotton gin of the past to high-tech manufacturing and the mobile computer devices of today (Ayres and Warr, 2009). See Figure 3.1.4.1 in Section 3.1 for estimates of the sources of the world's total primary energy supply for 1900–2009. Figure 3.2.1.1 shows the rapid increase in the use of coal in the United States beginning around 1850, then oil in 1900, followed by natural gas in 1920. Wood remained the main source of fuel in the United States until about 1883, when it was overtaken by coal. Energy consumption followed somewhat similar trajectories in many other countries, with differences determined by natural resource endowments, assignment of private property rights to natural resources, and government policies.

Figure 3.2.1.1 History of energy consumption in the United States, 1775–2009



Source: EIA, 2011.

In 2016, 81% of global energy consumption is supplied by fossil fuels (IEA, 2018.). Approximately 63% of electricity worldwide was produced by the combustion of fossil fuels (coal, oil, or natural gas), while nuclear accounted for 20% and all renewable energies (solar, wind, biomass, geothermal, and hydroelectric) combined accounted for the remaining 17% (EIA, n.d.). Wind energy generated 6.3% of electricity and solar generated 1.3%.

Key to the ongoing technological developments of the three Industrial Revolutions was the fact that initial technologies accelerated the generation of ideas that facilitated even better technologies through, among other things, greater accumulation of human capital (via greater populations, time-expanding illumination, and time-saving machinery) and more rapid exchange of ideas and knowledge (via greater and faster trade and communications) (Smil, 1994, 2005; Bradley, 2000). The benefits continue to accumulate today as cleaner-burning fossil fuels bring electricity to developing countries and replace wood and dung as sources of indoor heating (Yadama, 2013).

Without cheap and reliable energy, there would be less food (and what food we had would be less fresh, less nutritious, and less safe), no indoor plumbing, no air conditioning, no labor-saving home appliances such as washing machines and clothes driers, no agricultural machinery, few hospitals, and no speedy ambulances to take us to a hospital when we need urgent medical care. Sterilizing medical devices would be extremely difficult without electricity. Natural gas is also the fuel stock of plastics; without it, the hospital we might succeed in finding would have no syringes, no tubes, and no bags for plasma.

Goklany (2012) summarized the benefits as follows: "Americans currently have more creature comforts, they work fewer hours in their lifetimes, their work is physically less demanding, they devote more time to acquiring a better education, they have more options to select a livelihood and live a more fulfilling life, they have greater economic and social freedom, and they have more leisure time and greater ability to enjoy it." Goklany's research shows these trends are also evident in other industrialized nations (Goklany, 2007).

Fossil fuels made possible the growth of America's largest cities. Platt (1991) observed,

> Although generally ignored by scholars, energy fuels constitute a natural resource that has had a major impact on regional economies, including the growth of their urban centers. With the shift from wood to coal, the Midwest's virtually unlimited supply of that fuel became crucial to maintaining transportation rates on a par with or lower than those in cities farther east. Vast fields of bituminous (soft) coal throughout Illinois would allow Chicago's commerce and manufacturing to develop in step with those of its counterparts in the East. In contrast, regions of relative coal scarcity such as the Southwest would lag behind in manufacturing while high transportation rates added an extra tax on their commerce (p. 7).

Platt emphasizes the role played by coal in attracting industry to the Chicago area:

> The importance of this natural resource to the growth of the industrial cities of the Midwest cannot be overstressed. A "glut" of cheap coal would act as a magnet attracting a wide array of energy-intensive industries to locate and flourish in Chicago, the transportation hub of the region. … And it was these very energy-intensive industries that represented the vanguard of the industrial revolution. The rise of big business and the jobs it created were in large part responsible for the city's phenomenal growth in the late nineteenth century (*Ibid.,* pp. 7, 9).

Calling Chicago "the city that coal built," Platt wrote: "Whereas the region's grain, hogs, and timber fed the growth of the first city, its abundance of cheap coal fueled the second wave of industrial development." Coal-gas-powered gas lamps, inaugurated in 1850, were 12 to 14 times more powerful than the standard candle or oil lamp. Gas streetlamps made nightlife possible, improved safety for travelers and protection against muggers, and lowered the odds of accidental fires. Safe indoor lighting came within reach of the non-rich for the first time in history. The same story can be told of all the world's cities.

Fossil fuels also made possible a vast expansion of human mobility (Rae, 1965; Lomasky, 1997; O'Toole, 2001; Cox, 2006). O'Toole (2009) described eight "transportation revolutions," only one of which could have occurred without fossil fuels. They were, in chronological order, steamboats, canals, roads across mountains, railroads, horse-powered streetcars, automobiles, superhighways, and jetliners (*Ibid*., pp. 8–20). Fossil fuels were essential to creating the steel and powering the factories used to create streetcars, so even horse-powered streetcars would have been rare without fossil fuels. Increased mobility produced major economic benefits as employers were able to draw workers from a larger area and workers were able to choose among a larger number of potential employers without having to relocate their families. O'Toole cites research in France that found for every 10% increase in travel speeds, the pool of workers available to employers increased by 15%. He noted, "This gives employers access to more highly skilled workers, which in turn increases worker productivity by 3%." Research in California, he says, found "doubling the distance workers can commute to work increases productivity by 25%," citing Prud'homme and Lee (1999) and Cervero (2001) (*Ibid.,* p. 5).

Collier (2007) explained how global economic development today depends on the continued availability of fossil fuel-powered transportation. Some of the poorest countries in the world are landlocked and face high transportation costs, preventing them from being able to participate in the global economy. He mentions Burkina Faso, Central African Republic, Chad, Malawi, and Uganda. For these countries, "air freight offers a potential lifeline into European markets. The key export products are likely to be high-value horticulture…" (p. 180). He further observes that coastal resource-poor countries are unable to access international markets because they lack ports and airports to compete with China and other first-movers. "Breaking out of limbo," he says, requires "big-push aid" for "raising export infrastructure up to globally competitive levels" (p. 182). More than aid, they need affordable and reliable fossil fuels to build and utilize this infrastructure.

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3.2.2 Electrification

> *Electricity powered by fossil fuels has made the world a healthier, safer, and more productive place.*

Fossil fuels' greatest contribution to human prosperity is making electricity affordable and dispatchable. In 2000, the U.S. National Academy of Engineering (NAE) announced "the 20 engineering achievements that have had the greatest impact on quality of life in the 20th century." The achievements were nominated by 29 professional engineering societies and ranked by "a distinguished panel of the nation's top engineers" chaired by H. Guyford Stever, former director of the National Science Foundation and science advisor to the president. The experts ranked electrification the number one achievement. "[E]lectrification powers almost every pursuit and enterprise in modern society," NAE reported. "It has literally lighted the world and impacted countless areas of daily life, including food production and processing, air conditioning and heating, refrigeration, entertainment, transportation, communication, health care, and computers" (NAE, 2000).

NAE contrasted modern life with life before electricity, saying "One hundred years ago, life was a constant struggle against disease, pollution, deforestation, treacherous working conditions, and enormous cultural divides unbreachable with current communications technologies. By the end of the 20th century, the world had become a healthier, safer, and more productive place, primarily because of engineering achievements" (*Ibid.*). Constable and Somerville, in a book published in 2003 by the National Academies Press, commented on the extraordinary engineering achievements electricity launched:

> The greatest engineering achievements of the twentieth century led to innovations that transformed everyday life. *Beginning with electricity*, engineers have brought us a wide range of technologies, from the mundane to the spectacular. Refrigeration opened new markets for food and medicine. Air conditioning enabled population explosions in places like Florida and Arizona. The invention of the transistor, followed by integrated circuits, ushered in the age of ubiquitous computerization, impacting everything from education to entertainment. The control of electromagnetic radiation has given us not only radio and television, but also radar, x-rays, fiber optics, cell phones, and microwave ovens. The airplane and automobile have made the world smaller, and highways have transformed the landscape (Constable and Somerville, 2003, p. 9, Box 1, italics added).

Fossil fuels brought electricity to the homes and workplaces of billions of people around the world. Bryce (2014) wrote,

> Edison's breakthrough designs at the Pearl Street plant [the world's first coal-fired electricity generating plant] allowed humans to reproduce the lightning of the sky and use it for melting, heating, lighting, precision machining, and a great many other uses. Electric lights meant workers could see better and therefore make more precise drawings and fittings. Electricity allowed steel producers to operate their furnaces with greater precision, which led to advances in metallurgy. Electric power allowed factories to operate drills and other precision

> equipment at speeds unimaginable on the old pulley-driven systems, which relied on waterwheels or steam power. As Henry Ford wrote in 1930, without electricity "there could be nothing of what we call modern industry" (pp. 30–31).

Electrification made its first contribution to modernity by bringing light to cities. Government regulators routinely granted monopolies to coal gas companies for street, business, and residential lighting, and those companies formed cartels to keep prices high even as technology improved and supplies increased. The arrival of the electric arc lamp and then Edison's incandescent lamp "set off separate revolutions in the technology of making gaslights and in the business practices of local utilities," triggering "intense competition to sign up customers and extend service territories, including working-class neighborhoods" (Platt, 1991, p. 16).

Manufacturers began to adopt the new technology in 1890. At first they connected electric generators to existing steam engines on their premises to power lights. Then electric motors were mounted on ceilings, upper floors, and in attics to replace the rotating shafts that had been hung from ceilings and connected to machines on shop floors by long belts. Then electric motors were moved to the shop floor, often at individual workstations, making the belts unnecessary. The final step was connecting the factory to a central electric generation station that would replace the on-site steam engines.

The results of the switch to central electric power stations "were revolutionary," Platt wrote (p. 216). "From the eve of the war [WWI] to the onset of the Great Depression, industrial power use [in the Chicago area] increased tenfold, or a spectacular 68% annually over the fifteen-year period. Energy consumption by commercial and residential customers also grew at a vigorous rate of almost 30% a year, while public transportation lagged behind with an anemic annual rate of 3.5%" (p. 217). It was, he wrote, "the birth of the machine age" (p. 226).

Electricians wired homes first for electric lights and then outlets to power everything from stoves and refrigerators to space heaters, radios, clocks, toasters, washing machines and clothes dryers, and vacuum cleaners. Every aspect of daily life was changed. "By the late twenties the use of more and more electricity, gas, and oil in everyday life had become so ubiquitous as to wrap urban America in an 'invisible world' of energy. Even the shock wave of the Great Depression could not halt the steady rise in household consumption of electricity, preserving the new standard of living" (Platt, 1991, pp. 235–6).

Electricity had a powerful effect on culture. Suddenly, millions of people were listening to radios and then watching television, hearing news and music and reading newspapers printed on electric printing presses. "Popular culture" emerged for the first time, knitting together communities once separated by distance and unaware of the music, ideas, and lifestyles of people who lived farther away than a day's journey on horseback or in a horse-drawn carriage. While the greater mobility made possible by cars and trucks caused a radical decentralization of authority and society itself (with the creation of suburbs), the new electric media brought the nation closer together by creating a shared body of knowledge and entertainment. "For the first time, Midwestern farmers, Italian immigrants, the suburban elite, small children, and myriad others were all spending leisure time in the same pursuit" (Platt, 1991, p. 286).

While Chicago and other cities in the Midwest benefited from their ample supplies of coal, cities in the South were benefitting from another invention made possible by electricity: climate control, most importantly air conditioning. Willis Carrier originally developed climate control to facilitate ink drying in the printing industry in New York City in the early 1900s, but his signature technology soon produced nearly incalculable benefits to society. Air conditioning made factory work tolerable in the South, reduced infant mortality, eliminated malaria, and allowed developers to build skyscrapers and apartment buildings. Air conditioning industrialized and urbanized the South, lifting it out of its post-Civil War depression (Arsenault, 1984).

In the United States, many of the central changes in society since World War II would not have been possible without air conditioning in homes and workplaces. Arizona, Florida, Georgia, New Mexico, Southern California, and Texas all experienced above-average growth during the latter half of the twentieth century – which would have been impossible without air conditioning. Air conditioning was crucial for the explosive postwar growth of Sunbelt cities like Houston, Las Vegas, Miami, and Phoenix. Without it people simply could not live and thrive in such hot locations.

Air conditioning launched new forms of architecture and altered the ways Americans live, work, and play. From suburban tract houses to glass skyscrapers, indoor entertainment centers, high-tech manufacturers' clean rooms, and pressurized modules for space exploration, many of today's structures and products would not exist without the invention of climate control. As the technology of climate control developed, so also did the invention of more sophisticated products that required increasingly precise temperature, humidity, and filtration controls – consumer products such as computer chips and CDs must be manufactured in "clean rooms" that provide dust-free environments. The development of the entire information technology (IT) industry could not have occurred without the cooling technologies first pioneered by air conditioning.

Electricity propelled the transportation revolution begun by fossil fuels by making possible headlights for cars and trucks, street lighting, traffic lights, airlines, mass transit, and telecommuting. It revolutionized health care by making possible modern hospitals and clinics, and agriculture by allowing the refrigeration of produce. Electricity created the "global village" via advances in communication including the telephone, radio, television, fax machines, cell phones, computers, the Internet, satellites, email, social media, and more. Electricity powered by fossil fuels, in short, created the modern age.

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3.2.3. Human Well-being

Access to energy is closely associated with key measures of global human development including per-capita GDP, consumption expenditure, urbanization rate, life expectancy at birth, and the adult literacy rate.

The prosperity made possible by the use of fossil fuels enabled societies to invest in education, health care, housing, and other essential goods and services that lead to major improvements in human well-being. According to Moore and Harnett White (2016), "The story of human advancement is the story of the discovery of cheap, plentiful, and versatile energy. Fossil fuels are the ignition switch to modern life" (p. xiii). Alternative sources of energy such as wind turbines, hydroelectric dams, and biofuels were replaced by fossil fuels with superior properties. "It wasn't until man harnessed fossil fuels – predominantly oil, gas, and coal – that industrialization achieved unprecedented productivity. ... Energy, in short, is the wellspring of mankind's greatest advances" (*Ibid*., p. xiv). Similarly, Epstein (2014) writes,

> [T]he benefits of cheap, reliable energy to power the machines that civilization runs on are enormous. They are just as fundamental to life as food, clothing, shelter, and medical care – indeed, all of these require cheap, reliable energy. By failing to consider the benefits of fossil fuel energy, the experts didn't anticipate the spectacular benefits that energy brought about in the last thirty years (p. 16).

Tucker (2008) adds, "Coal is the most important fossil fuel in history. The Industrial Revolution would never have occurred without it. In fact, for all intents and purposes, coal *was* the Industrial Revolution. Only a few nations have ever industrialized without shifting most of their energy dependence to coal, as the experience of China and India proves again today" (p. 61).

That access to affordable and reliable energy is the key to human well-being throughout the world can be demonstrated by the close correlations between energy consumption and GDP. Bezdek (2014) plotted global CO_2 emissions data from the U.S. Energy Information Administration and International Energy Agency and global GDP data from the U.S. Bureau of Economic Analysis to produce the graph shown in Figure 3.2.3.1.

Other scholars compare per-capita energy consumption to rank on the United Nations' Human Development Index (HDI) scorecard, a summary composite index measuring on a scale of 0 to 1 a nation's average achievement in three dimensions of human development: health, knowledge, and standard of living. Health is measured by life expectancy at birth; knowledge is measured by a combination of the adult literacy rate and the combined primary, secondary, and tertiary education gross enrollment ratio; and standard of living is measured by GDP per capita (UNDP, 2015). United Nations member states are listed and ranked each year according to these measures.

Kanagawa and Nakata (2008) examined data from 120 countries and found countries with higher per-capita electricity consumption showed higher scores with respect to the HDI. Similarly, statistical analysis by Clemente (2010) found countries using at least 2,000 kWh of electricity per capita a year have a significantly higher HDI than those that use less. Other researchers using different indices arrive at similar conclusions:

- Niu *et al.* (2013) found electricity consumption is closely correlated with five basic human development indicators: per-capita GDP, consumption expenditure, urbanization rate, life expectancy at birth, and the adult literacy rate.

- Manheimer (2012) plotted yearly per-capita energy use versus yearly per-capita GDP in the year 2000 for a number of countries, producing the graph reproduced as Figure 3.2.3.2 below. He observed "the two are very strongly correlated; there are no rich countries that use little energy per capita. Countries high up on the graph have more educated populations who live more pleasant, longer lives, and who live in cleaner environments than countries lower down on the graph."

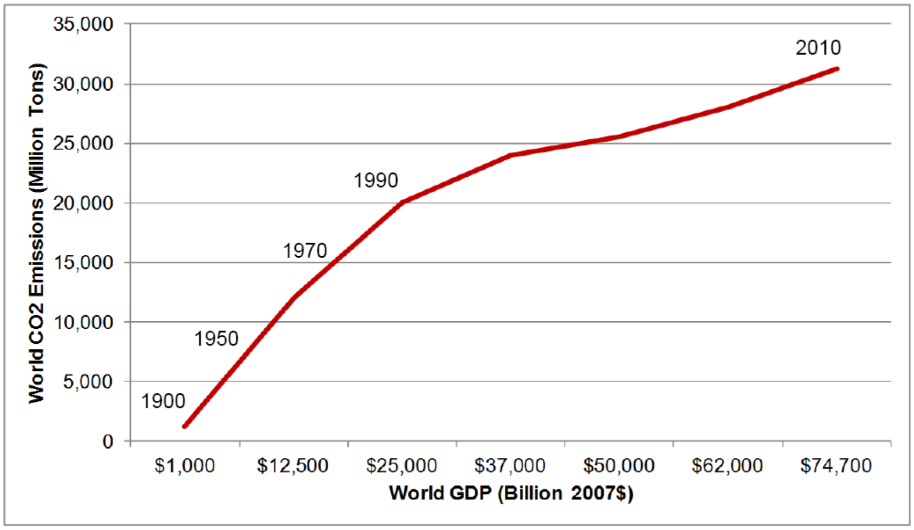
- Mazur (2011) found electricity consumption is essential for improvement and well-being in less-developed countries, especially in populous nations such as China and India.

- Ghali and El-Sakka (2004) report per-capita energy and electricity consumption are highly correlated with economic development and other indicators of modern lifestyle.

Epstein (2014) illustrated the close correlation between global CO_2 emissions produced by the combustion of fossil fuels with rising human life expectancy, per-capita GDP, and global population in the four graphs shown in Figure 3.2.3.3. Numerous scholars have documented the close relationship between the cost of energy (typically electricity but sometimes petroleum and natural gas) and GDP growth in the United States and globally. Their work is reported in Section 3.5.1.

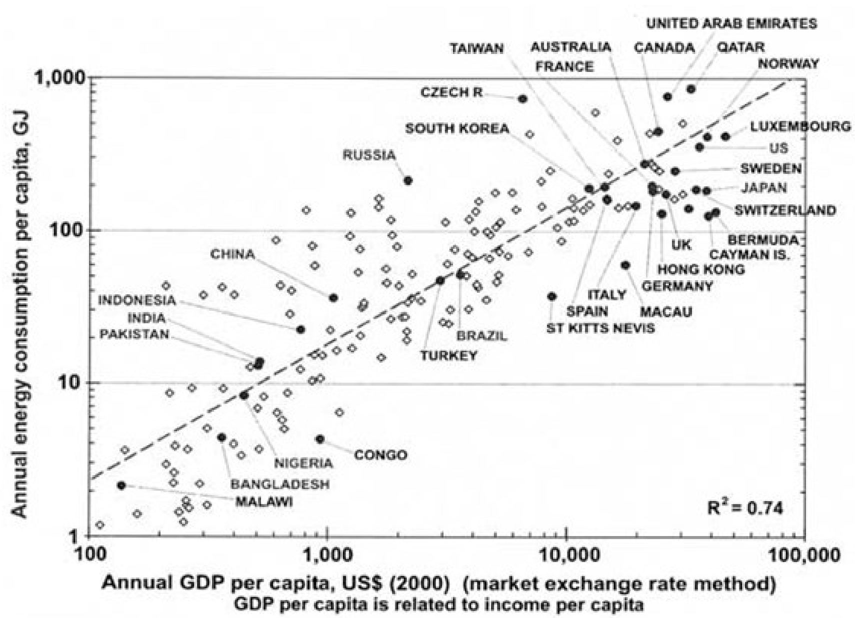
The disparity in access to electricity around the world is staggering. Approximately 3.9 billion people – 12 times the population of the United States and almost half the population of the world – have either no electricity or rely on biomass, coal, or kerosene for cooking (IEA, 2017). The average consumer in Germany, for example, uses 15 times as much power each year as the average citizen of India. In Europe, virtually no household lacks access to electricity. By contrast, in India, more than 400 million people have no electricity, 600 million cook with wood or dung, and more than one billion have no refrigeration (*Ibid.*). The consequences of these differences in electricity access are revealed in a comparison of each country's HDI score. In Germany, a newborn can expect to live until age 79, while in India its life expectancy is 64, 15 years less. In Germany, primary education completion and literacy rates are about 100%; in India, they hover around 70%. In Germany, GDP per capita is $34,401; in India it is $2,753. Consequently, Germany's HDI is 0.947, while India's is just 0.612.

Figure 3.2.3.1
Relationship between world GDP and annual CO_2 emissions



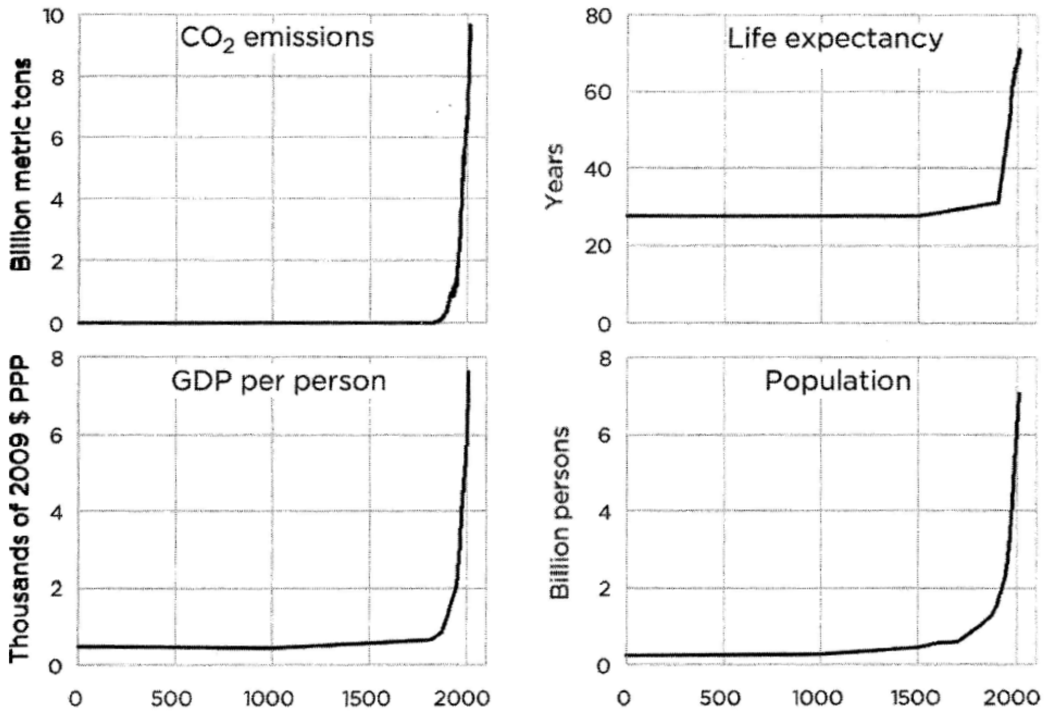
Source: Bezdek, 2014, p. 127, citing data from U.S. Energy Information Administration, International Energy Agency, and U.S. Bureau of Economic Analysis to 2007.

Figure 3.2.3.2
Per-capita GDP and per-capita energy consumption



Source: Manheimer, 2012. Author says "Chart compiled by D. Lightfoot from information available from Energy Information Administration, *International Energy Annual* 2003; see also www.mcgill.ca/gec3/gec3members/lightfoot]."

Figure 3.2.3.3
Fossil fuel use and human progress, 0 AD – 2000 AD



Source: Epstein, 2014, Figure 3.1, p. 77, citing Boden, Marland, and Andres, 2010; Bolt and van Zanden, 2013; and World Bank, World Development Indicators (WDI) Online Data, April 2014.

The connection between prosperity and public health can be illustrated by comparing Ethiopia and the Netherlands. According to ifitweremyhome.com, a website that allows international comparisons on a wide range of characteristics, Ethiopia has about three times as much good farmland per person as the Netherlands. (Good farmland has fertile soils, good weather, and enough rainfall to support substantial crop production.) About the same percentage of each country's land area is covered by forests. But residents of Ethiopia consume, on average, 99.52 percent less electricity and 99.27 percent less oil than those of the Netherlands. The result is dramatic: The average Ethiopian makes 97.7 percent less money than the average Netherlander. If you lived in Ethiopia instead of the Netherlands you would:

- be 10.5 times more likely to have HIV/AIDS;
- have a 17 times higher chance of dying in infancy;
- die 23.75 years sooner; and
- spend 99.25 percent less money on health care.

These numbers reveal an almost unimaginable difference in the quality of life between these two countries. Of course Ethiopia is not the only developing country in the world facing severe challenges. Lomborg (2007) noted, "[I]t is obvious that there are many other and more pressing issues for the third world, such as almost four million people dying [annually] from malnutrition, three million from HIV/AIDS, 2.5 million from indoor and outdoor air pollution, more than two million from lack of micronutrients (iron, zinc, and vitamin A), and almost two million from lack of clean drinking water" (p. 42). The lack of access to affordable energy and the prosperity it makes possible, not climate change, threatens the health of millions of people in developing countries. Lomborg also wrote,

> … local surveys in that country [Tanzania] show the biggest concerns are the lack of capital to buy seeds, fertilizers, and pesticides; pests and animal diseases; costly education; high HIV-infection rates; malaria; and low-quality health services. I believe we have to dare to ask whether we help Tanzanians best by cutting CO_2, which would make no difference to the glaciers, or through HIV policies that would be cheaper, faster, and have much greater effect (*Ibid*., p. 57).

These examples make it clear that the prosperity made possible by fossil fuels was not equally shared by all the peoples of the world. Still, a rising tide lifts all boats. Pinkovskiy and Sala-i-Martin (2009) estimated the income distribution for 191 countries between 1970 and 2006 and found,

> Using the official $1/day line [the United Nations' definition of poverty], we estimate that world poverty rates have fallen by 80% from 0.268 in 1970 to 0.054 in 2006. The corresponding total number of poor has fallen from 403 million in 1970 to 152 million in 2006. Our estimates of the global poverty count in 2006 are much smaller than found by other researchers. We also find similar reductions in poverty if we use other poverty lines. We find that various measures of global inequality have declined substantially and measures of global welfare increased by somewhere between 128% and 145%.

In conclusion, the close correlation between energy consumption and many measures of quality of life show the value of fossil fuels isn't just something to read about in history books. Billions of lives are improved *every day* by having access to safe and affordable energy produced from fossil fuels.

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3.3 Food Production

The United Nations' Intergovernmental Panel on Climate Change (IPCC) projects the net impact of climate change on global agriculture will be negative, although it seems far from confident in its prediction. According to the Working Group II contribution to its Fifth Assessment Report:

> For the major crops (wheat, rice, and maize) in tropical and temperate regions, climate change without adaptation is projected to negatively impact production for local temperature increases of 2°C or more above late-20th-century levels, although individual locations may benefit (*medium confidence*). Projected impacts vary across crops and regions and adaptation scenarios, with about 10% of projections for the period 2030–2049 showing yield gains of more than 10%, and about 10% of projections showing yield losses of more than 25%, compared to the late 20th century. After 2050 the risk of more severe yield impacts increases and depends on the level of warming (IPCC, 2014, pp. 17–18).

There are numerous problems with the IPCC's forecast that make it unreliable. The prediction is for "local temperature increases of 2°C or more above late-20th-century levels," which the IPCC's models do not predict will occur globally until the *end* of the twenty-first century. This means the IPCC's forecast is irrelevant for eight decades or, as is more likely, even longer if its forecasts are wrong, as the climate science reviewed in Chapter 2 suggests. Extensive biological research suggests plants would *benefit* from a warming of less than 2°C, yet the IPCC is silent about that benefit of climate change.

The IPCC assumes no adaptation by the world's farmers, even though adaptation is already taking place as farmers continuously choose crops and hybrids and change such parameters as when to plant, fertilize, and harvest to maximize their output. *This mistake alone invalidates the IPCC's predictions.* No credible expert on global agriculture believes farmers will fail to adjust their practices to accommodate and benefit from climate changes as they occur. The slow pace of climate change predicted by the IPCC's own models suggests such gradual adaptation could be accomplished easily.

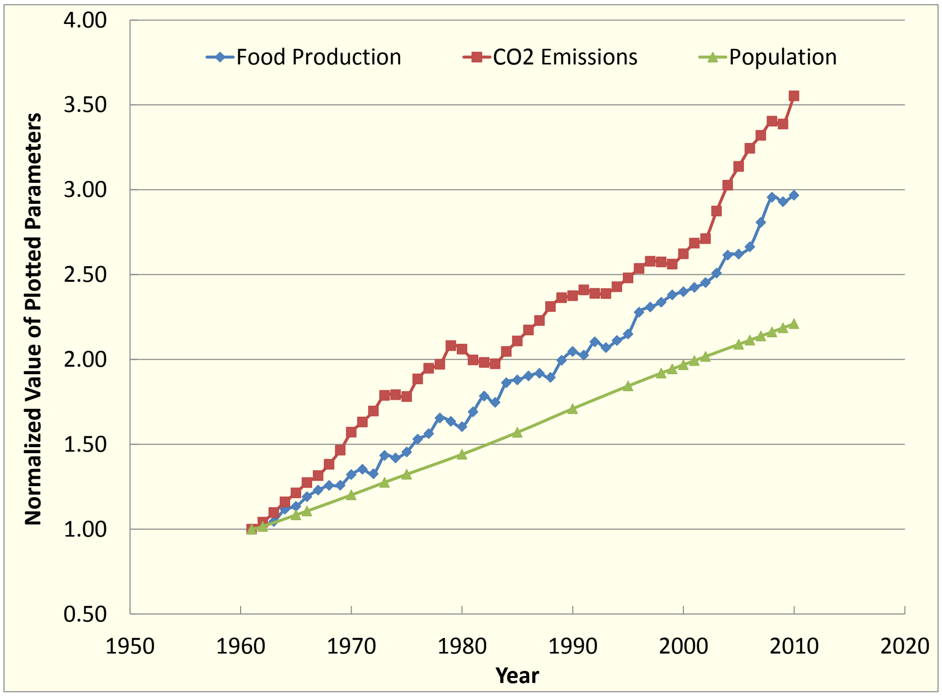
Note as well that the IPCC makes its prediction with only "medium confidence," which presumably means "better than a 50% chance." This is little more than a guess and not a scientific forecast. Finally, the forecast oddly focuses on the tails of the distribution of possible outcomes, where apparently only 10% predict positive effects and 10% predict negative effects. One supposes 80% predict no net impact, but this is not what the IPCC's opening sentence implies or the message the media took from its report.

For all these reasons, the IPCC's forecasts regarding global food production are not credible. *So what is more likely to occur?* We know that fossil fuels revolutionized agriculture, making it possible for an ever-smaller part of the population to raise food sufficient to feed a growing global population without devastating nature or polluting air and water. The aerial fertilization effect of higher levels of atmospheric CO_2 has further increased food production. Contradicting forecasts of global famine and starvation by such popular figures as Paul Ehrlich and John Holdren (Ehrlich, 1971; Ehrlich, Ehrlich and Holdren, 1977), the world's farmers increased their production of food at a faster rate than population growth, as shown in Figure 3.3.1.

Growing global food production is resulting in less hunger and starvation worldwide. In 2015, the Food and Agriculture Organization of the United Nations (FAO) reported "the number of hungry people in the world has dropped to 795 million – 216 million fewer than in 1990–92 – or around one person out of every nine" (FAO, 2015). In developing countries, the share of the population that is undernourished (having insufficient food to live an active and healthy life) fell from 23.3 percent 25 years earlier to 12.9 percent. A majority of the 129 countries monitored by FAO reduced undernourishment by half or more since 1996 (*Ibid*.).

Section 3.3.1 explains how fossil fuels created and today sustain the fertilization and mechanization that made possible the Green Revolution so plainly visible in Figure 3.3.1. Section 3.3.2 explains the phenomenon of aerial fertilization: Rising levels of atmospheric CO_2 promote plant growth, increasing agricultural yields beyond levels farmers would otherwise achieve. Sections 3.3.3 and 3.3.4 calculate the current and future value of aerial fertilization. Section 3.3.5 estimates the value of global food production that would have been lost had the world adopted and actually achieved the goal President Barack Obama set for reducing U.S. greenhouse gas emissions.

Figure 3.3.1
Global population, CO_2 emissions, and food production from 1961 to 2010, normalized to a value of unity at 1961



On the x axis, a "normalized value" of 2 represents a value that is twice the amount reported in 1961. Food production data represent the total production values of the 45 crops that supplied 95% of the total world food production over the period 1961–2011, using sources and a methodology described later in this section. *Source*: Idso, 2013, p. 24, Figure 8.

Extensive documentation regarding the positive effects of fossil fuels, CO_2, and higher surface temperatures on plants and animals appears in Chapter 5. To avoid needless repetition, it is referenced but not presented in this chapter.

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3.3.1 Fertilizer and Mechanization

Fossil fuels have greatly increased farm worker productivity thanks to nitrogen fertilizer created by the Haber-Bosch process and farm machinery built with and fueled by fossil fuels.

Cars and trucks dramatically improved the quantity and quality of food while reducing its cost in several ways: by improving productivity in fields with artificial fertilizer and increasingly specialized vehicles for sowing, cultivating, and reaping; by speeding the delivery of food from fields to processing plants and grocery stores; by inducing more competition among grocers and farmers by greatly expanding the range of businesses competing for a consumer's business; and by allowing food crops to be grown on land that would have been devoted to grazing or raising feed for horses. Historian Harold Platt (1991) wrote,

> The application of massive amounts of energy to every step in the commercial food chain was chiefly responsible for the revolution in what Americans ate. The war brought recent innovations to the manufacture of artificial fertilizers to technological maturity, helped ice makers kill off the natural ice business, turned shoppers toward the new cash-and-carry supermarkets, and made processed foods socially acceptable among the middle classes. During the 1920s, the food industry made intensive use of heat and refrigeration to offer a wider variety of better-tasting canned and baked goods as well as fresh fruits, dairy products, vegetables, and meats year round. "Foods formerly limited to the well-to-do," Hoover's economic experts noted in 1929, "have come more and more within the reach of the masses" (p. 221).

Gasoline-powered tractors similarly transformed agriculture with life-saving consequences. Thanks in large part to productivity gains made possible by tractors and increasingly specialized gasoline-powered vehicles, the percentage of the U.S. working population engaged in agriculture fell from about 80 to 90 percent in 1800 to just 1.5 percent in 2011 (Goklany, 2012, p. 19). Other developed countries witnessed the same trend. Agricultural labor has always been more hazardous than occupations in manufacturing and other industries, hence this migration to other occupations has saved countless lives.

The gasoline-powered tractor was invented in 1892, and farmers swiftly began replacing their horses and mules with the new technology. By the start of the twenty-first century, U.S. farmers were using some five million tractors (McKnight and Meyers, 2007, p. 12, citing Dimitri *et al.*, 2005). Tractors brought their own risks –30,000 people in the United States were killed from the early twentieth century to 1971 by farm tractor overturns – but continued technological innovation is addressing that problem, too. "Roll-over protection structures" on new tractors reduced the annual number of deaths from tractor overturns from about 500 in 1966 to 200 deaths per year by 1985 (*Ibid*.).

One of the greatest achievements in human history was the discovery of a way to make ammonia from natural gas, thereby enabling farmers to add ammonia to their soil and dramatically increase crop yields. Ammonia (NH_3) is a potent organic fuel for most soil bacteria and plants (see Kiefer, 2013, citing Mylona *et al.*, 1995; Matiru and Dakora, 2004; Sanguinetti *et al.,* 2008; and Hayat *et al.,* 2010). Ammonia is added to soil naturally by symbiotic soil and root bacteria, but at a slower rate than plants are able to use.

The discovery was made in 1909 by Fritz Haber and Carl Bosch, and the process is now known as the Haber-Bosch process. Natural gas and atmospheric nitrogen are converted into ammonia using an iron catalyst at high temperature and pressure. In 2014, U.S. farmers applied 19 million tons of man-made ammonia-based fertilizer to their fields (USDA, 2018), helping to make possible the "Green Revolution," an enormous increase in yields around the world beginning in the early 1960s due mainly to the use of cultivars that more responsive to nitrogen fertilizer, chemical pesticides, and irrigation. The Green Revolution brought to an end the conversion of wildlife habitat into cropland (Ausubel *et al.,* 2013). Today, more land is being converted from cropland to forests and prairies than vice versa each year (*Ibid.*). This point is explained and documented in Chapter 5, Section 5.2.

Following the Green Revolution is what some call the "Gene Revolution" (Davies, 2003), the application of biotechnology to food crops resulting in a second wave of yield improvements. This wave, while initiated by breakthroughs in genetic engineering and related fields of research, will rely on energy-intensive technologies to produce the fertilizers, pesticides, irrigation, and dissemination of information needed for new ideas to be widely implemented in fields throughout the world.

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3.3.2 Aerial Fertilization

> *Higher levels of carbon dioxide (CO_2) in the atmosphere act as fertilizer for the world's plants.*

Since CO_2 is the basic "food" of essentially all terrestrial plants, the more of it there is in the atmosphere, the bigger and better they grow. At locations across the planet, the increase in the atmosphere's CO_2 concentration has stimulated vegetative productivity (Zhu *et al.,* 2016; Cheng *et al*., 2017). Long-term studies confirm the findings of shorter-term experiments, demonstrating numerous growth-enhancing, water-conserving, and stress-alleviating effects of elevated atmospheric CO_2 on plants growing in both terrestrial and aquatic ecosystems (Idso and Idso, 1994; Ainsworth and Long, 2005; Bunce, 2005, 2012, 2013, 2014, 2016; Bourgault *et al.,* 2017; Sanz-Sáez *et al*., 2017; Sultana *et al*., 2017). Chapter 5 summarizes extensive research in support of this finding.

Since the start of the Industrial Revolution, it can be calculated on the basis of the work of Mayeux *et al*. (1997) and Idso and Idso (2000) that the 120 ppm increase in atmospheric CO_2 concentration increased agricultural production per unit land area by 70% for C_3 cereals, 28% for C_4 cereals, 33% for fruits and melons, 62% for legumes, 67% for root and tuber crops, and 51% for vegetables. A nominal doubling of the atmosphere's CO_2 concentration will raise the productivity of Earth's herbaceous plants by 30% to 50% (Kimball, 1983; Idso and Idso, 1994), while the productivity of its woody plants will rise by 50% to 80% (Saxe *et al*. 1998; Idso and Kimball, 2001).

Claims that global warming will reduce global food output are frequently made (e.g., Challinor *et al.*, 2014), but these forecasts invariably are based on computer models not validated by real-world data. Crop yields have continued to rise globally despite predictions and claims of higher temperatures, more droughts, etc. As Sylvan Wittwer (1995), the father of agricultural research on this topic, so eloquently put it more than two decades ago:

> The rising level of atmospheric CO_2 could be the one global natural resource that is progressively increasing food production and total biological output, in a world of otherwise diminishing natural resources of land, water, energy, minerals, and fertilizer. It is a means of inadvertently increasing the productivity of farming systems and other

> photosynthetically active ecosystems. The effects know no boundaries and both developing and developed countries are, and will be, sharing equally … [for] the rising level of atmospheric CO_2 is a universally free premium, gaining in magnitude with time, on which we all can reckon for the foreseeable future.

The relationship described by Wittwer is illustrated in Figure 3.3.1, showing anthropogenic CO_2 emissions, food production, and human population all experienced rapid and interlinked growth over the past five decades.

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3.3.3 Economic Value of Aerial Fertilization

> *The aerial fertilization effect of rising levels of atmospheric CO_2 produced global economic benefits of \$3.2 trillion from 1961 to 2011 and currently amount to approximately \$170 billion annually.*

Calculating the economic value of aerial fertilization begins with the United Nations' Food and Agriculture Organization (FAO) database, called FAOSTAT, of historic annual global crop yield and production data and the monetary value associated with that production for more than 160 crops grown and used world-wide since 1961 (FAO, 2013). No data are available prior to that time, so the present analysis is limited to the 50-year time window of 1961–2011.

More than half of the crops in the FAOSTAT database each account for less than 0.1% of the world's total food production. The analysis below focuses only on those crops that account for 95% of global food production. This was accomplished by taking the average 1961–2011 production contribution of the most important crop, adding to that the contribution of the second most important crop, and continuing in like manner until 95% of the world's total food production was reached. The results of this procedure produced the list of 45 crops shown in Figure 3.3.3.1.

Other data needed to estimate the economic value of aerial fertilization are annual global atmospheric CO_2 values since 1961 and plant-specific CO_2 growth response factors. The annual global CO_2 data were obtained from the IPCC report titled *Annex II: Climate System Scenario Tables – Final Draft Underlying Scientific-Technical Assessment* (IPCC, 2013). The plant-specific CO_2 growth response factors – which represent the percent growth enhancement expected for each crop listed in Figure 3.3.3.1 in response to a known rise in atmospheric CO_2 – were acquired from the online Plant Growth Database (PGD) maintained by the Center for the Study of Carbon Dioxide and Global Change at www.co2science.org/ (Idso, 2013b).

Figure 3.3.3.1
The 45 crops that supplied 95% of the global food production from 1961 to 2011

Crop	% of Total Production	Crop	% of Total Production
Sugar cane	20.492	Rye	0.556
Wheat	10.072	Plantains	0.528
Maize	9.971	Yams	0.523
Rice, paddy	9.715	Groundnuts, with shell	0.518
Potatoes	6.154	Rapeseed	0.494
Sugar beet	5.335	Cucumbers and gherkins	0.492
Cassava	3.040	Mangoes, mangosteens, guavas	0.406
Barley	2.989	Sunflower seed	0.398
Vegetables fresh nes	2.901	Eggplants (aubergines)	0.340
Sweet potatoes	2.638	Beans, dry	0.331
Soybeans	2.349	Fruit Fresh Nes	0.321
Tomatoes	1.571	Carrots and turnips	0.320
Grapes	1.260	Other melons (inc.cantaloupes)	0.302
Sorghum	1.255	Chillies and peppers, green	0.274
Bananas	1.052	Tangerines, mandarins, clem.	0.264
Watermelons	0.950	Lettuce and chicory	0.262
Oranges	0.935	Pumpkins, squash and gourds	0.248
Cabbages and other brassicas	0.903	Pears	0.243
Apples	0.886	Olives	0.241
Coconuts	0.843	Pineapples	0.230
Oats	0.810	Fruit, tropical fresh nes	0.230
Onions, dry	0.731	Peas, dry	0.228
Millet	0.593		
Sum of All Crops = 95.2%			

"Nes" is "not elsewhere specified." "Clem." is clementines. *Source*: Idso, 2013a, Table 1, p. 8.

Figure 3.3.3.2
Mean percentage yield increases produced by a 300 ppm increase in atmospheric CO_2 concentration for crops accounting for 95 percent of global food production

Crop	% Biomass Change	Crop	% Biomass Change
Sugar cane	34.0%	Rye	38.0%
Wheat	34.9%	Plantains	44.8%
Maize	24.1%	Yams	47.0%
Rice, paddy	36.1%	Groundnuts, with shell	47.0%
Potatoes	31.3%	Rapeseed	46.9%
Sugar beet	65.7%	Cucumbers and gherkins	44.8%
Cassava	13.8%	Mangoes, mangosteens, guavas	36.0%
Barley	35.4%	Sunflower seed	36.5%
Vegetables fresh nes	41.1%	Eggplants (aubergines)	41.0%
Sweet potatoes	33.7%	Beans, dry	61.7%
Soybeans	45.5%	Fruit Fresh Nes	72.3%
Tomatoes	35.9%	Carrots and turnips	77.8%
Grapes	68.2%	Other melons (inc.cantaloupes)	4.7%
Sorghum	19.9%	Chillies and peppers, green	41.1%
Bananas	44.8%	Tangerines, mandarins, clem.	29.5%
Watermelons	41.5%	Lettuce and chicory	18.5%
Oranges	54.9%	Pumpkins, squash and gourds	41.5%
Cabbages and other brassicas	39.3%	Pears	44.8%
Apples	44.8%	Olives	35.2%
Coconuts	44.8%	Pineapples	5.0%
Oats	34.8%	Fruit, tropical fresh nes	72.3%
Onions, dry	20.0%	Peas, dry	29.2%
Millet	44.3%		

"Nes" is "not elsewhere specified." "Clem." is clementines. *Source*: Idso, 2013a, Table 2, p. 9.

The PGD was used to calculate the mean crop growth response to a 300-ppm increase in atmospheric CO_2 concentration, a simulation often used in experiments, for each crop listed in Figure 3.3.3.1. In cases where no CO_2 enrichment data appeared in the database, the mean responses of similar plants or groups of plants were utilized. Also, there were some instances where the plant category in the FAO database represented more than one plant in the PGD. For example, the designation *Oranges* represents a single crop category in the FAO database, yet there were two different types of oranges listed in PGD (*Citrus aurantium* and *Citrus reticulata x C. paradisi x C. reticulata*). To produce a single number to represent the CO_2-induced growth response for the *Oranges* category, a weighted average from the growth responses of both orange species listed in the PGD was calculated. This procedure was repeated in other such circumstances. The final results for all crops appear in Figure 3.3.3.2 above.

Figure 3.3.3.2 reveals the significant impact a hypothetical rise of 300 ppm in atmospheric CO_2 concentrations would have on yields of the world's 45 most important crops. The increases range from less than 10% for pineapples and "other melons" to more than 60% for sugar beets, grapes, beans, fruits, and carrots and turnips.

Determining the monetary benefit of atmospheric CO_2 enrichment on historic crop production begins by calculating the *increased annual yield* for each crop due to each year's increase in atmospheric CO_2 concentration above the baseline value of 280 ppm that existed at the beginning of the Industrial Revolution. Illustrating this process for wheat, in 1961 the global yield of wheat from the FAOSTAT database was 10,889 hectograms per hectare (Hg/Ha), the atmospheric CO_2 concentration was

317.4 ppm, representing an increase of 37.4 ppm above the 280 ppm baseline, and the CO_2 growth response factor for wheat as listed in Figure 3.3.3.2 is 34.9% for a 300 ppm increase in CO_2. To determine the impact of the 37.4 ppm rise in atmospheric CO_2 on 1961 wheat yields, the wheat-specific CO_2 growth response factor of 34.9% per 300 ppm CO_2 increase (mathematically written as 34.9%/300 ppm) is multiplied by the 37.4 ppm increase in CO_2 that has occurred since the Industrial Revolution. The resultant value of 4.35% indicates the degree by which the 1961 yield was enhanced above the baseline yield value corresponding to an atmospheric CO_2 concentration of 280 ppm.

The 1961 yield is then divided by this relative increase (1.0435) to determine the baseline yield in Hg/Ha (10,889/1.0435 = 10,435). The resultant baseline yield amount of 10,435 Hg/Ha is subtracted from the 1961 yield total of 10,889 Hg/Ha, revealing that 454 Hg/Ha of the 1961 yield was due to the 37.4 ppm rise in CO_2 since the start of the Industrial Revolution. Similar calculations are then made for each of the remaining years in the 50-year period, as well as for each of the 44 remaining crops accounting for 95% of global food production.

The next step is to determine what percentage of the *total annual yield* of each crop in each year was due to CO_2. This is accomplished by taking the results calculated in the previous step and dividing them by the corresponding total annual yields. For example, using the calculations for wheat from above, the 454 Hg/Ha yield due to CO_2 in 1961 was divided by the total 10,889 Hg/Ha wheat yield for that year, revealing that 4.17% of the total wheat yield in 1961 was due to the historical rise in atmospheric CO_2. Again, such percentage calculations were completed for all crops for each year in the 50-year period 1961–2011.

Knowing the annual percentage influences of CO_2 on all crop yields (production per Ha), the next step is to determine how that influence is manifested in total *crop production value*. This is accomplished by multiplying the CO_2-induced yield percentage increases by the corresponding annual *production* of each crop, and by then multiplying these data by the gross production *value* (in constant 2004–2006 U.S. dollars) of each crop per metric ton, which data were obtained from the FAOSTAT database. The end result of these calculations becomes an estimate of the *annual monetary benefit* of atmospheric CO_2 enrichment (above the baseline of 280 ppm) on crop production since 1961. These findings appear in Figure 3.3.3.3.

As can be seen from Figure 3.3.3.3, the benefit of Earth's rising atmospheric CO_2 concentration on global food production is enormous. Such benefits over the period 1961–2011 amounted to at least $1.8 billion for each of the 45 crops examined; and for nine of the crops the monetary increase due to CO_2 over this period was well over $100 billion. The largest of these benefits is noted for rice, wheat, and grapes, which saw increases of $579 billion, $274 billion, and $270 billion, respectively.

Figure 3.3.3.4 plots the rise in the annual total monetary value of the CO_2 benefit for all 45 crops over the 50-year period from 1961 to 2011. The curve rises because the CO_2 effect each year must be examined relative to the baseline value of 280 ppm. Thus, the CO_2 benefit is getting larger each year as the atmospheric CO_2 level rises. At 410 ppm presently, the CO_2 effect is 40 percent greater now than it was around the turn of the twentieth century. Whereas the annual value of the CO_2 benefit amounted to approximately $18.5 billion in 1961, by the end of the record it had grown to more than $140 billion annually. Projecting the line forward to 2015 (not shown in the figure) puts the annual benefit at approximately $170 billion. Summing these annual benefits across the 50-year time period of 1961–2011, as is done in Figure 3.3.3.3, shows the cumulative CO_2-induced benefit on global food production since 1961 is $3.2 trillion.

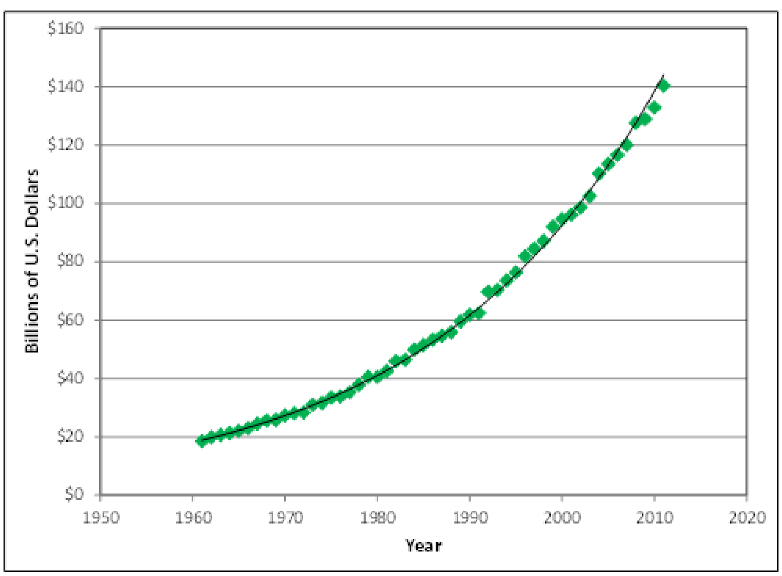
In conclusion, aerial fertilization by higher levels of CO_2 increased the monetary value of crop production by approximately $170 billion in 2015 and the benefit is rising every year. The cumulative economic value of aerial fertilization since 1961 is more than $3.2 trillion. This is a major benefit to human prosperity and well-being due to the use of fossil fuels.

Figure 3.3.3.3
Annual average monetary value of CO_2 aerial fertilization on global crop production from 1961–2011 (in constant 2004–2006 U.S. dollars)

Crop	Production Rank	Monetary Benefit of CO_2	Crop	Production Rank	Monetary Benefit of CO_2
Rice, paddy	4	$579,013,089,273	Carrots and turnips	35	$36,439,812,318
Wheat	2	$274,751,908,146	Cucumbers and gherkins	29	$33,698,222,461
Grapes	13	$270,993,488,618	Watermelons	16	$32,553,055,795
Maize	3	$182,372,524,324	Pears	41	$31,577,067,767
Soybeans	11	$148,757,417,756	Fruit Fresh Nes	34	$29,182,817,600
Potatoes	5	$147,862,516,739	Fruit, tropical fresh nes	44	$28,837,991,342
Vegetables fresh nes	9	$143,295,147,644	Millet	23	$24,748,422,190
Tomatoes	12	$140,893,704,588	Eggplants (aubergines)	32	$22,794,746,004
Sugar cane	1	$107,420,713,630	Cassava	7	$21,850,017,436
Apples	19	$98,329,393,797	Onions, dry	22	$20,793,394,925
Sugar beet	6	$69,247,223,819	Sorghum	14	$20,579,850,257
Barley	8	$63,046,887,462	Tangerines, mandarins, clem.	38	$18,822,174,419
Bananas	15	$58,264,644,460	Coconuts	20	$17,949,253,896
Yams	26	$56,163,446,226	Sunflower seed	31	$17,585,395,685
Groundnuts, with shell	27	$51,076,843,461	Plantains	25	$17,384,141,669
Olives	42	$50,604,186,875	Lettuce and chicory	39	$15,029,691,577
Oranges	17	$50,173,178,154	Pumpkins, squash and gourds	40	$13,140,422,653
Beans, dry	33	$47,240,266,167	Oats	21	$12,615,396,815
Mangoes, mangosteens, guavas	30	$40,731,776,757	Rye	24	$8,981,587,998
Sweet potatoes	10	$39,889,080,598	Peas, dry	45	$5,667,935,087
Chillies and peppers, green	37	$39,813,008,532	Other melons (inc.cantaloupes)	36	$2,477,799,109
Rapeseed	28	$38,121,172,234	Pineapples	43	$1,779,091,848
Cabbages and other brassicas	18	$37,501,047,431	**Sum of all crops = $3,170,050,955,544**		

"Nes" is "not elsewhere specified." "Clem." is clementines. *Source:* Adapted from Idso, 2013a, Table 3, p. 11.

Figure 3.3.3.4
Annual monetary value of CO_2 aerial fertilization on global crop production for 45 crops from 1961 to 2011



Source: Idso, 2013a, Figure 1, p. 12.

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3.3.4 Future Value of Aerial Fertilization

Over the period 2012 through 2050, the cumulative global economic benefit of aerial fertilization will be approximately \$9.8 trillion.

Future monetary benefits of rising atmospheric CO_2 concentrations on crop production also can be estimated. The methodology for doing so is slightly different from that used in calculating the historic values. In explaining these methods, sugar cane will serve as the example.

First, the 1961–2011 historic yield data for sugar cane are plotted as the blue line in Figure 3.3.4.1. The portion of each year's annual yield due to rising atmospheric CO_2, as per calculations described in Section 3.3.3, are presented as the green line. The annual yield due to rising CO_2 is subtracted from total annual yield to generate the red line, which is the contribution of everything else that tended to influence crop yield over that time period. Although many factors play a role in determining the magnitude of this latter effect, it is referred to here as the *techno-intel effect*, as it derives primarily from continuing advancements in agricultural technology and scientific research that expands our knowledge or intelligence base. For the most part, these advances were part of the three Industrial Revolutions discussed in Section 3.2.

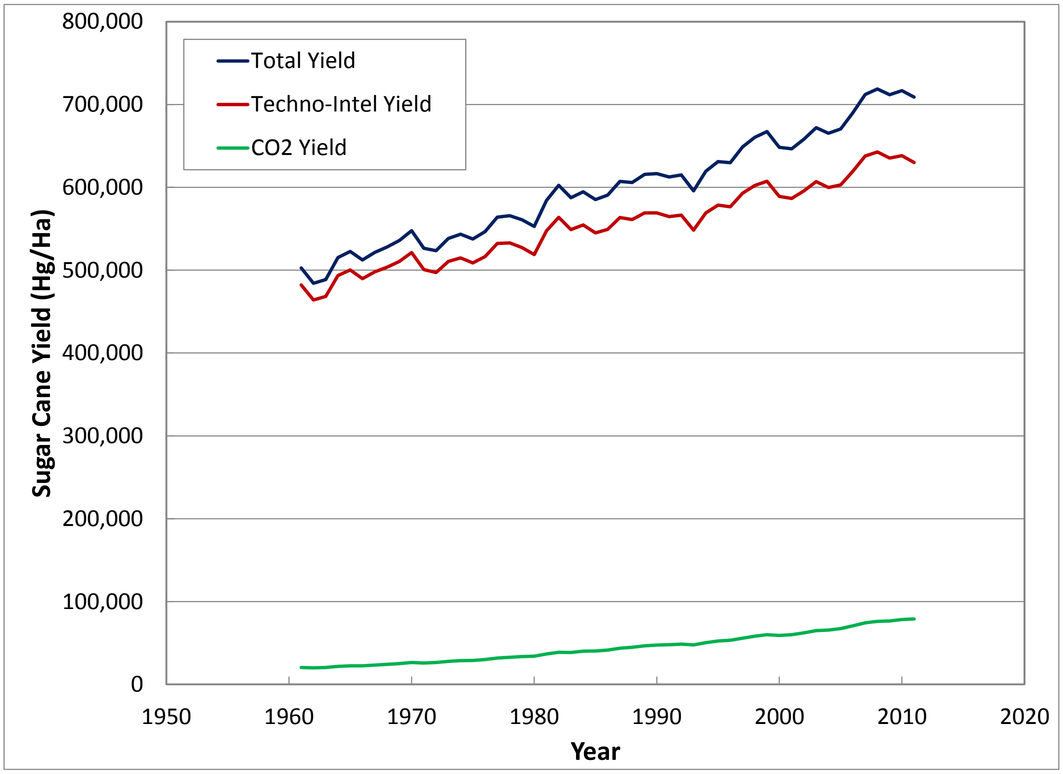
As depicted in Figure 3.3.4.1, the relative influence of atmospheric CO_2 on the total yield of sugar cane is increasing with time. This fact is further borne out in Figure 3.3.4.2, where techno-intel yield values are plotted as a percentage of total sugar cane yield. Whereas the influence of technology and intelligence accounted for approximately 96% of the observed yield values in the early 1960s, by the end of the record in 2011 it accounted for only 89%.

The three trends revealed in Figure 3.3.4.1 can be projected forward to the year 2050 using a second-order polynomial fitted to the data. The results are depicted in Figure 3.3.4.3. By knowing the annual total yield, as well as the portion of the annual total yield that is due to the techno-intel effect between 2012 and 2050, the part of the total yield that is due to CO_2 can be calculated by subtracting the difference between them. These values appear in the figure as the dashed green line.

Linear trends for each crop's 1961–2011 production data were next extended forward in time to provide projections of annual production values through 2050. As with the historic calculations discussed in the previous section, these production values were multiplied by the corresponding annual percentage influence of CO_2 on 2012–2050 projected crop yields. The resultant values were then multiplied by an estimated gross production value (in constant 2004–2006 U.S. dollars) for each crop per metric ton. As there are several potential unknowns that may influence the future production value assigned to each crop, a simple 50-year average of the observed gross production values was applied over the period 1961–2011. The ensuing monetary values for each of the 45 crops over the period 2012 through 2050 are listed in Figure 3.3.4.4.

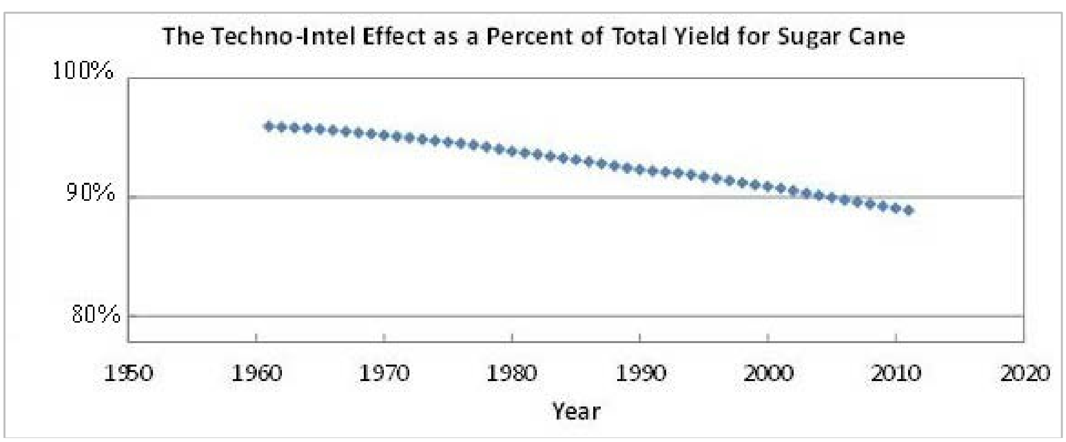
The economic benefit of aerial fertilization by CO_2 can be expressed as an annual benefit per ton of CO_2 emitted by the combustion of fossil fuels. This is accomplished by dividing the annual dollar benefit of CO_2 on global food production by annual global CO_2 emissions. The resultant values are plotted in Figure 3.3.4.5. The social benefit was near \$2 per ton of CO_2 emitted during the 1960s and 1970s. Thereafter, it rose in linear fashion to a value of \$4.14 at the end of the record. Although comparisons of the social benefits and costs of fossil fuels are not discussed in this chapter (they are taken up in Chapter 8), we note our estimate of the annual benefit of aerial fertilization in 2010, \$4.14, is similar to EPA's Interagency Working Group's (IWG) 2010 estimate, \$4.70, of the "social cost of carbon" using a 5% discount rate (IWG, 2010). This is remarkable because

Figure 3.3.4.1
Sources of increasing sugar cane yields from 1961 to 2011



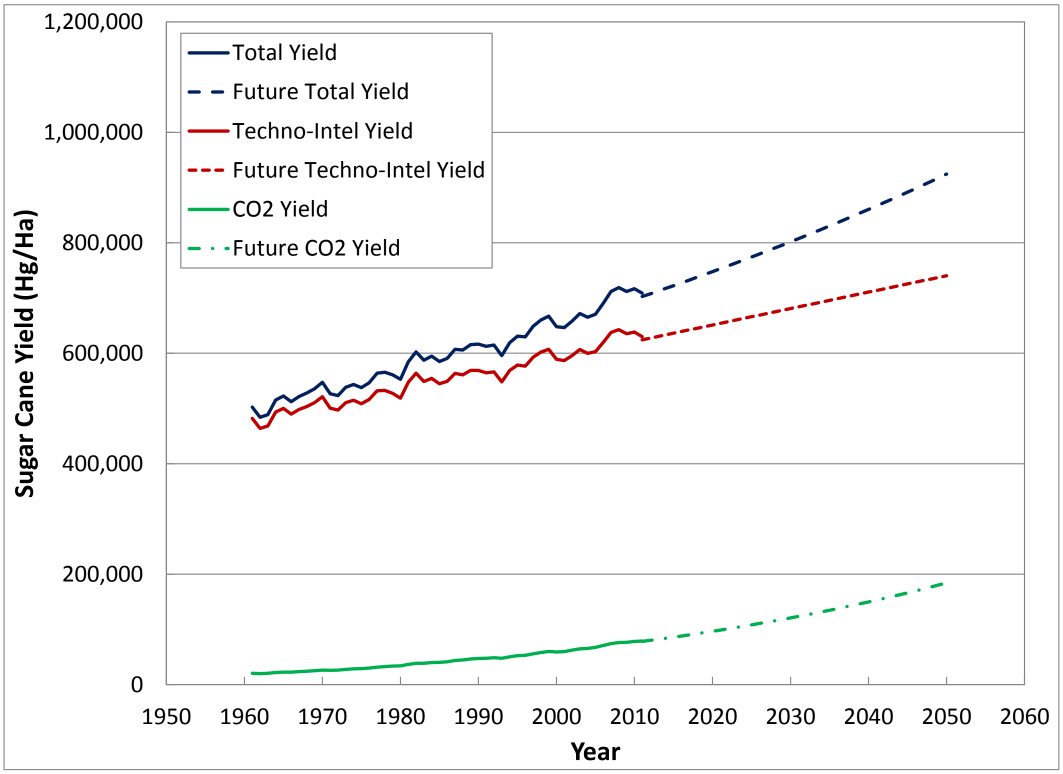
Source: Idso, 2013, Figure 2, p. 13.

Figure 3.3.4.2
Percentage of the total annual yield of sugar cane from 1961 to 2011 attributable to the techno-intel effect



Source: Idso, 2013, Figure 3, p. 14.

Figure 3.3.4.3
Historical and projected increases in total yield and the portion of the total yield due to the techno-intel and CO_2 effects from 2012 to 2050



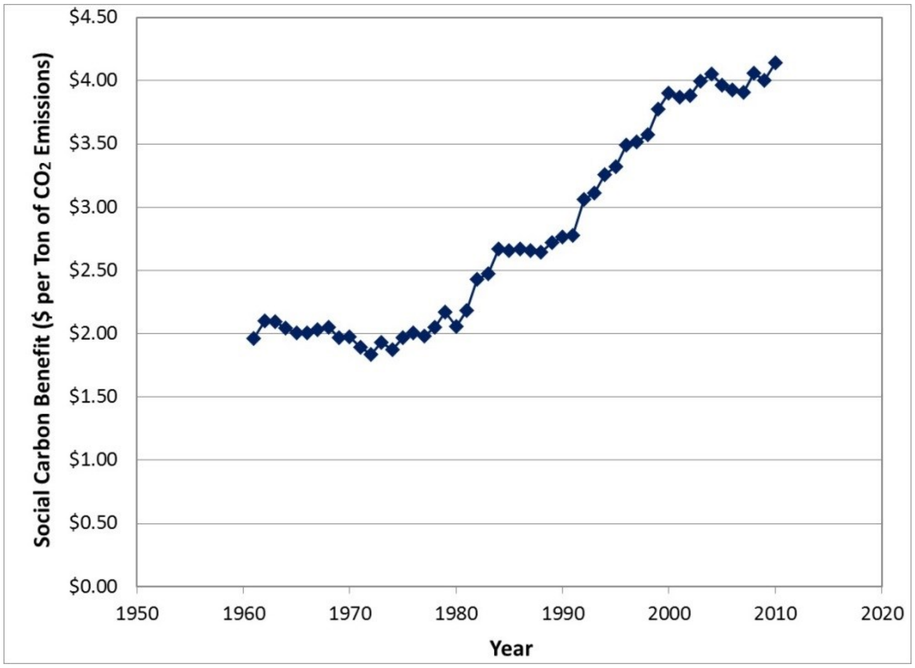
Source: Idso, 2013, Figure 4, p. 13.

Figure 3.3.4.4
Monetary benefit (in 2004–2006 $) of Earth's rising atmospheric CO_2 concentration on 45 crops for the period 2012–2050

Crop	Production Rank	Monetary Benefit of CO_2	Crop	Production Rank	Monetary Benefit of CO_2
Rice, paddy	4	$1,847,162,847,355	Beans, dry	33	$121,672,752,990
Wheat	2	$731,810,134,138	Eggplants (aubergines)	32	$121,040,127,404
Soybeans	11	$622,840,779,401	Sugar beet	6	$118,016,992,389
Vegetables fresh nes	9	$603,158,136,300	Pears	41	$106,648,093,649
Maize	3	$582,352,695,047	Fruit Fresh Nes	34	$96,939,989,779
Tomatoes	12	$538,622,004,026	Tangerines, mandarins, clem.	38	$94,049,613,976
Grapes	13	$507,943,670,190	Fruit, tropical fresh nes	44	$92,676,868,053
Sugar cane	1	$366,333,858,080	Onions, dry	22	$83,094,062,469
Apples	19	$306,866,752,703	Sweet potatoes	10	$70,623,018,596
Potatoes	5	$268,944,859,065	Cassava	7	$66,454,408,155
Yams	26	$206,504,638,016	Pumpkins, squash and gourds	40	$65,141,087,416
Bananas	15	$200,878,216,972	Lettuce and chicory	39	$54,406,821,316
Rapeseed	28	$176,560,583,707	Coconuts	20	$52,278,524,212
Cucumbers and gherkins	29	$165,126,686,871	Sunflower seed	31	$50,554,512,301
Oranges	17	$165,014,960,801	Plantains	25	$45,996,854,219
Chillies and peppers, green	37	$162,527,401,900	Millet	23	$43,337,359,355
Olives	42	$157,323,187,194	Sorghum	14	$38,314,226,074
Groundnuts, with shell	27	$148,440,689,387	Other melons (inc.cantaloupes)	36	$11,163,081,357
Watermelons	16	$144,909,503,686	Peas, dry	45	$10,484,435,272
Barley	8	$127,842,645,165	Pineapples	43	$6,926,670,057
Carrots and turnips	35	$126,282,174,308	Rye	24	$5,804,121,850
Mangoes, mangosteens, guavas	30	$124,067,842,115	Oats	21	$4,904,374,119
Cabbages and other brassicas	18	$122,664,616,192	**Sum of all crops = $9,764,706,877,630**		

Source: Adapted from Idso, 2013, Table 4, p. 17.

Figure 3.3.4.5
Economic benefits of aerial fertilization of CO_2 in $ per ton of CO_2 emissions, 1961 to 2010



Source: Calculations from data in Idso, 2013.

it means the economic benefits of aerial fertilization *alone* will offset nearly all the projected social costs forecast by IWG

Figure 3.3.4.4 reveals a tremendous future economic benefit of Earth's rising atmospheric CO_2 concentration. Over the period 2012 through 2050, the cumulative benefit is $9.8 trillion, much larger than the $3.2 trillion that was observed in the longer 50-year historic period of 1961–2011.

By incorporating the additional CO_2-induced productivity benefits realized by the timber industry, along with those experienced outside the human timber and agricultural industries – i.e., the rest of the plants existing and sustaining wild nature – it is likely that this CO_2-induced productivity benefit is sufficient to completely overpower all the hypothetical human welfare damages forecast by the IPCC.

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3.3.5 Proposals to Reduce CO_2 Emissions

> *Reducing global CO_2 emissions by 28% from 2005 levels, the reduction President Barack Obama proposed in 2015 for the United States, would reduce aerial fertilization benefits by $78 billion annually.*

In 2015, the Obama administration proposed reducing CO_2 emissions by 28% below 2005 levels (Showstack, 2015). While that proposal would have applied only to the United States, other countries are contemplating similar or larger emission reductions. *What effect would a global 28% reduction of CO_2*

emissions have on the aerial fertilization benefits discussed above?

Globally, 29.7 billion tons of CO_2 were emitted in 2005. A 28% reduction would drop annual emissions to 21.4 billion tons, a value last seen more than 30 years ago, in 1987. As shown in Figure 3.3.4.5, the social benefit of CO_2 from increased agricultural productivity amounted to $2.65 per ton of CO_2 emitted at that time, meaning the world would lose a minimum of $1.49 per ton of CO_2 in benefits ($4.14, the value in 2010, minus $2.65, the value in 1987), or $78 billion annually.

The decline in aerial fertilization by CO_2 caused by mandated emission reductions could cause food shortages in countries that presently have only limited food supplies, causing malnutrition and starvation, and possibly igniting conflict and war. There is no reason to believe advocates of reducing the use of fossil fuels have taken this into consideration.

* * *

The world's rising population and prosperity since the start of widespread use of fossil fuels have led to rising CO_2 emissions and likely contribute to rising CO_2 concentrations in the atmosphere. This development has benefited food production, creating an economic value calculated here of $3.2 trillion from 1961 to 2011, annual benefits as of 2015 of approximately $170 billion, and cumulative anticipated benefits worth $9.8 trillion over the period 2012 through 2050.

The economic benefits of aerial fertilization alone will offset nearly all the social costs forecast by climate change activists, even granting their highly dubious assumptions and methodologies. Reducing global CO_2 emissions by 28% from 2005 levels, the target President Barack Obama proposed for the United States in 2015, would reduce aerial fertilization benefits by $78 billion annually.

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3.4 Why Fossil Fuels?

> *Fossil fuels – coal, oil, and natural gas – replaced alternative energy sources because they have a higher power density than any substitute except nuclear power and are in abundant supply, flexible, and inexpensive.*

Fossil fuels have four qualities that made them uniquely suited to fuel the three industrial revolutions that created modernity: they are (1) able to deliver more power per unit of space (energy density) than any competing fuel except nuclear power, (2) available in sufficient supply to meet human needs, (3) flexible enough to support dispatchable power generation in a wide range of circumstances, and (4) so inexpensive that they make electricity and transportation affordable for even low-income households. These qualities enabled fossil fuels to displace other resources that were less dense, in shorter supply, less flexible, and more expensive. These qualities also explain why fossil fuels continue to dominate the global energy supply today.

3.4.1 Power Density

> *Fossil fuels have higher power density than all alternative energy sources except nuclear power.*

Power density was defined in Section 3.1 as energy flow per unit of time, which can be measured in joules per second (watts) divided by a unit of space, as in watts per square meter or W/m^2. When energy sources are ranked by their relative power density, as shown in Figure 3.4.1.1, it quickly becomes clear that fossil fuels dominate all fuels except nuclear power. A natural gas well, for example, is nearly 50 times more power-dense than a wind turbine, more than 100 times as dense as a biomass-fueled power plant, and 1,000 times as dense as corn ethanol. Coal (not shown in the figure) has an energy density 50% to 75% that of oil, still far superior to solar, wind, and biofuels (Layton, 2008; Smil, 2010).

According to Smil (2016), "fossil fuels are enormously concentrated transformations of biomass, and hence the power densities associated with their extraction are unrivaled by any other form of terrestrial energy" (p. 97). Smil also notes, "Obviously, the higher the density of an energy resource, the lower are its transportation (as well as

Figure 3.4.1.1
Relative power density

W/m^2	Energy Sources
56	nuclear
53	natural gas well
28	gas stripper well
27	oil stripper well (10 barrels/day)
6.7	solar PV
5.5	oil stripper well (2 barrels/day)
1.2	wind turbine
0.4	biomass-fueled power plant
0.05	corn ethanol

Source: Bryce, 2010, p. 93. See sources in original.

storage) costs, and this means that its production can take place farther away from the centers of demand. Crude oil has, at ambient pressure and temperature, the highest energy density of all fossil fuels (42 Gj/t), and hence it is a truly global resource, with production ranging from the Arctic coasts to equatorial forests and hot deserts" (*Ibid.,* p. 12).

High power density explains why a basket of coal light enough for a single person to carry can heat a home for an entire day and night even in the cold of winter, and why the lights did not go out in New England states in the United States during the exceptionally frigid winter of 2013–2014. It explains how a car can travel more than 300 miles on a 13-gallon tank of gasoline, and how a pipe less than one inch in diameter can provide enough natural gas to meet the cooking, heating, and hot water needs of even large homes. High power density explains why jet airplanes powered by kerosene can make non-stop ocean-crossing trips and how ships can make similarly long trips without having to stop at ports. High power density means fossil fuels can be conveniently stockpiled near where they will be used, making them less vulnerable to supply interruptions (National Coal Council, 2014; U.S. Department of Energy, 2017). All of these features produce huge economic benefits.

The uranium used in nuclear reactors has an energy density even higher than fossil fuels (80,620 GJ/kg), but the facilities needed to harness that power reduce its power density to closer to that of fossil fuels, as shown in Figure 3.4.1.1. Unjustified public concern over the safety of nuclear power, fueled by environmental advocacy groups and yellow journalism, has slowed or stopped the expansion of nuclear power in the United States and in most other parts of the world, though not in China (Hibbs, 2018).

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3.4.2 Sufficient Supply

> *Fossil fuels are the only sources of fuel available in sufficient quantities to meet the needs of modern civilization.*

Bithas and Kalimeris (2016) write,

> The milestone that determined the transition from the organic economy to the fossil fuel economy, the invention that characterized the era called "The Industrial Revolution," was the steam engine. The unique process that the steam engine initiated was the conversion of chemical energy (heat) into mechanical energy (motion) (McNeill, 2000). The biomass energy stocks accumulated in the

earth's crust for hundreds of millions of years were now available to serve human needs for the first time in mankind's history, to such an extent that the dawn of the fossil fuel era was about to begin (p. 7).

Three figures appearing earlier in this chapter, Figures 3.1.4.1, 3.1.4.3, and 3.2.1.1, illustrated how fossil fuels were able to produce the enormous amounts of energy required globally and in the United States since the beginning of the industrial age. According to the U.S. Energy Information Administration (EIA, 2018), fossil fuels supplied 78% of total U.S. primary energy in 2017 and according to the International Energy Agency (IEA, n.d.) they supplied 81% of global energy use in 2016.

Fossil fuels quickly supplanted wood as the preeminent form of energy, rescuing millions of acres of forests from logging. Fossil fuels supply, as wood never could, the vast amount of energy needed by businesses using new labor-saving technologies and urban centers needing fuels for home and business heating, cooling, and lighting. Without ample supplies of coal, electrification of many processes from manufacturing to home heating, cooking, and laundry would not have taken place. Wood, wind turbines, and biofuels (and more recently solar PV panels) could not and still cannot provide more than a small fraction of total energy needs.

The demand for energy is expected to grow dramatically in the years ahead. According to the International Energy Agency (IEA, 2017), even in its "New Policies Scenario" which assumes subsidies and tax policies that discriminate against fossil fuels and raise the price of energy, global energy needs still expand by 30% between today and 2040. "This is the equivalent of adding another China and India to today's global demand," the authors write. "A global economy growing at an average rate of 3.4% per year, a population that expands from 7.4 billion today to more than 9 billion in 2040, and a process of urbanisation that adds a city the size of Shanghai to the world's urban population every four months are key forces that underpin our projections. The largest contribution to demand growth – almost 30% – comes from India, whose share of global energy use rises to 11% by 2040 (still well below its 18% share in the anticipated global population)." Figure 3.4.2.1 illustrates where the biggest increases in energy demand are expected to occur between 2016 and 2040. Note that according to the IEA, energy demand in the United States, Europe, and Japan is projected to decline.

The growing population and per-capita incomes of a prosperous world underscore the importance of having an ample supply of high-quality energy. However, since supplies of fossil fuels are thought to be exhaustible (though there are theories to the contrary, see Gold (1992, 1999) and Colman *et al.* (2017)), some fear the possibility of eventual depletion. Similar fears were raised by economist William Stanley Jevons in an 1865 book ominously titled *The Coal Question; An Inquiry Concerning the Progress of the Nation, and the Probable Exhaustion of Our Coal Mines*. During the 1970s, environmental advocacy groups such as the Sierra Club and Club of Rome and even national governments proclaimed fossil fuels would run out or be in short supply by the turn of the century (Holdren, 1971; Meadows *et al.,* 1972; Joint Economic Committee, 1980). Pessimists who have followed Jevons' lead are still prominent (e.g., Gore, 1992, 2007; Klare, 2012), but their predictions have repeatedly been found to be wrong (e.g., Simon, 1999; Bailey, 2015; Pinker, 2018; and many others). Commenting on such predictions, Clayton (2013) wrote,

> The logic appears unimpeachable at first glance. But it's wrong. The prices of raw materials have not traveled the path this story would predict for any traded commodity once inflation is factored in, over long stretches of time. One of the most powerfully counter-intuitive and empirically conclusive findings in economic history is that the real prices of nearly all major resources have actually trended lower over very long periods of time, even if they're produced at higher and higher rates. (Oil, once OPEC got involved, is the glaring exception. But even oil prices since OPEC came about haven't simply climbed higher and higher as global consumption has grown.) Though non-renewable commodity prices can rise steeply over years or even decades when supply and demand conditions warrant, over the centuries they've tended to decline after adjusted for inflation.

According to the U.S. Energy Information Administration, as of December 31, 2014, total world proven recoverable reserves of coal were about 1.2 trillion short tons, enough to last for centuries at projected rates of demand. In the United States alone,

Figure 3.4.2.1
Change in primary energy demand, 2016–2040 (Mtoe)

Source: IEA, 2017.

estimated recoverable reserves of coal totaled 254,896 million short tons, enough to last about 348 years. EIA estimates that as of January 1, 2016, there were an estimated 6,879 trillion cubic feet (Tcf) of total world proven reserves of gross natural gas. The United States had 2,462 Tcf of technically recoverable resources of dry (consumer-grade) natural gas, enough to last about 90 years, with advancing technology (such as the combination of horizontal drilling and hydraulic fracturing) and higher prices likely to make that reserve last for decades or even centuries (EIA, n.d.). In short, if humanity ever stops using fossil fuels it will not be because the supply ran out.

One sign of fossil fuels' continued abundance is its relatively stable price. According to the U.S. Energy Information Administration (EIA, 2018), "U.S. energy expenditures declined for the fifth consecutive year [in 2016], reaching $1.0 trillion in 2016, a 9% decrease in real terms from 2015. Adjusted for inflation, total energy expenditures in 2016 were the lowest since 2003. Expressed as a percent of gross domestic product (GDP), total energy expenditures were 5.6% in 2016, the lowest since at least 1970." In the nearly half-century since Holdren, Meadows, and others warned of an imminent energy crisis, total U.S. energy consumption rose 44% (from 67.8 quadrillion Btu in 1970 to 97.4 in 2016), yet spending on energy as a percentage of GDP did not increase at all. If fossil fuels – responsible for some 78% of U.S. energy supply – were becoming scarce, their prices would be rising relative to other goods and services.

It is not only fossil fuels whose supply is probably inexhaustible. According to Clayton, "Raw materials prices show a secular deterioration relative to manufactured goods over long stretches of time. Since 1871, the *Economist* industrial commodity-price index has sunk to roughly half its value in real terms, seeing average annual compound growth of -0.5% per year over the ensuing 140 years. Even after the boom years of the 2000s – in 2008, for instance, as commodity indexes soared, the *Economist* index never climbed more than halfway above where it stood 163 years earlier, in real terms" (*Ibid.*). As explained in Chapter 1, the prices of scarce goods do not fall over time. Fossil fuels are becoming more, not less, abundant with time.

"The exhaustion of fossil fuels on the global scale is not imminent," wrote McNeill (2000). "Predictions of dearth have proved false since the 1860s. Indeed, quantities of proven reserves of coal, oil, and natural gas tended to grow faster than production in the twentieth century. Current predictions, which will be revised, imply several decades before oil or gas should run out, and several centuries before coal might. We can continue to live off the accumulated geologic capital of the eons for some time to come – if we can manage or accept the pollution caused by fossil fuels."

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3.4.3 Flexibility

Fossil fuels provide energy in the forms needed to make electricity dispatchable (available on demand 24/7) and they can be economically transported to or stored near the places where energy is needed.

Following their high power density and sheer abundance, the third reason fossil fuels have been the fuel of choice since the beginning of the Industrial Revolution is their flexibility. Fossil fuels can be economically transported to or stored near the places where energy is needed and they can power technologies able to generate electricity on demand 24 hours a day, seven days a week. This feature is extremely valuable because modern economies require a constant supply of electricity 24/7, not just when the sun shines and the wind blows (Clack *et al.,* 2017). Electric grids need to be continuously balanced – energy fed into the grid must equal energy leaving the grid – which requires dispatchable (on-demand) energy and spinning reserves (Backhaus and

Chertkov, 2013; Dears, 2015). Today, only fossil fuels and nuclear power can provide dispatchable power in sufficient quantities to keep grids balanced.

Coal, the fossil fuel that takes the solid form, can be safely mined, processed, transported in railcars, and stored in outdoor piles until it needs to be used. Its inexpensive storage capacity makes it the fuel of choice for electricity generation (Stacy and Taylor, 2016). Even natural gas is more vulnerable to supply interruptions than is coal, and both are more reliable than alternatives except for nuclear energy (U.S. Department of Energy, 2017; Bezdek, 2017).

Oil, the liquid fossil fuel, is ideal for autonomous transportation vehicles such as cars, trucks, airplanes, and ships. Smil (2016) was quoted earlier in this chapter saying "crude oil has, at ambient pressure and temperature, the highest energy density of all fossil fuels (42 Gj/t), and hence it is a truly global resource, with production ranging from the Arctic coasts to equatorial forests and hot deserts." Oil's superior properties are apparent when modern forms of transportation are compared to those powered by wind (schooners) and biofuels (horses and horse-drawn carriages). It is also superior to hydrogen, which sometimes is proposed as a substitute for gasoline for transportation uses. Hydrogen gas is highly flammable and will explode at concentrations in air ranging from 4% to 75% by volume in the presence of a flame or a spark. Because hydrogen is so light it must be stored under pressure, introducing more cost, weight, and risk, and this is difficult to do because hydrogen embrittles many metals. A typical automobile gas tank holds 15 gallons of gasoline weighing 90 pounds, while the corresponding hydrogen tank would need to hold 60 gallons and would need to be insulated (McCarthy, 2005).

Natural gas, the fossil fuel in a gaseous state, is ideal for home heating and cooking since it burns so cleanly that it causes little indoor air pollution. Natural gas is typically compressed to about 15 times atmospheric pressure for pipeline distribution over many hundreds of miles, making it instantly available when needed to produce electricity or meet other energy needs. Pipeline pressure is reduced to about 30% over atmospheric pressure at a customer's home, making it safe for use by furnaces, water heaters, and stoves. Pipelines allow natural gas to be economically transported to areas that are far removed from well sites and where on-site storage of coal or oil would be uneconomical. The unique features of natural gas make it superior to coal or oil for specific applications, while offering the high energy density, abundant supply, and "always on" availability that make it superior to other alternatives (Hayden, 2015).

High-pressure natural gas lines, transporting gas over long distances, have much lower loss of energy per unit of energy transported than high-voltage electric lines. A gas line is often buried in the ground, with a narrow safety zone around it, whereas high-voltage power systems require wide clearances in forests and rural areas above ground.

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3.4.4 Inexpensive

Fossil fuels in the United States are so inexpensive that they make home heating, electricity, and transportation affordable for even low-income households.

The most dense, abundant, and flexible energy source in the world would be little used if it came at a price so high that few people could afford to use it. Fossil fuels do not suffer from this hypothetical problem. Coal, oil, and natural gas are often the least expensive sources of energy for many applications. Despite the enormous contribution of energy to industry and quality of life, total energy expenditures in the United States were only 5.6% of GDP in 2016 (EIA, 2018). The U.S. average energy price was $15.92 per million British thermal units (MBtu) in 2016. Expenditures on electricity accounted for 74% of residential expenditures, 80% of commercial expenditures, and 37% of industrial expenditures. (*Ibid*.).

Electricity for home and industrial uses in the United States, where fossil fuels produce 78% of electricity, is less expensive than in many other parts of the world, where taxes, regulations, and forced reliance on alternative energies have artificially inflated its price. According to the National Coal Council (2014), "in 2013 the average price of residential and industrial electricity in the U.S. was one-half to one-third the price of electricity in Germany, Denmark, Italy, Spain, the UK, and France" (p. 1 referencing Table B-1).

Except in areas near hydroelectric dams and in some cases nuclear power facilities, electricity generated by fossil fuels is almost always less expensive than alternatives. Since this is a contentious issue, it is discussed in detail in Section 3.5.4. Here we can focus on why fossil fuels are able to generate electricity so much less expensively than alternatives (except nuclear power).

The efficiencies of converting natural resources to energy and then using that energy differ dramatically from place to place and depend on many variables. Using hydroelectric power to generate electricity in the Pacific Northwest, for example, is more efficient than using coal or natural gas due to its abundant availability, while coal and natural gas are better choices in the Midwest where hydroelectric power opportunities are more limited. Nevertheless, it is possible to estimate and rank fuels by their average or typical *energy return on investment* (EROI), which is the amount of useful energy a fuel yields divided by how much energy is required to produce it. This calculation reveals the superior efficiency of fossil fuels compared to alternative energies and the reason they are so much more affordable.

Kiefer (2013) conducted a thorough literature review of the EROIs for 12 fuels in the United States. Figure 3.4.4.1 reproduces the graph showing his results, with EROI scores on the vertical axis and the amount of energy each fuel produced in 2010 on the horizontal. According to Kiefer,

> [C]urrent petroleum diesel and gasoline production EROIs are variously estimated between 10:1 and 20:1. A conservative approach least favorable to petroleum is to postulate an 8:1 EROI, which represents the lowest value calculated since 1920. An 8:1 EROI means that one barrel of liquid fuel energy input can support the exploration, drilling, extraction, and refining of enough crude oil to make eight new barrels of liquid fuel energy – which for petroleum happens to come with a bonus of one barrel of chemical feedstock for plastics, lubricants, organic compounds, industrial chemicals, and asphalt (p. 124).

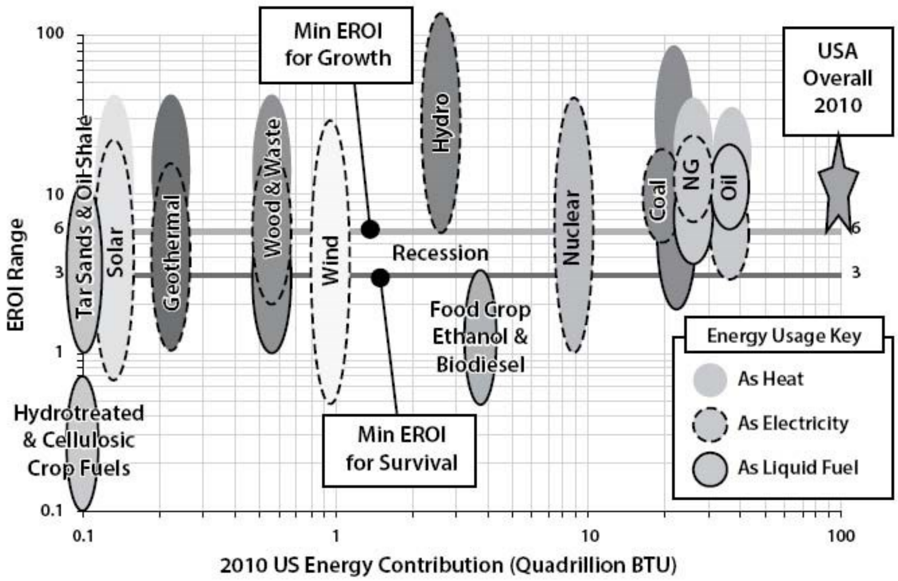
Figure 3.4.4.1 illustrates the high efficiency of coal (for electricity production), natural gas, and petroleum relative to that of any other source of energy save hydroelectric, the supply of which is limited by geography and opposition to the construction of new dams, and nuclear, to which opposition is also fierce. Wind and solar are seen as having highly variable EROIs, extending below 1:1 at their low points (meaning they consume more energy during production than they release when used) and reaching the EROIs achieved by fossil fuels only in their best circumstances. Ethanol and biodiesel fuels barely reach a 3:1 EROI and often are below 1:1. The figure also demonstrates, by their position to the right of all other fuels, how fossil fuels dominate the supply of energy in the United States.

More evidence of the affordability of fossil fuels can be seen in Figure 3.4.4.2, which plots electricity prices in the 50 U.S. states against the percentage of electric power produced with coal in each of those states. Except for a few states where hydropower produces inexpensive energy, the price of electricity is lowest in states where coal is the preeminent source of electric power.

* * *

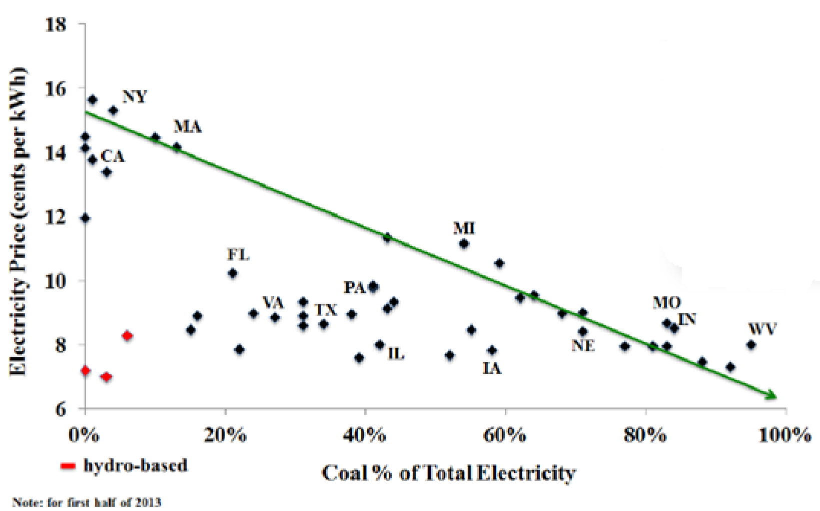
In conclusion, fossil fuels produce 81% of the primary energy consumed globally and 78% in the U.S due to four characteristics: power density, abundant supply, flexibility, and low cost. These are the reasons fossil fuels were indispensable to the creation of Modernity, to the electrification of the world, and to the dramatic improvement in human well-being.

Figure 3.4.4.1
Energy return on investment (EROI) of U.S. energy sources



Min EROI for Growth (6:1) is minimum EROI historically required by the U.S. economy to avoid economic recessions. Min EROI for Survival (3:1) is the minimum quality a raw energy feedstock must have to overcome production costs and conversion losses and still deliver positive net energy to modern civilization. Note the vertical axis is a logarithmic scale, equal differences in order of magnitude are represented by equal distances from the value of 1. *Source:* Kiefer, 2013, p. 120. Sources appear in author's footnotes 21–24 on p. 143.

Figure 3.4.4.2
Relationship between coal generation and retail electricity prices by state



Source: Bezdek, 2014, p. 10, citing U.S. Energy Information Administration, *Electric Power Monthly*, August 2013.

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3.5 Alternatives to Fossil Fuels

Could today's level of global prosperity be sustained without fossil fuels? The United Nations' Intergovernmental Panel on Climate Change (IPCC) claims that avoiding a climate catastrophe requires "substantial cuts in anthropogenic GHG emissions by mid-century through large scale changes in energy systems and potentially land use (*high confidence*)" and "emissions levels near zero $GtCO_2eq$ or below in 2100" (IPCC, 2014, pp. 10, 12). (Emissions can supposedly fall to below zero through the use of "carbon dioxide removal technologies.") The IPCC estimates the cost of reducing emissions to meet these goals would be 1% to 4% (median: 1.7%) of global GDP in 2030, 2% to 6% (median: 3.4%) in 2050, and 3% to 11% (median: 4.8%) in 2100 relative to consumption in baseline scenarios (*Ibid.,* pp. 15–16, text and Table SPM.2).

The IPCC's belief that human greenhouse gas emissions must be reduced to "near zero or below" to avoid a climate catastrophe is simply wrong, as shown by the science reviewed in Chapter 2 and elsewhere in this volume. There is no impending climate crisis that requires such action. Also wrong is the IPCC's claim that the cost of such a draconian reduction in the use of fossil fuels would be only a few percentage points of baseline global GDP. Modern civilization relies on quantities and qualities of energy that only fossil fuels can deliver. Alternative energies such as wind turbines, solar PV cells, and biofuels do not have the features that made fossil fuels the fuel of choice for the past two centuries – high density, abundant supply, flexibility, and low cost. The *apparent* cost of a forced transition would be far more than the IPCC's estimates, and the *opportunity* cost would be greater still.

Reference

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3.5.1 Low Power Density

> *The low power density of alternatives to fossil fuels is a crippling deficiency that prevents them from ever replacing fossil fuels in most applications.*

"The fundamental problem with both wind and biofuels," writes Bryce, "is that they are not dense. Producing significant quantities of energy from either wind or biomass simply requires too much land. The problem is not one of religious belief, it's simple math and basic physics" (Bryce, 2014, p. 212). "The punch line," he writes, is this:

> [E]ven if we ignore wind energy's incurable intermittency, its deleterious impact on wildlife, and how 500-foot-high wind turbines blight the landscape and harm the landowners who live next to them, its paltry power density simply makes it unworkable. Wind-energy projects require too much land and too much airspace. In the effort to turn the low power density of the wind into electricity, wind turbines standing about 150 meters high [492 feet] must sweep huge expanses of air. (A 6-megawatt offshore turbine built by Siemens sports turbine blades with a total diameter of 154 meters [505 feet] that sweep an area of 18,600 square meters [200,209 square feet]. That sweep area is nearly three times the area of a regulation soccer pitch.) By sweeping those enormous expanses of air, wind turbines are

killing large numbers of bats and birds (*Ibid.,* p. 212).

Bryce estimates replacing U.S. coal-fired generation capacity in 2011 (300 gigawatts) with wind turbines at 1 watt per square meter would have required 300 billion square meters, roughly 116,000 square miles (Bryce, 2014, pp. 217–218). Driessen, using a number of conservative assumptions, estimated using windmills to produce the same amount of energy as is currently produced globally by fossil fuels would require 14.4 million onshore turbines requiring some 570 million acres (890,625 square miles), an area equal to 25% of the entire land area of the United States (30% of the lower 48 states) (Driessen, 2017).

A study of the use of biofuels to replace fossil fuels conducted by the UK's Energy Research Centre and published in 2011 found that replacing half of current global primary energy supply with biofuels would require an area ranging from twice to ten times the size of France. Replacing the entire current global energy supply with biofuels would require …

> an area of high yielding agricultural land the size of China. … In addition these estimates assume that an area of grassland and marginal land larger than India (>0.5Gha) is converted to energy crops. The area of land allocated to energy crops could occupy over 10% of the world's land mass, equivalent to the existing global area used to grow arable crops (Slade *et al.,* 2011, p. vii).

Kiefer (2013) wrote, "Biofuel production is a terribly inefficient use of land, and this can best be illustrated with power density, a key metric for comparing energy sources" (p. 131). Biodiesel and ethanol produced from soy and corn have power densities of only 0.069 and 0.315 W/m^2 respectively, "300 times worse than the 90 W/m^2 delivered by the average US petroleum pumpjack well on a two-acre plot of land" (*Ibid.*). Replacing the energy used by the United States each year just for transportation "would require more than 700 million acres of corn. This is 37% of the total area of the continental United States, more than all 565 million acres of forest, and more than triple the current amount of annually harvested cropland. Soy biodiesel would require 3.2 billion acres – one billion more than all US territory including Alaska" (*Ibid.*).

The power density estimates cited above probably underestimate the advantage fossil fuels have over renewable energies by not taking into account the resources needed to build wind turbines or the difficulty of transporting ethanol, which is corrosive and cannot be transported through pipelines. Concerning the former, Bryce (2010) reports,

> [E]ach megawatt of wind power capacity requires about 870 cubic meters of concrete and 460 tons of steel. For comparison, each megawatt of power capacity in a combined-cycle gas turbine power plant … requires about 27 cubic meters of concrete and 3.3 tons of steel. In other words, a typical megawatt of reliable wind power capacity requires about 32 times as much concrete and 139 times as much steel as a typical natural gas-fired power plant (p. 90).

Wind turbines are designed to last approximately 35 years, and there is some evidence they frequently do not last that long (Hughes, 2012). It is unlikely that wind turbines generate enough energy in their lifetimes to recover the enormous amounts of energy used to create their enormous pads and the infrastructure needed to bring their power to businesses and consumers (*Ibid.*). Facts like these prompted even James Hansen, an outspoken global warming activist and former director of the NASA Goddard Institute for Space Studies, to admit in 2011 that "suggesting that renewables will let us phase rapidly off fossil fuels in the U.S., China, India, or the world as a whole is almost the equivalent of believing in the Easter Bunny and Tooth Fairy" (Hansen, 2011, p. 5).

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3.5.2 Limited Supply

Wind, solar, and biofuels cannot be produced and delivered where needed in sufficient quantities to meet current and projected energy needs.

Combined, geothermal, wind, solar, and other non-hydro, non-biofuels contributed only 1.6% of global energy supplies in 2016 (IEA, n.d.). With the best locations for hydroelectric facilities already in use and public opposition to the building of new facilities, proposals to achieve a 100% renewable energy world rely on fantastic increases in energy from wind, solar, and biofuels or equally fantastic reductions in per-capita energy consumption, and more often a combination of the two.

Renewable energy's tiny installed capacity is not due to a lack of public taxpayer support; globally, hundreds of billions of dollars have been spent subsidizing solar and wind power generation. In the United States, many states even have laws mandating the public utilities pay premium prices to purchase power from solar and wind companies. Nor is the limited capacity of renewables a problem that can be solved by pouring more money into research and development, as was demonstrated in Section 3.1 and Figure 3.1.4.5. Rather, it is due to physical limitations inherent to renewable energies:

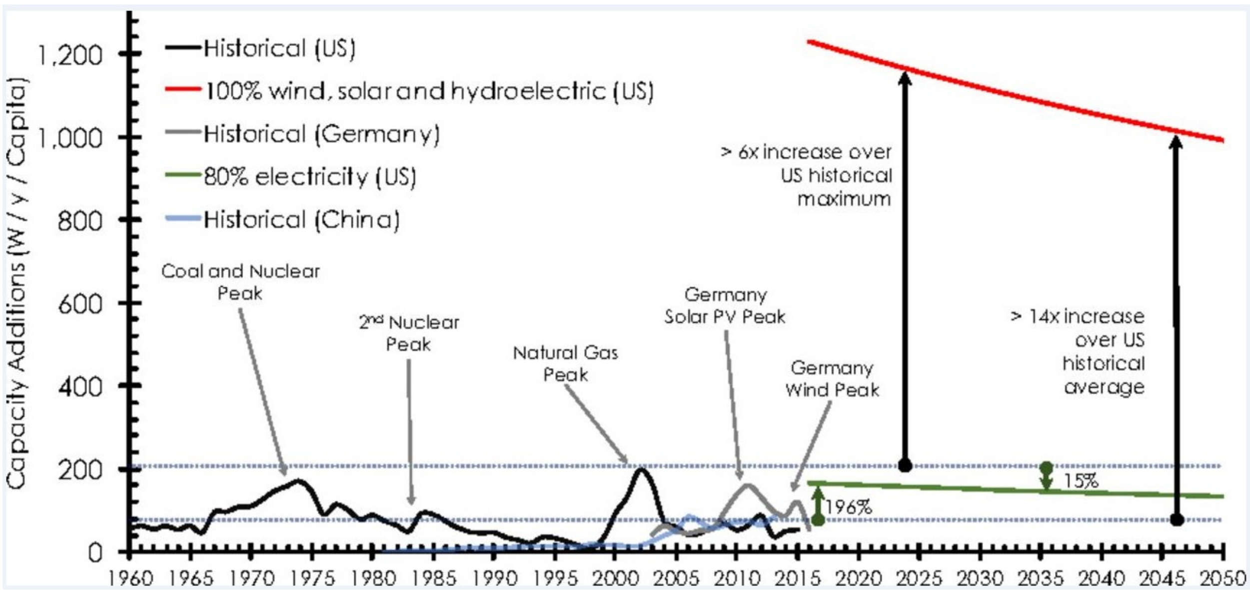
- *Low density:* renewable energy's low energy density would require unacceptably large areas be covered with wind turbines or solar panels, or planted in soy or corn destined to become ethanol, in order to meet even a fraction of total energy demand in the United States or in most other countries. Low density means limited supply because many areas cannot accommodate the massive industrial wind facilities or arrays of solar panels envisioned by their advocates (Bryce, 2010).

- *Intermittency:* wind and solar power are intermittent, making their output of low or even no value to electric grid operators seeking dispatchable energy available 24/7. Wind and solar power require redundant coal or natural gas back-up generation capacity for when the wind does not blow and the sun does not shine, effectively doubling its cost (E.ON Netz, 2005). Ethanol must be trucked to refineries and end users because it corrodes pipelines, and its low BTU content makes it an undesirable transportation fuel. Wind and solar cannot supply power for ships or airplanes or in emergency situations during and after floods, winter storms, or natural disasters.

- *Expensive:* Advocates of solar and wind power have claimed for decades that they are closing the price gap with fossil fuels, yet power from new investment in solar and wind (plus back-up power from natural gas) still costs approximately three times as much as power from existing long-lived coal plants (Stacy and Taylor, 2016). Claims of cost parity invariably hide subsidies and tax breaks, ignore intermittency and the cost of integrating solar and wind into electric grids, and attribute fictional "social costs" to fossil fuels while ignoring the very real social costs imposed by wind turbines on people and on wildlife (Bezdek, 2014).

Clack *et al.* (2017), critiquing a report by Mark Jacobson *et al.* (2015) claiming wind, solar, and hydropower could completely replace fossil fuels, illustrated how unrealistic Jacobson *et al.'s* forecast is with the graphic reproduced as Figure 3.5.2.1 below. The graphic shows how achieving "100% decarbonization" in the United States would require a 14-fold increase in wind, solar, and hydroelectric capacity additions (measured as watts per year per capita) versus the U.S. historical average *every year* from 2015 to 2047 and beyond. That expansion of capacity is not just unprecedented in the United States (as well as German) history, it is *six times* as much as has ever been added in any one year in U.S. history.

Figure 3.5.2.1
Wind, solar, and hydroelectric capacity additions required in United States to achieve 100% decarbonization versus historical trends in United States, Germany, and China



Source: Clack *et al.,* 2017, Figure 4.

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3.5.3 Intermittency

Due to their intermittency, solar and wind power cannot power the revolving turbine generators needed to create dispatchable energy.

Modern economies require a constant supply of electricity 24/7, not just when the sun shines and the wind blows. The grid needs to be continuously balanced – energy fed into the grid must equal energy leaving the grid – which requires dispatchable (on-demand) energy and spinning reserves (Backhaus and Chertkov, 2013). Today, only fossil fuels and nuclear power can provide dispatchable power in sufficient quantities to keep grids balanced. Clack *et al.* observed in 2017,

> Wind and solar are variable energy sources, and some way must be found to address the issue of how to provide energy if their immediate output cannot continuously meet instantaneous demand. The main options are to (*i*) curtail load (i.e., modify or fail to satisfy demand) at times when energy is not available, (*ii*) deploy very large amounts of energy storage, or (*iii*) provide supplemental energy sources that can be dispatched when needed. It is not yet clear how much it is possible to curtail loads, especially over long durations, without incurring large economic costs. There are no electric storage systems available today that can affordably and dependably store the vast amounts of energy needed over weeks to reliably satisfy demand using expanded wind and solar power generation alone. These facts have led many U.S. and global energy system analyses to recognize the importance of a broad portfolio of electricity generation technologies, including sources that can be dispatched when needed (p. 6722).

Section 3.1 explained why wind and solar power are inevitably intermittent and Figures 3.1.5.1, 3.1.5.2, and 3.1.5.3 showed the impact this variability has on energy supplies in southeastern Australia. South Australia, a state in the southern central part of Australia with a population in 2013 of 1.677 million, relies on renewable energy sources for 53% of its electric power generation. In 2016 it experienced a blackout caused by a series of tornadoes that lasted 12 days, and it has since experienced numerous more, albeit shorter, blackouts due to the closure of coal-fired power plants unable to compete with subsidized wind power and the unreliable nature of its industrial wind turbine installations (Orr and Palmer, 2018). South Australia's reliance on renewable energy has also led to dramatically higher energy prices, the highest in the world and some three times higher than in the United States (Potter and Tillett, 2017).

E-ON Netz, a global company that operates industrial wind facilities in Germany, the UK, and elsewhere, reported in 2005 that "Wind energy is only able to replace traditional power stations to a limited extent. Their dependence on the prevailing wind conditions means that wind power has a limited load factor even when technically available. It is not possible to guarantee its use for the continual cover of electricity consumption. Consequently, traditional power stations with capacities equal to 90% of the installed wind power capacity must be permanently online in order to guarantee power supply at all times" (E-ON Netz, 2005). This is a remarkably candid admission of a flaw in wind power which, in the absence of government subsidies and mandates, would render it useless as a supplier of energy for electricity production.

The intermittency of wind and solar means greater reliance on them requires a correspondingly larger investment in back-up generating capacity powered by fossil fuels or nuclear power, or not-yet-invented energy storage systems. Given the vagaries of wind and solar, such a storage system would have to be large enough to store all the energy that will be demanded for many days, possibly weeks, until the wind and solar systems come back online. The technology to safely and economically store such large amounts of electricity does not exist, at least not outside the few areas where large bodies of water and existing dams make pumped-storage hydroelectricity possible. The frequent announcements of "breakthroughs" in battery technology have not resulted in commercial products capable of even a small fraction of the storage needed to transition away from fossil fuels.

To use Australia once again as an example, in November 2017, the world's largest lithium ion battery was installed in South Australia to help avoid blackouts caused by the variability of wind power (BBC, 2017). The battery cost $50 million and, according to its creator, when fully charged can power up to 30,000 homes for one hour. While hailed by some as a milestone in the effort to accommodate the intermittency of wind and solar power, this battery proves just the opposite. While sufficient to smooth out small interruptions in power supply for short periods of time, it is clearly not scalable. To understand why, consider the following:

- One hour of back-up energy is trivial compared to the amount of time wind and solar power are unavailable and during and following storms and natural disasters, when solar and wind power are most likely to be unavailable.

- 30,000 homes is trivial compared to the number of homes affected by blackouts due to south Australia's reliance on renewable energy. The city of Adelaide has a population of 1.3 million living in 515,000 private homes, 17 times more than could be served (for one hour) by the new battery.

- The high cost of Musk's battery relative to the benefit becomes apparent with a little math. The $50 million battery could power just 3.4 homes for one year at a cost of $14.6 million per home per year or $1.2 million per month per home. A battery large enough to power all of Adelaide for just one hour would cost $2.2 billion.

- For roughly the same investment, South Australia (or Adelaide) could buy a state-of-the-art 650 MW Ultra Supercritical coal-powered plant (EIA, 2017, Table 1), which could provide continuous power for the entire city of Adelaide every year for decades to come (650 MW x 750 homes/MW = 487,500 homes, see California ISO Glossary, n.d).

In addition to the storage problem, the variability of wind and solar power creates problems for electrical grid operators that may be unsolvable at high penetration rates. Clack *et al.* (2017) write: "In a system where variable renewable resources make up over 95% of the U.S. energy supply, renewable energy forecast errors would be a significant source of uncertainty in the daily operation of power systems. The LOADMATCH model does not show the technical ability of the proposed system … to operate reliably given the magnitude of the architectural changes to the grid and the degree of uncertainty imposed by renewable resources." Hirth (2013) estimated the integration costs of wind energy to be up to 50% of total generation costs at penetration rates of 30% to 40%. Gowrisankaran *et al.* (2016) estimated the social cost for 20% solar generation is $46.00 per MWh due to intermittency. See also IER (2014) for a discussion of the "energy duck curve," whereby increasing penetration by solar power during the day creates a need to rapidly ramp up power from fossil fuel generation in the evening as workers return to their homes and start using lights and electrical appliances.

A power system relying on wind and solar power for more than 20% to 40% of total power needs begins to experience serious problems with frequency stability, voltage stability and clearing of faults in the power system. For frequency stability a power system must have turbine generators with a very large flywheel effect. If there is insufficient flywheel effect a small disturbance will result in the system frequency increasing or decreasing very rapidly, leading to a system collapse. Wind power has a very small flywheel effect and solar power and batteries have none. Conventional rotating turbine generators make a major contribution to voltage stability because, when needed, they can rapidly import or export what is known as "reactive power" that is essential for system voltage stability. Wind and solar power installations cannot do this to the same extent.

If the conductors in a major transmission line break and fall to the ground it is essential to isolate the faulty section of line rapidly to avoid system collapse. Conventional generators provide the high currents for short periods needed to maintain system voltage and indicate that a fault has occurred and which line needs to be isolated. Wind, solar power and batteries cannot provide the necessary high currents. So if a fault occurs in a system dominated by wind and solar power the chances are that there will be a massive drop of voltage followed by a system collapse.

Restoring the power after a collapse in a system supplied by wind and solar power is almost impossible. Conventional rotating turbine machines are needed to supply the step changes in electricity demand as the system is restored block by block. Wind and solar power cannot do this. For technical reasons turbines at a pumped storage scheme cannot do this either and there is always a risk that the pumped storage lakes will be empty when a system collapse occurs.

Open cycle gas turbines that can respond rapidly to fluctuations caused by changing loads and changing generation from wind and solar are the only practical option. When they are operating in this back-up mode, carbon dioxide emissions are increased compared to operating at a steady high load and, anyway, open cycle gas turbines are substantially less efficient than combined cycle gas turbines. Unfortunately combined cycle gas turbines cannot change output in the time scale needed.

A system that gets more than 50% of its energy from wind and solar and uses gas turbines when wind and solar output is low or absent also incurs huge losses. A system with a demand of 1000 MW would require 4000 – 5000 MW of wind and solar power and at least 800 MW of gas turbines. For quite a large proportion of the time wind and solar would be capable of providing all the energy demanded – but it would be unable to do so because of system stability problems referred to above. When the wind and solar generation was at a maximum, there would be 2000 – 3000 MW of surplus power available that would have to be dumped in one way or another. As a result, the capacity factor of the wind and solar plants would be much reduced, thus further increasing the cost of energy from them.

In short, dispatchable baseload power is physically, conceptually, and economically different from unpredictable bursts of power. The latter has very few practical uses unless accompanied by storage. The low worth of intermittent power has been disguised in NW Europe where shortfalls can be backed up by imports and surplus production is readily exported at good prices. International cost-benefit assessments are heavily influenced by the unique experience of this region, which has the world's greatest penetration of renewables. However, more than 90% of countries do not import or export electricity.

Since renewables cannot replace fossil fuel or nuclear generation stations, *both* renewable generators and traditional generators must be built and maintained. This forces an overcapacity of generation, with approximately half of all capacity being idle much of the time, depressing the wholesale price of electricity. From 1990 to 2014, Europe built 70% more capacity, the majority of it renewables, while demand for electricity increased by only 26%. Wholesale electricity prices paid to generators continue to decline. Today, no new power plant, either renewable or conventional, can be built in Europe without a government subsidy.

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3.5.4 High Cost

> *Electricity from new wind capacity costs approximately 2.7 times as much as electricity from existing coal, 3 times more than natural gas, and 3.7 times more than nuclear power.*

Advocates of rapid decarbonization say the cost of wind and solar power is falling relative to fossil fuels and either has already reached parity or soon will. This has been the claim and the promise since the 1970s, yet electricity generated by wind turbines and solar PV cells is still much more expensive than power from coal, natural gas, and nuclear-powered generators. Claims to the contrary invariably feature methodological errors that ignore or under-estimate real costs while heaping imaginary costs onto fossil fuel generation. Of course, energy costs vary among countries, regions, and states in the United States due to many factors – including local climate conditions, existing infrastructure, population density, and regulations and taxes – so no estimate applies to all areas and circumstances and all estimates are to some degree inaccurate.

Levelized cost of electricity (LCOE)

To accurately compare the cost of producing electricity with each type of fuel requires a methodology that takes into account "capital costs, fuel costs, fixed and variable operations and maintenance (O&M) costs, financing costs, and an assumed utilization rate for each plant type" (EIA, 2018a). The results of such comparisons, called the levelized cost of electricity (LCOE), are estimates of "per-megawatthour cost (in discounted real dollars) of building and operating a generating plant over an assumed financial life and duty cycle" (*Ibid*.). The U.S. Energy Information Administration (EIA) calculates the LCOE for 15 energy sources in the United States, divided into "dispatchable technologies" (generally available regardless of time of day or season) and "non-dispatchable technologies" (generally available only during daytime (solar) or when weather allows wind turbines to operate), for *new* generation resources only. The results of EIA's latest calculations, for facilities entering service in 2022, appear in Figure 3.5.4.1.

According to EIA's projections, the LCOE of new coal generation with 30% carbon capture and storage (CCS) is $130.10/MWh, while the LCOE of new coal with 90% CCS is $119.10/MWh. New natural gas generation is substantially less, ranging from $49.00/MWh for advanced combined-cycle to $98.70/MWh for conventional combustion turbine. Wind and solar energy are categorized as non-dispatchable technologies since their intermittent nature makes them unworkable as a source of baseload power. Off-shore wind at $138.00/MWh and solar thermal at $165.10/MWh, without tax credits, are more expensive than even the most expensive uses of fossil fuels, although tax credits bring the LCOE of both below the LCOE of new coal with 30% CCS, which does not benefit from tax credits. Surprisingly, EIA puts new on-shore wind costs at $59.10/MWh and new solar photovoltaic (PV) costs at $63.20/MWh without subsidies, making them competitive with most fossil fuels. If these figures are accurate, it is difficult to understand why government policies subsidize these facilities at all.

EIA's analysis is valuable, but it is frequently misinterpreted in the climate change debate. The analysis looks only at *future* construction, ignoring the enormous current investment in *existing* long-lived fossil-fuel generation capacity. As Stacy and Taylor (2016) write,

> The approach taken by the federal Energy Information Administration (EIA) … ignores the cost of electricity from all of our existing resources and publishes LCOE calculations for new generation resources only. If no existing generation sources were closed before the end of their economic life, EIA's approach would provide sufficient information to policymakers on the costs of different electricity policies. ... However, in the current context of sweeping environmental regulations on conventional generators – coupled with mandates and subsidies for intermittent resources – policies are indeed forcing existing generation sources to close early. Federal policies alone threaten to shutter 110 gigawatts of coal and nuclear generation capacity (p. 1).

The point is an important one. Coal-powered stations with abundant fuel do not simply disappear at the end of a nominal 50-year life. Their infrastructure, technology, and hardware are continuously replaced and upgraded in much the same way as an electrical grid. They will continue producing for as long as their short-run marginal costs remain competitive with the long-run marginal costs of new generators. Even decommissioned plants are likely to be replaced in situ by new power plants, whose costs will be significantly lower than those of a theoretical "greenfield" site. Climate policy is said to be "urgent" and there is much rhetoric to the effect that the next 30-odd years will be crucial (e.g., Lovins *et al.*, 2011). During that period, the generating capacity of most countries (especially developed countries) will be entirely dominated by existing sites, meaning the EIA's LCOEs will have virtually no application.

A second misinterpretation is assuming EIA's LCOE calculations take into account the intermittency of solar and wind power, and consequently the need for those facilities to maintain additional reserve capacity of dispatchable back-up generation units. As explained in Sections 3.1.4 and 3.5.3, every wind turbine and solar panel needs a fossil fuel-powered generator of nearly equal capacity standing behind it ready to generate power when the wind does not blow or the sun does not shine (Rasmussen, 2010; E.ON Netz, 2005). Joskow (2011) noted:

Figure 3.5.4.1
Estimated levelized cost of electricity (unweighted average) for new generation resources entering service in the United States in 2022 (2017 $/MWh)

Plant type	Capacity factor (%)	Levelized capital cost	Levelized fixed O&M	Levelized variable O&M	Levelized transmission cost	Total system LCOE	Levelized tax credit[1]	Total LCOE including tax credit
Dispatchable technologies								
Coal with 30% CCS[2]	85	84.0	9.5	35.6	1.1	130.1	NA	130.1
Coal with 90% CCS[2]	85	68.5	11.0	38.5	1.1	119.1	NA	119.1
Conventional CC	87	12.6	1.5	34.9	1.1	50.1	NA	50.1
Advanced CC	87	14.4	1.3	32.2	1.1	49.0	NA	49.0
Advanced CC with CCS	87	26.9	4.4	42.5	1.1	74.9	NA	74.9
Conventional CT	30	37.2	6.7	51.6	3.2	98.7	NA	98.7
Advanced CT	30	23.6	2.6	55.7	3.2	85.1	NA	85.1
Advanced nuclear	90	69.4	12.9	9.3	1.0	92.6	NA	92.6
Geothermal	90	30.1	13.2	0.0	1.3	44.6	-3.0	41.6
Biomass	83	39.2	15.4	39.6	1.1	95.3	NA	95.3
Non-dispatchable technologies								
Wind, onshore	41	43.1	13.4	0.0	2.5	59.1	-11.1	48.0
Wind, offshore	45	115.8	19.9	0.0	2.3	138.0	-20.8	117.1
Solar PV[3]	29	51.2	8.7	0.0	3.3	63.2	-13.3	49.9
Solar thermal	25	128.4	32.6	0.0	4.1	165.1	-38.5	126.6
Hydroelectric[4]	64	48.2	9.8	1.8	1.9	61.7	NA	61.7

Notes:

1 The tax credit component is based on targeted federal tax credits such as the PTC [Production Tax Credit] or ITC [Investment Tax Credit] available for some technologies. It reflects tax credits available only for plants entering service in 2022 and the substantial phase out of both the PTC and ITC as scheduled under current law. Technologies not eligible for PTC or ITC are indicated as NA or not available. The results are based on a regional model, and state or local incentives are not included in LCOE calculations.

2 Because Section 111(b) of the Clean Air Act requires conventional coal plants to be built with CCS [carbon capture and storage] to meet specific CO_2 emission standards, two levels of CCS removal are modeled: 30%, which meets the NSPS [New Source Performance Standards], and 90%, which exceeds the NSPS but may be seen as a build option in some scenarios. The coal plant with 30% CCS is assumed to incur a 3 percentage-point increase to its cost of capital to represent the risk associated with higher emissions.

3 Costs are expressed in terms of net AC power available to the grid for the installed capacity.

4 As modeled, hydroelectric is assumed to have seasonal storage so that it can be dispatched within a season, but overall operation is limited by resources available by site and season.

CCS=carbon capture and sequestration. CC=combined-cycle (natural gas). CT=combustion turbine. PV=photovoltaic.

Source: EIA, 2018a, Table 1b, p. 5.

> Economic evaluations of alternative electric generating technologies typically rely on comparisons between their expected "levelized cost" per MWh supplied. I demonstrate that this metric is inappropriate for comparing intermittent generating technologies like wind and solar with dispatchable generating technologies like nuclear, gas combined cycle, and coal. It overvalues intermittent generating technologies compared to dispatchable base load generating technologies. It also likely overvalues wind generating technologies compared to solar generating technologies.

On the one hand, the LCOEs assume a tabula rasa, such as might occur in remote areas of less developed countries, where there are no sunk costs or stranded investments in fossil fuel production. But on the other hand, the LCOEs also assume fossil fuel back-up or spinning reserve exists to supply back-up power at zero cost when needed. The assumptions of the scenario are internally inconsistent. Instead, the capital cost of coal or natural gas back-up power should be added to the LCOE of wind and solar power along with fuel costs when they are called up to provide power. Crucially, back-up power capacity will not be maintained or built because "imposed costs" described later will render it uneconomic if the renewables have dispatch priority.

Another problem encountered when using EIA's LCOE estimates is the transmission costs for electricity from solar and wind do not rise fast enough to reflect the higher integration costs (as high as 50% of total generation costs) at penetration rates of 30% to 40% (Gowrisankaran *et al.,* 2016; Hirth, 2013). A fourth problem is that EIA's LCOEs account for some but not all of the many subsidies, tax breaks, and regulatory protections renewable energies enjoy over fossil fuels. This is described in more detail below. A fifth problem is EIA already adds 3% to the cost of capital for coal-fired power and coal-to-liquids plants, equivalent to an emissions fee of $15 per metric ton of carbon dioxide emissions (EIA, 2018a, p. 3). Unless there is a national $15 per metric ton tax on carbon emissions, such an "adjustment" prejudges the answer to the very question LCOEs are often invoked to answer.

Sixth and finally, LCOE estimates are sensitive to assumptions about realized capacity factors: the average power a facility delivers divided by its rated peak power (also known as "nameplate capacity"). Realized capacity factors vary for individual power plants, for different times of day and times of year, and for different locations (Boccard, 2009; Pomykacz and Olmsted, 2014). EIA (2018b) reported the following average realized capacity factors for power plants across the United States in June 2018:

CC Natural Gas	54.8
Coal	53.5
Wind	36.7
Solar PV	27.0
Solar Thermal	21.8

On average, coal and combined cycle natural gas have realized capacity factors substantially greater than wind and solar. When LCOE estimates are being made, an error of several percentage points in the capacity factor assumptions for coal and CC natural gas facilities would have a small effect in terms of the percentage change of overall capacity and hence energy costs. A similar error in the case of renewable energy, like wind, could mean a considerable increase or decrease in LCOE. For example, an error by 10 percentage points for wind would translate into 30% lower realized capacity factor and 30% higher LCOE, since the main costs of wind are fixed costs, "fuel" costs are zero.

Stacy and Taylor (2016) produced "much-needed cost comparisons between existing resources that face early closure and the new resources favored by current policy to replace them." They used data from documents (known as Form 1) submitted to the Federal Energy Regulatory Commission (FERC) to estimate the LCOE of existing fossil fuel generation. They also added to the LCOE of alternative energies "the amount intermittent resources increase the LCOE for conventional resources by reducing their utilization rates without reducing their fixed costs. We refer to these as 'imposed costs,' and we estimate them to be as high as $25.9 per megawatt-hour of intermittent generation when we model combined cycle natural gas energy displaced by wind, and as high as $40.6 per megawatt-hour of intermittent generation when we model combined cycle and combustion turbine natural gas energy displaced by PV solar" (Stacy and Taylor, 2016, p. 1). Their findings appear in Figure 3.5.4.2.

According to Stacy and Taylor's analysis, *existing* conventional coal generation resources in 2015 had an LCOE of only $39.9/MWh and natural gas of $34.4/MWh, far below the cost of electricity from *new* wind ($107.40/MWh) and *new* solar PV ($140.30/MWh). The results, the authors write,

> show the sharp contrast between the high cost of electricity from new generation resources and the average low cost from the existing fleet. Existing coal-fired power plants, for example, generate reliable electricity at an LCOE-E [LCOE-Existing] of $39.9 per megawatt-hour on average. Compare that to the LCOE of a new coal plant, which is $95.1 per megawatt-hour according to EIA estimates. This analysis also shows that, on average, continuing to operate existing natural gas, nuclear, and hydroelectric resources is far less costly than building and operating new plants to replace them. Existing generating facilities produce electricity at a substantially lower levelized cost than new plants of the same type (p. 1).

Despite the appearance of precision, this calculation produces only an approximation of values that are highly uncertain and are not observed in the real world. The methodology and its use here are complicated by the different year-dollars used by the EIA (2017) and Stacy and Taylor (2013), and while Stacy and Taylor used numbers from EIA's *Annual Energy Outlook 2015,* EIA reduced the cost of wind by 20% and the cost of solar PV by 50% in the latest, 2018, *Outlook.* Such changes reflect the rising benefits of taxes, mandates, and subsidies and their growing adverse effects on fossil fuel capacity factors and operating costs.

The difference between the LCOE of existing and new generation is salient to the current public policy debate because existing coal power plants are long-lived facilities, with useful lives estimated at 50 years and likely to be longer, compared to only 25 years or less for wind and solar installations (Pomykacz and Olmsted, 2014; IER, 2018). Moreover, electricity demand in the United States is essentially flat, with net generation falling 2.5% between 2008 and 2017 (from 4,119,388 thousand MWh to 4,014,804 thousand MWh) (EIA, 2018c). According to Stacy and Taylor, "absent mandates for new generation and the onset of new federal environmental regulations forcing some coal fired generating capacity to retire, almost no new generation capacity would have been necessary" between 2004 and 2014 (Stacy and Taylor, 2016, p. 6). The situation is similar in much of Europe, though not in developing countries. Recall from Section 3.4 that global energy needs are expected to rise by 30% between today and 2040 and total electricity generation will rise even more.

Comparing the LCOE for existing fossil-fuel generation to new wind capacity + imposed costs finds wind costs 2.69 times as much as coal (107.4/39.9), 3.12 times as much as CC gas (107.4/34.4), and 3.69 times as much as nuclear

Figure 3.5.4.2
Levelized cost of electricity (LCOE) of existing and new generation resources, in 2013 $ / MWh

Generator Type	LCOE of EXISTING Generation (at actual 2015 Capacity Factors and Fuel Costs)	LCOE of NEW Generation (at actual 2015 Capacity Factors and Fuel Costs)
Dispatchable Full-Time-Capable Resources		
Conventional Coal	39.9	N/A
Conventional Combined Cycle Gas (CC gas)	34.4	55.3
Nuclear	29.1	90.1
Hydro	35.4	122.2
Dispatchable Peaking Resources		
Conventional Combustion Turbine Gas (CT gas)	88.2	263.0
Intermittent Resources – As Used in Practice		
Wind including cost imposed on CC gas	N/A	107.4 + other costs
PV Solar including cost imposed on CC and CT gas	N/A	140.3 + other costs

Source: Stacy and Taylor, 2016.

power (107.4/29.1). These are sizeable differences indeed, and important since a change of even 10% in the cost of electricity in the United States results in a loss of approximately 1.3% of GDP, about $253 billion in 2017, as reported in Section 3.6.1 below.

Stacy and Taylor conclude, "Electricity from the existing generating fleet is less expensive than from its available new replacements, and existing generators whose construction cost repayment and recovery obligations have been substantially or entirely met are often the least-cost producers in their resource fleet. Cost trends extracted from Form 1 indicate the fleet average cost of electricity from existing resources is on track to remain a lower cost option than new generation resources for at least a decade – and possibly far longer" (p. 35).

Stacy and Taylor's analysis concentrated on the EIA's LCOE estimate, but other estimates are similarly flawed. For example, an LCOE calculated by Lazard, a financial services company with offices in New York City and London, is often cited as providing proof that solar and wind power are achieving or have already achieved parity with fossil fuels, but the following disclaimer appears in bold print on the first page of the latest report:

> Other factors would also have a potentially significant effect on the results contained herein, but have not been examined in the scope of this current analysis. These additional factors, among others, could include: capacity value vs. energy value; stranded costs related to distributed generation or otherwise; network upgrade, transmission or congestion costs or other integration-related costs; significant permitting or other development costs, unless otherwise noted; and costs of complying with various environmental regulations (e.g., carbon emissions offsets, emissions control systems) (Lazard, 2017, p. 1).

On the next page of its report, Lazard admits to not taking into account "reliability or intermittency-related considerations (e.g., transmission and back-up generation costs associated with certain Alternative Energy technologies)" (*Ibid.*, p. 2). It is precisely the stranded costs, integration expenses, and "intermittency-related considerations" that cause wind and solar power to incur some of their largest costs. Any LCOE that fails to take these matters into account is inaccurate and useless for public policy purposes.

Subsidies

Renewable energies sometimes appear to be cost-competitive with fossil fuels due to the extremely wide and complicated web of government policies biased in favor of renewable energy. Consumers may be told they can sign up for "100% renewable energy" without any increase in their monthly utility bill, not realizing that renewable portfolio mandates on utilities force all ratepayers to subsidize their choice by paying higher rates. In the United States, state governments add a layer of subsidies and tax credits to those provided by the national government. Schleede (2010) notes EIA does not account properly for five-year double declining balance accelerated depreciation, state and local tax breaks, state mandates, and more that make wind and solar appear to be less costly than they really are.

The U.S. Energy Information Administration regularly reports on federal subsidies to energy producers and consumers. In its latest report (EIA, 2018d), EIA estimated subsidies to producers totaled $7.5 billion in 2016. Additional subsidies for smart grid and transmission, conservation, and to end users totaled $7.45 billion. Of the subsidies directly to producers, renewables received 89%, coal received 17%, and nuclear received 5%. Natural gas and petroleum liquids producers paid $940 million more than they received via energy-specific tax provisions (expensing of exploration, development, and refining costs), which EIA reports as a *negative net subsidy* to the industry of -$773 million. This huge subsidy imbalance between renewables and other fuels is even more apparent when the subsidies are calculated on a per-unit-of-output basis. According to EIA, hydroelectric power received no federal subsidies in 2016. Remaining renewables generated 7.9 quadrillion Btu of primary energy in 2016 (EIA, 2018e). On a per-Btu basis, the subsidies to renewables were 10 times larger than for coal power and 2 times larger than for coal power. Natural gas and petroleum liquids received no net subsidy, and indeed recorded a *negative* subsidy of -$15 million per quadrillion Btu of energy produced. See Figure 3.5.4.3.

Figure 3.5.4.3
Direct U.S. federal financial interventions and subsidies, 2016

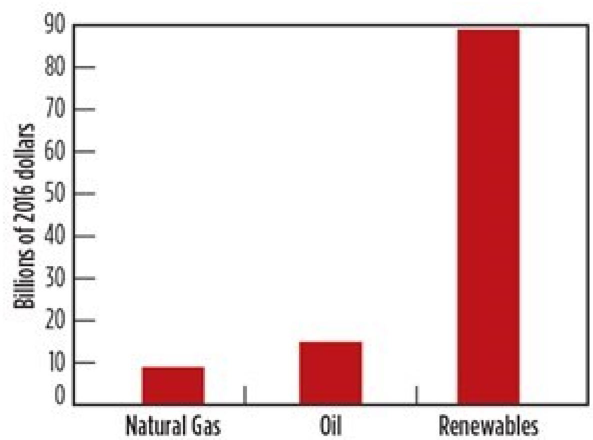
Beneficiary	2016 subsidies and support (millions)	Primary energy production (quadrillion Btu)	% of subsidies	Subsidy per quadrillion Btu (millions)	Subsidy per Btu to non-hydro renewables: other fuels
Non-hydro renewables	$6,682	7.856	88.67%	$850.56	--
Coal	$1,262	14.667	16.75%	$86.04	10:1
Nuclear	$365	8.427	4.84%	$43.31	2:1
Natural gas and petroleum liquids	($773)	50.94	-10.26%	($15.17)	--
Total	$7,536	81.89	100.00%	$92.03	--

Source: EIA, 2018d, Table 2, p. 5 and Table 3, p. 9; EIA, 2018e, Table 1.2, p. 5.

The massive subsidization of renewables relative to fossil fuels in the United States is not new. During the years 2011–2016, renewable energy (solar, wind, biomass, geothermal, and hydro) received $89 billion in federal incentives, nearly four times the federal incentives for oil and natural gas combined (Bezdek, 2017). See Figure 3.5.4.4. Notably, oil and gas supplied more than 61% of U.S. energy needs whereas wind and solar provided less than 3%. Thus, per unit of energy, renewables are massively subsidized compared to oil and gas. In much of the world, renewables are even more heavily favored than fossil fuels than in the United States.

Stiglitz (2018) claims below-cost federal leases are driving prices and giving fossil fuels an advantage. But less than half of U.S. coal production is from federal leases (BLM, 2018a) and less than one-third for both oil and gas production (Humphries, 2016). Oil and gas production from federal lands is declining while U.S. production has increased about 60% since 2008. This would not be the case if federal leases were underpriced. Stiglitz claims leases are sold "at prices far below what the competitive equilibrium price would be," but lease winners bear risks (geological characteristics of reservoir, cost of extraction, and the future retail price for output are all uncertain) so the "competitive equilibrium price" is undefined. Underprices leases would create profitable opportunities for other businesses to bid for them, thus driving up lease prices. Further, winners pay royalties on oil and gas recovered, so lease price is not even the most relevant issue (BLM, 2018b).

Figure 3.5.4.4
U.S. federal tax incentives for oil, natural gas, and renewables, 2011–2016



Source: Bezdek, 2017.

Because oil and natural gas are traded internationally, their prices are set by the world market. The U.S. government and its lessees are bargaining over distribution of rents, not over the price of the product. The United States produces about 15% of world petroleum and 20% of natural gas (EIA, 2018f). This haggling over how rents will be split is highly unlikely to be driving down world prices. Finally, proof that solar and wind are not cost-competitive is seen when investment in new installations virtually stops when subsidies are interrupted. New wind and solar power can compete with fossil fuels only if utilities are required to buy it, often at prices that are two and three times as high as the price of coal and natural gas-generated power.

Other Costs

Stacy and Taylor (2016) found electricity produced by solar and wind generators in the United States cost approximately three times as much as electricity produced with fossil fuels. Their calculation of the LCOE for solar and wind is likely still too low because it does not take into account all the subsidies described above or other costs. Some unaccounted costs are deterioration of wind turbine output over time, negative environmental and neighborhood effects, and opportunity costs.

The performance and capacity factors of wind turbines deteriorate over time. A seminal study analyzed the rate of aging of a national fleet of wind turbines using public data for the actual and theoretical ideal load factors from the UK's 282 industrial wind facilities (Staffell and Green, 2014). It found:

- Load factors declined with age, at a rate similar to that of other rotating machinery.
- Onshore wind installations' output declines 16% a decade.
- Performance declines with age occurred in all wind installations and all generations of turbines.
- Decreasing output over a wind installation's life increased the levelized cost of electricity.

The study determined this degradation rate was consistent for different vintages of turbines and for individual wind installations, from those built in the early 1990s to early 2010s.

The Renewable Energy Foundation, an organization that actually advocates in favor of renewable energy facilities, also conducted a comprehensive study of the available capacity factors over time for wind turbines in the UK and came to similar findings. Using monthly observations for 282 onshore installations in the UK with an age range of zero to 19 years, it found "the normalized load factor for UK onshore wind farms declines from a peak of about 24 percent at age one to 15 percent at age 10 and 11 percent at age 15" (Hughes 2012). In other words, the capacity factors for wind generators decline significantly every year after installation.

Other costs attributable to renewable energy but not counted in the LCOE exercises include e*nvironmental harms* such as killing birds and bats. According to Smallwood (2013), "I estimated 888,000 bat and 573,000 bird fatalities/year (including 83,000 raptor fatalities) at 51,630 megawatt (MW) of installed wind-energy capacity in the United States in 2012." Since wind turbine capacity in the United States has grown since then, it is certain bird and bat kills have increased apace.

According to Hambler (2013), "Because wind farms tend to be built on uplands, where there are good thermals, they kill a disproportionate number of raptors. In Australia, the Tasmanian wedge-tailed eagle is threatened with global extinction by wind farms. In North America, wind farms are killing tens of thousands of raptors including golden eagles and America's national bird, the bald eagle. In Spain, the Egyptian vulture is threatened, as too is the Griffon vulture – 400 of which were killed in one year at Navarra alone. Norwegian wind farms kill over ten white-tailed eagles per year and the population of Smøla has been severely impacted by turbines built against the opposition of ornithologists."

According to Taylor (2015), the Ivanpah solar power plant in the Mojave Desert in California killed 3,500 birds in its first year of operation. According to the Institute for Energy Research (IER, 2015), "The [Ivanpah] facility is estimated to have killed 83 different species of birds. The most commonly killed birds were mourning doves (14 percent of fatalities), followed by yellow-rumped warblers, tree swallows, black-throated sparrows and yellow warblers. Of the birds that died from known causes, about 47 percent died from being toasted by the heat of the solar flux. Just over half of the known deaths were attributed to collisions."

Tang *et al.* (2017) reported that construction of the wind turbines in the area of China they studied elevated both day (by 0.45-0.65°C) and night (by 0.15-0.18°C) temperatures, which increase, they say, "suppressed soil moisture and enhanced water stress in the study area." As a result, they calculated an approximate 14.5%, 14.8%, and 8.9% decrease in leaf area index (LAI), enhanced vegetation index (EVI), and normalized difference vegetation index (NDVI), respectively, over the period of study, as well as "an inhibiting [wind farm] effect of 8.9% on summer gross primary production (GPP) and 4.0% on annual net primary production (NPP).” These several findings led Tang *et al.* to conclude that their research “provides significant observational evidence that wind farms can inhibit the growth and productivity of the underlying vegetation.”

Increased use of biofuels (primarily wood and ethanol) also has negative environmental consequences that often go unreported. Di Fulvio *et al.* (2019) studied the ecological impact of land use changes expected to be made in the European Union to meet its goal of reducing greenhouse gas emissions by 80% by 2050. They estimate such changes would result in the extinction of approximately 1% of the total of all global species by 2050. Models used to predict extinctions are notoriously inaccurate, as explained in Chapter 5, but there is little doubt that the massive expansion of acreage devoted to the production of ethanol and other biofuels would have a negative effect on many species.

Another uncounted cost of renewable energy is *negative neighborhood effects,* such as those caused by wind turbines on crop yields and property values. Linowes (2013) reports on soil compacting, destruction of irrigation piping and crops, and the end of aerial spraying of insecticides in fields near wind turbines. A study by a London School of Economics economist of some two million home sales in England and Wales from 2000 to 2011 found “Wind farms reduce house prices in postcodes where the turbines are visible; and they reduce prices relative to postcodes close to wind farms where the turbines are not visible. Averaging over wind farms of all sizes, prices fall by around 5–6% within 2km, by less than 2% in the range 2–4km and by less than 1% at 14km, which is the limit of likely visibility” (Gibbons, 2014).

There are many accounts of possible negative health effects due to the low-frequency sound and vibrations produced by wind turbines. Frequencies below 200Hz can be generated by thunder, volcano eruptions, earthquakes, or storms, all events that can cause anxiety or fear. It is possible humans are “wired” to respond this way, making nearby wind turbines a nuisance or worse. The Sahlgrenska Academy Institute of Medicine at the University of Gothenburg in Sweden has conducted extensive research on the issue (Sahlgrenska Academy, n.d.).

Opportunity cost

Research papers claiming to show the feasibility of a rapid and inexpensive transition from fossil fuels, such as Jacobson *et al.* (2015) and an earlier paper by Jacobson and a coauthor (Jacobson and Delucchi, 2009), fail to take into account the opportunity cost of abandoning the existing energy generation infrastructure. The sheer size of the global energy market makes replacing that infrastructure massively expensive and time consuming. The electric grids in the United States and around the world represent investments of trillions of dollars and require hundreds of billions of dollars a year in new investment simply to maintain, improve, and keep pace with population and consumption growth. They also generate hundreds of billions of dollars in revenue each year. Replacing them with more advanced grids and long-distance high-voltage power lines that could accommodate disbursed solar and wind energy or hydropower located far from urban centers would cost several times total past investments *in addition to* ongoing investments in modernization and expansion of the existing grid until it can be replaced, and would require decades to plan and implement. Given competing interests, decentralized government decision-making, already high levels of government indebtedness, and strong NIMBY (not in my backyard) opposition to new infrastructure projects around the world, such proposals for a 100% renewable future are no more than academic exercises.

Smil (2010) notes the global oil industry “handles about 30 billion barrels annually or 4 billion tons” and operates about 3,000 large tankers and more than 300,000 miles of pipelines. “Even if an immediate alternative were available, writing off this colossal infrastructure that took more than a century to build would amount to discarding an investment worth well over $5 trillion – and it is quite obvious that its energy output could not be replaced by any alternative in a decade or two” (Smil, 2010, p. 140). Later, Smil writes the cost of a transition “would be easily equal to the total value of U.S. gross domestic product (GDP), or close to a quarter of the global economic product” (*Ibid.,* p. 148).

A second opportunity cost is living without affordable and convenient energy. If renewable energies cannot produce the quantity and quality of energy needed to sustain current and future levels of human prosperity, then the quality of life for millions and potentially billions of people will be diminished. The cost of renewables therefore includes not being able to own or use a car or truck, live in a single-family dwelling, or work more than a short distance from home. It could mean reduced access to fresh and affordable food, clean water and sanitation, quality health care, and educational and recreational opportunities. A shortage of energy, even if prices are government-controlled and access to energy is rationed, would be profoundly costly.

* * *

In summary, the cheapest form of energy in most locations in the developed world is continued production from existing facilities with significant remaining lifespans. Those facilities are predominantly powered by fossil fuels. Energy produced by solar PV cells, wind turbines, and ethanol can contribute to the world's energy mix but they lack power density and sufficient supply, are not dispatchable when needed, and are too costly to meet more than a small fraction of the world's energy needs.

Without fossil fuels, most homes and businesses not located near a nuclear power plant or a river able to produce hydropower would be without electricity. While wind turbines and solar PV cells can generate power in some places and under some circumstances, only fossil fuels can produce enough energy to forge steel, make concrete, power locomotives and ocean-crossing ships and airplanes, and many other components of modern industry. Biofuels, such as ethanol, cannot replace more than a small fraction of petroleum used around the world for transportation. Indeed, without fossil fuels it would be impossible to manufacture wind turbines and solar PV cells, or build the massive concrete foundations for wind turbines or modern hydroelectric dams, or plant and irrigate and harvest corn or soybeans in sufficient quantity to power more than a percent or two of a modern civilization's daily energy consumption. There would also be no high-voltage power lines or towers to transport electricity generated by solar panels or wind turbines, and no batteries (or dams, in the case of hydropower) to store power for when it is needed.

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3.5.5 Future Cost

> *The cost of alternative energies will fall too slowly to close the gap with fossil fuels before hitting physical limits on their capacity.*

The research summarized above showed why alternative energies such as wind and solar cannot completely supplant fossil fuels and why their true cost is extremely high relative to fossil fuels. *How will this change in the future?* Short of a world government imposing its will by decree, will alternative energies *ever* replace fossil fuels?

Levelized cost of electricity (LCOE) exercises assume the rate of price reduction previously experienced for wind and solar electricity generation will continue indefinitely. This is most unlikely as the reductions of the last decade are due chiefly to falling manufacturing costs of turbines and PV panels – as those items graduated from bespoke (tailor-made) development to mass production. They also benefited from large government subsidies, especially in China and Germany, which have proven to be unsustainable (Reed, 2017; Reuters, 2018). Turbines and panels now comprise relatively minor components of the life-cycle costs of installations. The major remaining components (e.g., labor and raw materials) are likely to be much more resistant to progress.

Cost trends for renewable energy are usually summarized in the form of experience curves, a statistical relation between the installed capacity or total output and the unit costs of production. The curves reflect "learning rates" defined as the percentage decline in unit costs for each doubling of output or capacity. The experience curves approach dates back to the study by Wright (1936) documenting unit costs decreased by 10% to 15% every time production of an airplane doubled. Experience curves have been documented in a variety of other industries by Bruce Henderson of the Boston Consulting Group (Henderson, 1970) and other authors since then. The Stern Report (2006), which greatly affected environmental policy in the United Kingdom, used learning rates estimated by the International Energy Agency (IEA, 2000) in its analysis of options for clean energy production. The United Nations' Intergovernmental Panel on Climate Change (IPCC) also used learning rates in its Fourth Assessment Report (IPCC, 2007). More recently, Upstill and Hall (2018) estimated the learning rate for carbon sequestration and storage to be 6.3%.

Figure 3.5.5.1 provides a summary of the learning rates reported in the literature based on works of McDonald and Schrattenholzer (2001), Neij *et al.* (2003), and Junginger *et al*. (2004). The average of study results for wind energy suggests the per-unit cost of electricity from that source falls by about 16% (with a wide range from 4% to 32%) for each doubling of capacity. Solar exhibits higher learning rates of 15% to 25% for each doubling, with ethanol production estimated to have learning rates around 20% for each doubling of production.

An important limitation on the use of experience curves is the fact that one industry does not learn and become more efficient over time while its competitors are frozen in time and learn nothing at all. Electricity producers using coal, natural gas, and nuclear power are all climbing experience curves of their own and becoming more efficient over time. To use experience curves to predict when new wind energy + natural gas back-up will be cost-competitive with existing coal, for example, would require knowing the shape of the curves for all three energy producers and then estimating the difference, the net progress wind + natural gas would make over coal, over time. It is entirely possible coal will keep pace with the productivity gains of wind energy + natural gas in the coming decades – especially if the regulatory environment were to change so as not to disfavor coal (Orr and Palmer, 2018) – meaning new wind + natural gas would never become cost-competitive.

The wind energy industry faces physical limits on its ability to improve the efficiency of its turbines, regardless of learning, as explained in Section 3.1.2. Generally the industry has been lowering costs by increasing the height of the towers, but industrial wind facilities are facing increasing opposition from land owners and communities. Taller turbines will mean larger set-backs from houses and communities, constraining their ability to increase capacity. For many nations of Europe, recent building of wind systems has been offshore, despite the higher expense, because opposition to onshore facilities has been too high. The 20,000 land-based turbines in Denmark and Germany may not be possible to replace when they reach their end of life because of lack of subsidies and community opposition. These realities suggest the cost of electricity from wind power probably will fall by less than 16% (the average from studies listed in Figure 3.6.1) for each doubling of capacity.

Recall that Stacy and Taylor found the LCOE of new wind energy in 2015 was 2.69 times as much as coal, 3.12 times as much as CC gas, and 3.69 times as much as nuclear power. Assume that the per-unit price of electricity from wind energy will fall 16% relative to the price of coal, natural gas, and nuclear energy for every doubling in wind's output. How many doublings of wind capacity would have to occur before the per unit cost of wind equals or is less than coal, natural gas, or nuclear energy? The math is easy. Wind producers would need to double their output six times (64 times current output) to be price-competitive with existing coal, seven times (128 times current output) to be competitive with CC gas, and eight times (256 times current output) to be competitive with nuclear power. These are, of course, impossible output numbers. In the United States, sometime around the fourth doubling wind energy would hypothetically produce all of the electricity needed to meet demand without fossil fuels. (Four doublings from a base of 254 billion kWh would be 4,064 billion kWh. Total U.S. electricity production in 2017 was approximately 4,015 billion kWh (EIA, 2018)). Of course, wind by itself cannot power an electric grid. Given its current learning rate, the wind energy industry would have to produce four times the entire energy consumption of the United States before it will have lowered its cost-per-unit to the current cost of coal, eight times to be price-

Figure 3.5.5.1
Learning rates in different renewable energy technologies

Type of Energy	Region	Period	Dependent Variable	Explanatory Variable	Learning Rate	Source
Electricity from biomass	EU	1980–1995	sp. prod. cost ($/kWh)	cum. prod. (TWh)	0.15	IEA (2000)
Ethanol	Brazil	1979–1995	sp. sale price ($/boe)	cum. prod. (cubic meters)	0.2	Goldemberg (1996)
Ethanol	Brazil	1978–1995	sp. sale price ($/boe)	cum. prod. (cubic meters)	0.22	IEA (2000)
Solar PV	EU	1985–1995	sp. prod. cost (ECU/kWh)	cum. prod. (TWh)	0.35	IEA (2000)
Solar PV modules	EU	1976–1996	sale price ($/W peak)	cum. sales (MW)	0.21	IEA (2000)
Solar PV modules	World	1976–1992	sale price ($/W peak)	cum. sales (MW)	0.18	IEA (2000)
Solar PV modules	World	1968–1998	sp. inv. price ($/W peak)	cum. cap. (MW)	0.2	Harmon (2000)
Solar PV panels	US	1959–1974	sp. sale price ($/W peak)	cum. cap. (MW)	0.22	Maycock and Wakefield (1975)
Wind	Germany	1990–1998	specific investment price ($/kW)	cum. cap. (MW)	0.08	Durstewitz (1999)
Wind power	Denmark	1982–1997	sp. inv. price ($/kW)	cum. cap. (MW)	0.04	IEA (2000)
Wind power	EU	1980–1995	sp. prod. cost ($/kWh)	cum. prod. (TWh)	0.18	IEA (2000)
Wind power	Germany	1990–1998	sp. inv. price ($/kW)	cum. cap. (MW)	0.08	IEA (2000)
Wind power	US	1985–1994	sp. prod. cost ($/kWh)	cum. prod. (TWh)	0.32	IEA (2000)
Wind power	World	1992–2001	turnkey investment costs for UK and Spain	global installed cap. (MW)	0.15–0.18	Junginger *et al.* (2004)
Wind turbines	Denmark	1982–1997	specific investment price ($/kW)	cum. cap. (MW)	0.08	Neij (1999)
Wind turbines	Denmark	1981–2000	levelized production cost ($/kW)	cum. cap. produced (MW)	0.17	Neij *et al.* (2003)

Sources: Authors' summaries and interpretations as well as those by McDonald and Schrattenholzer (2001), Neij *et al.* (2003), and Junginger *et al*. (2004).

competitive with CC gas, and 16 times to be competitive with nuclear power.

A similar calculation could be done for solar power, but the point has been made. Despite optimistic assumptions about learning rates and economies of scale, wind and solar power will *never* achieve price parity with fossil fuels and nuclear power. They will reach the physical limits of their technologies long before their prices fall to that of competing fuels.

In 2008, the U.S. Department of Energy set a more realistic goal for wind + natural gas back-up to provide 20% of U.S. electricity needs (USDOE, 2008). Wind energy would achieve this with between one and two doublings, leaving its per-unit cost still between two and three times as high as power from coal, natural gas, and nuclear power. This finding contradicts the very optimistic forecasts of the wind industry, which were the basis for the USDOE report and parroted in the popular press.

The situation in countries other than the United States is different. Fossil fuels are not as abundant (often due to government policies, not differences in natural endowments) and international trade in electricity may substitute for the need for energy storage to offset the intermittency of wind and solar power. In many European countries, taxes are the largest part of the cost of energy, not production costs, so tax reform could keep energy affordable even as reliance on more expensive renewable fuels is increased. Issues of energy security also inform the international debate but are not addressed by the LCOE exercise.

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3.6 Economic Value of Fossil Fuels

The late Julian Simon, perhaps the leading resource economist of his time, wrote in 1981,

> Energy is the master resource, because energy enables us to convert one material into another. As natural scientists continue to learn more about the transformation of materials from one form to another with the aid of energy, energy will be even more important. Therefore, if the cost of usable energy is low enough, all other important resources can be made plentiful, as H.E. Goeller and A.M. Weinberg showed. ...
>
> On the other hand, if there were to be an absolute shortage of energy – that is, if there were no oil in the tanks, no natural gas in the pipelines, no coal to load onto the railroad cars – then the entire economy would come to a halt. Or if energy were available but only at a very high price, we would produce much smaller amounts of most consumer goods and services (p. 162).

More recently, Aucott and Hall (2014) write, "it was cheap energy that led to robust growth and made industrial economies rich. In our view it has been a serious failure on the part of traditional economics to consider the importance of energy only as related to its cost share rather than its absolute necessity, growth in use, and power to create the infrastructure and activities that support and drive industrial economies. In our view, the physical importance of energy makes it different from other commodities; the role of energy cannot be adequately equated strictly to traditional financial factors" (p. 6561). They add, "If the price of energy goes up, almost everything costs more, and this ripples through the economy. Fertilizer may be a useful analogy. Adding

50 kg of nitrogen per hectare can change the yield of corn by several tons per ha. This is because nitrogen is typically a 'limiting nutrient.' It may be that energy is the 'limiting nutrient' of the economy" (p. 6568).

Energy alone is not sufficient to create the conditions for prosperity, but it is absolutely necessary. It is impossible to operate a factory, run a store, grow crops, or deliver goods to consumers without using some form of energy. Access to reliable energy is particularly crucial to human development as electricity has, in practice, become indispensable for lighting, clean water and sanitation, refrigeration, and the running of household appliances.

Since fossil fuels provide 81% of the primary energy consumed in the world, its economic value must be considerable. Monetizing that value – expressing it in dollars, pounds, or euros – is not a simple task. There are many efforts reported in the literature, each covering different parts of the world, different time periods, or different fuels, and each with different assumptions leading to different conclusions. This section first documents the close association between the cost of energy and gross domestic product (GDP), then summarizes six studies illustrating six different methodologies, and finally offers a comparison of the estimates.

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3.6.1 Energy and GDP

Abundant and affordable energy supplies play a key role in enabling economic growth.

The job losses and price increases resulting from increased energy costs reduce incomes as firms, households, and governments spend more of their budgets on electricity and less on other items, such as home goods and services. Virtually all economists agree there is a negative relationship between energy price increases and economic activity, though there are differences of opinion in regard to the mechanisms through which price impacts are felt. Following is a sample of informed opinion on the issue:

- "Economic growth in the past has been driven primarily not by 'technological progress' in some general and undefined sense, but specifically by the availability of ever cheaper energy – and useful work – from coal, petroleum, or gas" (Ayres and Warr, 2009).

- "The theoretical and empirical evidence indicates that energy use and output are tightly coupled, with energy availability playing a key role in enabling growth. Energy is important for growth because production is a function of capital, labor, and energy, not just the former two or just the latter as mainstream growth models or some biophysical production models taken literally would indicate" (Stern, 2010).

- "The bottom line is that an enormous increase in energy supply will be required to meet the demands of projected population growth and lift the developing world out of poverty without jeopardizing current standards of living in the most developed countries" (Brown *et al.,* 2011).

Aucott and Hall (2014) found "a threshold exists in the vicinity of 4%; if the percent of GDP spent on fuels is greater than this, poorer economic performance has been observed historically" (p. 6567). Bildirici and Kayikci (2012a, 2012b; 2013) found causal relationships between electricity consumption and economic growth in the Commonwealth of Independent States countries and in-transition countries in Europe. Lee and Lee (2010) analyzed the demand for energy and electricity in OECD countries and found a statistically valid relationship between electricity consumption and economic growth. Baumeister *et al*. (2010) examined the economic consequences of oil shocks across a set of industrialized countries over time and found energy costs and GDP are negatively correlated.

Blumel *et al*. (2009) used Chilean data to estimate the long-run impact of increased electricity and energy prices on the nation's economy. Kerschner and Hubacek (2008) reported significant correlations between energy and GDP in a study of the potential economic effects of peak oil, although they noted sectoral impacts are more significant. Sparrow (2008) analyzed the impacts of coal utilization in Indiana and estimated electricity costs significantly affect economic growth in the state.

Figure 3.6.1.1 presents three decades of rigorous research on the relationship between GDP and energy and electricity prices. Some studies looked only at oil prices, others at all types of energy, and some only at electricity prices. These studies support price-GDP elasticity estimates of about -0.17 for oil, -0.13 for electricity, -0.14 for all sources of energy, and -0.15 for all the studies in the table.

A price-GDP elasticity of -0.1 implies a 10% increase in the price, *ceteris paribus*, will result in a 1% decrease in GDP or, in the case of a state, Gross State Product (GSP). Thus, for example, the elasticity estimate for electricity of -0.13 means a 10% increase in the price of electricity in the United States results in a loss of approximately 1.3% of GDP, about $253 billion in 2017 (BEA, 2018). Estimates of the impacts of oil shocks and other energy price perturbations have produced different results, with smaller time-series econometric models producing energy price change-output elasticities of -2.5% to -11%, while large disaggregated macro models estimate much smaller impacts, in the range of -0.2% to -1.0% (Brown and Hunnington, 2010).

Knowing the energy price-GDP elasticity enables us to determine the impact of higher energy costs on human prosperity and the value of fossil fuels. Those calculations appear in the following sections.

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Figure 3.6.1.1
Summary of energy- and electricity price-GDP elasticity estimates

Year Analysis Published	Author	Type of Energy	Elasticity Estimate
2017	Deloitte Consulting Pty (Ltd).	Electricity	~ -0.1
2017	Huntington, Barrios, and Arora	Energy	-0.024 to -0.17
2017	Lu, Wen-Cheng	Electricity	-0.07
2015	Hu & Wang	Energy	-.087 to -0.10
2011	Inglesi-Lotz and Blignaut	Electricity	-1.10
2010	Lee and Lee	Energy and electricity	-0.01 and -0.19
2010	Brown and Huntington	Oil	-0.01 to -0.08
2010	Baumeister, Peersman, and Robays	Oil	-0.35
2009	Blumel, Espinoza, and de la Luz Domper	Energy and electricity	-0.085 to -0.16
2008	Kerschner and Hubacek	Oil	-0.03 to -0.17
2008	Sparrow	Electricity	-0.3
2007	Maeda	Energy	-0.03 to -0.075
2007	Krishna Rao	Energy	-0.3 to -0.37
2007	Lescaroux	Oil	-0.1 to -0.6
2006	Rose and Wei	Electricity	-0.1
2006	Oxford Economic Forecasting	Energy	-0.03 to -0.07
2006	Considine	Electricity	-0.3
2006	Global Insight	Energy	-0.04
2004	IEA	Oil	-0.08 to -0.13
2002	Rose and Yang	Electricity	-0.14
2002	Klein and Kenny	Electricity	-0.06 to -0.13
2001	Rose and Ranjan	Electricity	-0.14
2001	Rose and Ranjan	Energy	-0.05 to -0.25
1999	Brown and Yucel	Oil	-0.05
1996	Hewson and Stamberg	Electricity	-0.14
1996	Rotemberg and Woodford	Energy	-0.25
1996	Joutz and Gardner	Energy	-0.072
1996	Hewson and Stamberg	Electricity	-0.5 and -0.7
1996	Hooker	Energy	-0.07 to -0.29
1995	Lee, Ni, and Ratti	Oil	-0.14
1982	Anderson	Electricity	-0.14
1981	Rasche and Tatom	Energy	-0.05 to -0.11

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3.6.2 Estimates of Economic Value

Estimates of the value of fossil fuels vary but converge on very high numbers. Coal alone delivered economic benefits worth between $1.3 trillion and $1.8 trillion of U.S. GDP in 2015.

Reducing global reliance on fossil fuels by 80% by 2050 would probably reduce global GDP by $137.5 trillion from baseline projections.

There are at least six ways to calculate the past and present economic value of fossil fuels:

1. *Comparing LCOEs:* Estimates of the levelized cost of electricity (LCOE) can be combined with energy price-GDP elasticity to estimate the cost of replacing fossil fuels with alternative fuels.

2. *Existence value:* The existence value of fossil fuels is the value of economic activity

specifically attributable to their low cost relative to alternative fuels.

3. *Historical relationships:* The historical relationships between electricity costs or per-capita energy consumption, on the one hand, and GDP and other measures of prosperity on the other hand, can be used to forecast the cost of switching to higher-priced and less-abundant alternative energies.

4. *Bottom-up estimates:* Bottom-up calculations use data concerning the cost of existing and new production capacity and transmission infrastructure, premature retirement of existing resources, and economic models to estimate the incremental cost of reducing reliance on fossil fuels.

5. *Macroeconomic models:* Specific policies designed to reduce the use of fossil fuels are entered into macroeconomic models to produce estimates of their impacts on GDP, employment, economic growth, and more.

6. *Modeled as a tax increase:* Since increases in energy costs have effects similar to tax hikes, proposals such as the Obama administration's Clean Power Plan can be treated as though they were taxes on carbon dioxide emissions and entered into macroeconomic models as such.

In most of these methodologies, the economic value of fossil fuels appears as the *cost avoided* by not shifting to higher-priced, less-reliable forms of energy. This section describes a single example of each of these six methodologies and then compares the results of all six studies. There are many more studies than the ones summarized here, but the ones chosen are authoritative or representative of the findings of others.

3.6.2.1 Comparing LCOEs

Combining the levelized cost of electricity (LCOE) for electricity produced by coal and alternative energies reported in Section 3.5.4 with the electricity-GDP elasticity estimate reported in Section 3.6.1 allows us to estimate the present value, measured in GDP, of the current level of reliance on fossil fuels by the United States. The same technique allows us to consider a number of scenarios under which some or all of the electricity currently generated by coal is replaced by wind energy, the most cost-competitive alternative energy other than nuclear power. The results of such an analysis are reported in Figure 3.6.2.1.1.

Figure 3.6.2.1.1 offers stylized facts answering the question, "Given the current cost differences between existing coal resources and new wind energy resources, how would replacing some or all of current coal powered generators with wind turbines affect the price of electricity, and how would that affect GDP?" Another way of framing the question is, "How much do consumers *benefit* from relying on coal rather than wind to produce the electricity they use?" This is not a forecast of the actual cost of converting from coal to wind energy since (a) replacing 100% of coal generation with wind power is not physically possible, (b) such a conversion could not take place in a single year, (c) the length of time allowed to retire existing coal resources and build new wind energy would substantially affect the cost of such a conversion, and (d) the methodology assumes no changes in the output and cost of other energy sources (nuclear, hydro, and others) that would be strongly affected by an overall increase in the cost of electricity. This is also not the only way to calculate an existence value. Another way, illustrated by a study by Rose and Wei (2006), is presented in Section 3.6.2.2 below.

It is also important to note the cost of replacing coal with wind is likely to be more logarithmic than what the table shows. New wind tends to be increas ingly expensive as the best sites have been selected already and major expansions of wind capacity would likely require positioning wind turbines offshore, which is considerably more expensive than onshore installations. Costs due to the intermittency of wind power escalate as its market penetration rises and sectors that rely on continuous high-quality energy must somehow accommodate intermittent power instead.

Figure 3.6.2.1.1
Cost of replacing coal power with wind energy in the United States, LCOE method

Generator Type	LCOE/ MWh [1]	% of production (2015) [2]	Current annual Output (TWh) [2]	Annual Cost (millions)	Replace 20% of coal power with wind energy (millions)	Replace 40% of coal power with wind energy (millions)	Replace 100% of coal with wind energy (millions)
Coal (existing)	$39.90	39.0%	1,596	$63,680	($12,738)	($25,476)	($61,297)
Wind (new)*	$107.4	4.4%	180	--	$34,288	$68,576	$171,439
Other	--	56.6%	2,317	--	--	--	--
Totals	--	100.0%	4,093	--	--	--	--
Net Cost	--	--	--	--	$21,550	$43,099	$110,142
% Change in Cost	--	--	--	--	33.83%	67.67%	172.93%
% Change in COE [3]	--	--	--	--	13.20%	26.39%	67.44%
Loss of GDP [4]	--	--	--	--	($307,059)	($614,118)	($1,569,409)
% of GDP lost	--	--	--	--	(1.72%)	(3.43%)	(8.77%)

Notes and sources:

* Including cost imposed on CC gas for back-up power generation.
[1] Stacy and Taylor, 2016.
[2] EIA, 2015.
[3] Coal's % of production x % change in cost = change in average cost of electricity (COE).
[4] Best estimate of electricity price-GDP elasticity in the United States of -0.13, from Figure 3.7.1.1, x 2015 GDP estimate of $17.9 trillion from BEA, 2015.

With these caveats in mind, the numbers in Figure 3.6.2.1.1 allow us to make the following statements:

- Coal in 2015 provided 39% of U.S. electricity (1,596 TWh in 2015) at a levelized cost of approximately $64 billion.

- If 20% of the power generated by coal were generated instead by wind with natural gas back-up generation, the annual net cost would increase by $22 billion and electricity prices would rise 13%, causing a loss of GDP of approximately $307 billion, 1.72% of U.S. GDP in 2015.

- If 40% of the power generated by coal were generated instead by wind + gas back-up, the annual net cost would increase by $43 billion and electricity prices would rise 26%, causing a loss of GDP of approximately $614 billion, 3.43% of U.S. GDP in 2015.

- If it were physically possible for 100% of the power generated by coal to be generated instead by wind + gas back-up, the annual net cost would increase by $110 billion and electricity prices would rise 67%, causing a loss of GDP of approximately $1.6 trillion, 8.77% of GDP in 2015.

These are enormous costs. Coal today, compared to the next best alternative energy (other than nuclear power), provides a direct annual benefit in the United States of about $110 billion, and by lowering electricity rates it increases GDP by approximately $1.6 trillion a year, about 9% of total U.S. GDP. The results would be similar if the comparison used natural gas rather than coal, since their LCOEs are similar ($39.9 for coal and $34.4 for natural gas). The LCOE of solar PV cells is 30% higher than wind power ($140.3 versus $107.4) so substituting solar for fossil fuels would cost even more.

As discussed in Section 3.5, the learning rate and economies of scale for wind energy would reduce this cost if coal were phased out only as wind energy became economically competitive on a non-subsidized basis, but this would cap wind's penetration at about 10% or less of U.S. electricity needs, a level it has already achieved. This is not the proposal made by the United Nations' Intergovernmental Panel on Climate Change (IPCC) or its followers. The analysis in Section 3.5 shows wind energy is so far from being cost-competitive with coal that even optimistic forecasts of costs falling 16% relative to coal with every doubling of output would mean wind would hit the physical limits of its production capacity and the country's need for electricity long before its cost fell to the level of coal or natural gas. This means a forced transition from affordable fossil fuels to alternative energies would impose considerable costs, resulting in lost income and slower economic growth.

Our analysis confirms the concerns expressed by many experts about the impact of anti-coal policies pursued by the Obama administration. For example, Ann Norman, a senior research fellow with the National Center for Policy Analysis, wrote in 2014: "Losing coal would not be as much of a problem if we had a cost-effective, large-scale energy alternative available. But the environmentalist left will not touch nuclear power (an energy source that produces no carbon emissions), and renewables are unreliable and expensive, hardly suited to replace coal" (Norman, 2014).

References

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Rose, A. and Wei, D. 2006. *The Economic Impacts of Coal Utilization and Displacement in the Continental United States, 2015*. Report prepared for the Center for Energy and Economic Development, Inc. State College, PA: Pennsylvania State University. July.

Stacy, T.F. and Taylor, G.S. 2016. *The Levelized Cost of Electricity from Existing Generation Resources*. Washington, DC: Institute for Energy Research.

3.6.2.2 Existence Values

Rose and Wei (2006) conducted a sophisticated analysis of the existence impacts of coal-fueled electricity generation and the likely impact on GDP, household income, and employment of displacing 33% and 66% of projected coal generation by alternative energy resources over a 10-year period beginning in 2006 and ending in 2015. Their analysis took into account the positive economic effects associated with alternative investments in oil, natural gas, nuclear, and renewable energy supplies.

A method of capturing the locational attractiveness of a good or service is not to claim the entirety of output of its direct and indirect users, but only an amount relating to the price advantage of the input over its competitors. Rose and Wei calculated a price differential between coal and alternative fuels in electricity production, then estimated how much economic activity was attributable to this cost saving. They used an economy-wide elasticity of output with respect to energy prices of -0.10, meaning the availability of coal-fueled electricity at a price 10% lower than that of its nearest competitor is responsible for increasing total state or regional economic activity by 1.0%.

Explaining the implications of this methodology, the authors write, "Essentially, we are measuring the economic activity attributable to relatively cheaper coal in contrast to what would take place if a state were dependent on more expensive alternatives, which we assume would be a combination of oil/gas, renewable, and nuclear electricity" (Rose and Wei, 2006, p. 13).

The authors first estimated the level of coal-based electricity generation in each of the lower-48 states in 2015 based on projections made in 2006 by the EIA and EPA. They used IMPLAN input-output tables to estimate the direct and indirect (multiplier) economic output, household income, and jobs created by coal-fueled electricity generation in each state. Two estimates were produced: (1) upper-range ("high") prices for coal substitutes (nuclear, natural gas, and renewables) and (2) a lower-range ("low") price substitutes scenario. The authors' findings are summarized in Figure 3.6.2.2.1. They summarized their findings (depicted in the gray-shaded three cells) as follows: "Our analysis shows that, in 2015, U.S. coal production, transportation and consumption for electric power generation will contribute more than $1 trillion (2005 $) of gross output directly and indirectly to the economy of the lower-48 United States. Based on an average of two energy price scenarios … we calculate that $362 billion of household income and 6.8 million U.S. jobs will be attributable to the production, transportation and use of domestic coal to meet the nation's electric generation needs" (p. 4).

The authors then evaluated the impacts of two scenarios in which alternative energies replaced 66% and 33% of coal generation over the ten-year period from 2006 to 2015. The found "the average impacts of displacing 66% of coal-fueled generation in 2015 [would be a] $371 billion (2005 $) reduction in gross economic output; $142 billion reduction of annual household incomes; and 2.7 million job losses" (p. 4). The average impacts of displacing 33% of coal-based generation in 2015 were estimated to be "$166 billion (2005 $) reduction in gross economic output; $64 billion reduction of annual household incomes;

Figure 3.6.2.2.1
Regional summary of the "existence" value of U.S. coal utilization in electric generation, 2015 (in billions of 2005 dollars and millions of jobs)

Region	High-Price Alternatives	Low-Price Alternatives	Average
Southeast			
Output	$309	$166	$238
Earnings	$106	$55	$80
Jobs	2.2	1.1	1.6
Northeast			
Output	$145	$65	$105
Earnings	$56	$24	$40
Jobs	0.9	0.4	0.6
Midwest			
Output	$409	$199	$304
Earnings	$137	$65	$101
Jobs	2.4	1.2	1.8
Central			
Output	$305	$149	$227
Earnings	$106	$50	$78
Jobs	2.1	1.0	1.5
West			
Output	$213	$135	$174
Earnings	$78	$48	$63
Jobs	1.5	0.9	1.2
48 States			
Output	$1,381	$714	$1,047
Earnings	$482	$242	$362
Jobs	9.0	4.6	6.8

Source: Rose and Wei (2006), Table S-I, p. 6.

and 1.2 million job losses" (p. 5). Using an inflation calculator we can convert Rose and Wei's 2005 $ to 2015 $, making them comparable to the LCOE-derived estimates reported in Section 3.6.2. Here are the results:

- Coal in 2015 will contribute $1,275 billion of GDP directly and indirectly to the economy of the lower-48 United States and $445 billion of household income.

- If 33% of the power generated by coal were generated instead by gas, nuclear power, and renewables, GDP would decline by $204 billion, annual household incomes would fall by $79 billion, and 1.2 million jobs would be lost.

- If 66% of the power generated by coal were generated instead by alternatives, GDP would fall $456 billion, annual household incomes would drop by $175 billion, and 2.7 million jobs would be lost.

Rose and Wei's estimates are lower than what the LCOE exercise reported in Section 3.6.2.1 would have found for 33% and 66% substitution scenarios. There are many reasons for the difference: use of a lower energy cost-GDP elasticity rate; this study's time frame (10 years) versus the static analysis in Section 3.6.2.1; the exclusion of Alaska and Hawaii; including natural gas and nuclear power as possible substitutes for coal; and possibly not including the added burden of wind and solar power on natural gas power generators producing back-up power.

Reference

Rose, A. and Wei, D. 2006. *The Economic Impacts of Coal Utilization and Displacement in the Continental United States, 2015*. Report prepared for the Center for Energy and Economic Development, Inc. State College, PA: Pennsylvania State University. July.

3.6.2.3 Historical Relationships

Section 3.6.1 reviewed the extensive literature on the close relationships between energy prices and GDP. That literature enables us to forecast the impact on GDP of rising energy prices due to substitution by renewables assuming past correlations continue. An example of this methodology applied to global rather than U.S.-only energy is Tverberg (2012). Using estimates of energy consumption by Vaclav Smil, BP, EIA, and other sources, Tverberg plotted a plausible scenario in which governments force fossil fuel consumption to fall by 80% by 2050, the target endorsed by the European Union (EU). She projects non-fossil fuel power sources to rise more rapidly than their historical rate but not fast enough to offset the loss of fossil fuel power, requiring a decrease in global energy consumption of 50%. She then divides energy consumption by global population estimates and forecasts from the United Nations to estimate actual and projected per-capita energy consumption over the period. The results are shown in Figure 3.6.2.3.1.

Next, Tverberg created a database of the annual rate of change in global energy consumption, population, and GDP for 11 multi-year periods since 1920 relying "on population and GDP estimates of Angus Maddison and energy estimates of Vaclav Smil, supplemented by more recent data (mostly for 2008 to 2010) by BP, the EIA, and USDA Economic Research Service." Tverberg applied regression analysis to the data and found a 10% increase in per-capita energy consumption correlates with an 8.9% increase in per-capita GDP. Applying this finding to her scenario of a 50% reduction in energy consumption by 2050 created what Tverberg called a "a best-case estimate of future GDP if a decrease in energy supply of the magnitude shown were to take place." Her results are sobering:

- World per-capita energy consumption in 2050 would fall to what it was in 1905.

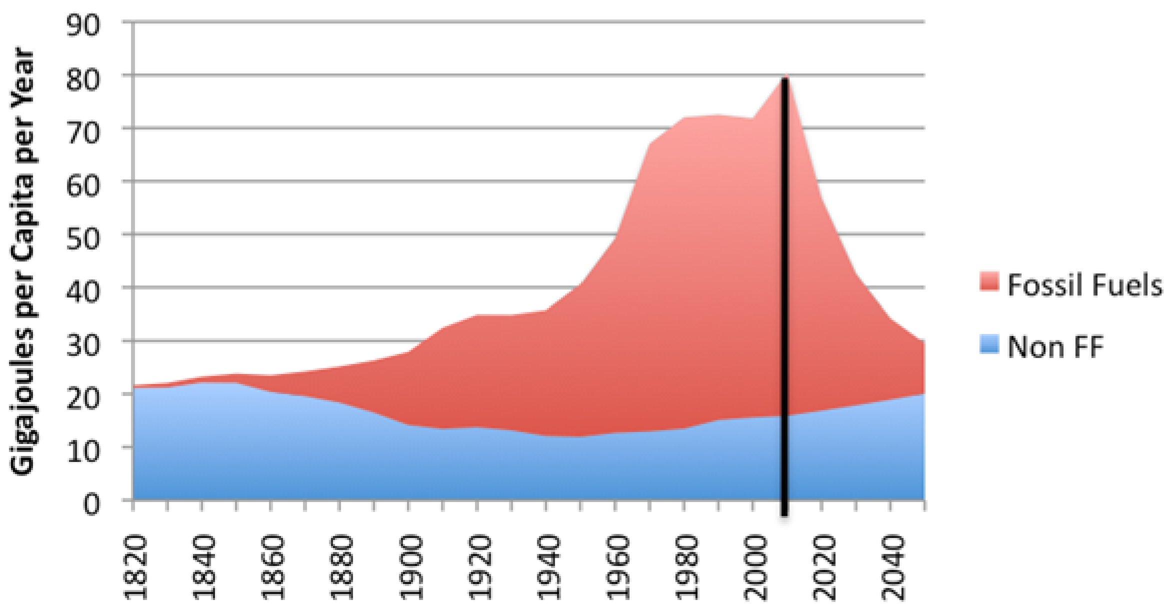
- Global per-capita GDP would decline by 42% from its 2010 level.

- Global GDP would be some $137.5 trillion (in 2015$) less in 2050 than baseline projections.

- The average global economic growth rate from 2012 to 2050 would be -0.59%.

A common baseline forecast for annual global GDP growth is 3% (PricewaterhouseCoopers LLP (2015). Tverberg's forecast could thus be stylized as an annual loss of 3.59% GDP from what it otherwise would have been. Since world GDP was approximately $74.4 trillion in 2015, the loss that year would have been $2.67 trillion.

Figure 3.6.2.3.1
A forecast of global per-capita energy consumption assuming 80% reduction in fossil fuel consumption by 2050



Assuming governments force consumption of fossil fuels to decrease by 80% by 2050, the goal set by the EU, and use of non-fossil fuels increases but not by enough to make up the entire gap, reducing total energy consumption by 50%. Amounts before the black vertical line are actual; after the black line are forecast in this scenario. *Source*: Tverberg, 2012.

Tverberg contends her estimates represent an optimistic "best-case" scenario since "the issue of whether we can really continue transitioning to a service economy when much less fuel in total is available is also debatable. If people are poorer, they will cut back on discretionary items. Many goods are necessities: Food, clothing, basic transportation. Services tend to be more optional – getting one's hair cut more frequently, attending additional years at a university, or sending grandma to an Assisted Living Center. So the direction for the future may be toward a mix that includes fewer, rather than more, services, and so will be more energy intensive" (*Ibid.*).

"If our per capita energy consumption drops to the level it was in 1905," Tverberg wrote, "can we realistically expect to have robust international trade, and will other systems hold together? While it is easy to make estimates that make the transition sound easy, when a person looks at the historical data, making the transition to using less fuel looks quite difficult, even in a best-case scenario." She concludes that such a worldwide reduction in reliance on fossil fuels is "very unlikely" (*Ibid.*).

References

PricewaterhouseCoopers LLP. 2015. The World in 2050: Will the shift in global economic power continue? London, UK.

Tverberg, G. 2012. An energy/GDP forecast to 2050. Our Finite World (website). July 26.

3.6.2.4 Bottom-up Estimates

In 2014, the U.S. Chamber of Commerce commissioned IHS Energy and IHS Economics, a global consulting firm, to produce a bottom-up estimate of the incremental cost of the Obama administration's proposal "to reduce gross U.S. greenhouse gas emissions by 42% below the 2005 level by 2030 (as stated in the administration's 2010 submission to the UN Framework Convention on Climate Change associating the U.S. with the Copenhagen Accord)" (U.S. Chamber of Commerce, 2014, p. 3). The administration's proposal eventually became the Clean Power Plan, a regulation with somewhat different targets, so the Chamber's analysis is not directly applicable to that regulation.

The authors establish a "Reference Case" describing energy trends expected in the absence of the administration's proposal. In the Reference Case, natural gas expands its market share due to "technological advancements in drilling techniques, a resulting reduction in unit production costs, and an expanded domestic resource base estimated at 3,400 trillion cubic feet (Tcf) – enough to supply demand at current levels for more than 100 years. …" (p. 20).

Also in the Reference Case, "generator retirements from 2011 through 2030 total 154 gigawatts (GW), with 85 GW of coal-fired power plants retiring in this time frame" (p. 17), reducing coal's share of electricity production from about 40% in 2013 to about 29% in 2030. U.S. total energy and electricity demand are forecast to grow an average of 1.4% per year and U.S. GDP is projected to grow 2.5% per year. The authors note, "prior to the mid-1980s, electricity demand grew more quickly than GDP; during the 1960s, electric demand grew twice as fast as GDP. Since 1980, electricity demand has grown more slowly than GDP. During the previous decade, for every 1% increase in GDP, electricity demand grew roughly 0.6%" (p. 19). They attribute the "progressively weaker relationship" to "the countervailing effect of rising retail electricity prices and a continued strong emphasis on energy efficiency policies at both the U.S. federal and state levels" (*Ibid.*).

The authors create a "Policy Case" to forecast the impacts of the proposal to reduce gross U.S. greenhouse gas emissions by 42% below the 2005 level by 2030. They predict "baseload coal plant retirements would jump sharply in the Policy Case, with an additional 114 gigawatts – about 40% of existing capacity – being shut down by 2030 compared with the Reference Case" (p. 3). They then do a bottom-up calculation of the incremental cost of such a forced transition away from coal, including "the costs for new incremental generating capacity, necessary infrastructure (transmission lines and natural gas and CO_2 pipelines), [and] decommissioning stranded asset costs…." (p. 4). These costs are partially offset by lower fuel use and operation and maintenance expenses incurred by coal-fired electricity producers. Their findings are summarized in Figure 3.6.2.4.1.

Figure 3.6.2.4.1
Cost to reduce U.S. greenhouse gas emissions by 42% below the 2005 level by 2030

Incremental cost item	Incremental cost (billions)
Power plant construction	$339
Electric transmission	$16
Natural gas infrastructure	$23
CCS pipelines	$25
Coal plant decommissioning	$8
Coal unit efficiency upgrades	$3
Coal unit stranded costs	$30
Demand-side energy efficiency	$106
Operations and maintenance costs	-$5
Fuel costs	-$66
Total incremental costs	$478

Source: U.S. Chamber of Commerce, 2014, Table ES-1, p. 4. Note in the original reads: "Please see Appendix C for power generation addition unit costs and more detail on the calculation of natural gas pipelines, transmission, CCS pipelines, coal plant decommissioning, and coal unit stranded assets."

As shown in Figure 3.6.2.4.1 the incremental cost of reducing existing coal generation output by 40%, net of savings, would be $478 billion (in constant 2012 dollars) by 2030. Most of the costs incurred by the coal industry would be passed on to consumers in the form of higher electricity rates. The authors estimate "the Policy Case will cause U.S. consumers to pay nearly $290 billion more for electricity between 2014 and 2030, or an average of $17 billion more per year" (p. 5). Average annual GDP during the same period is projected to be $51 billion less than in the Reference Case, "with a peak decline of nearly $104 billion in 2025" (p. 7). Average annual employment would be an average of 224,000 fewer per year, "with a peak decline in employment of 442,000 jobs in 2022."

The U.S. Chamber of Commerce's estimate of the cost of reducing reliance on coal by 42% below the 2005 level by 2030, the pledge made by the Obama administration in 2010, \$478 billion, is not far from what the less sophisticated LCOE methodology used in Section 3.6.2.1 would predict (\$644 billion, not shown in Figure 3.6.2.1.1). The major difference is likely that the LCOE methodology assumed coal would be replaced by wind power and not a combination of wind power, gas, and other less-expensive alternatives.

Reference

U.S. Chamber of Commerce. 2014. *Assessing the Impact of Potential New Carbon Regulations in the United States*. Institute for 21st Century Energy. Washington, DC: U.S. Chamber of Commerce.

3.6.2.5 Macroeconomic Models

In 2014, the U.S. Energy Information Administration (EIA, 2015a) used a macroeconomic model to estimate the cost of the Clean Power Plan (CPP), a regulation setting targets for reductions in greenhouse gas emissions associated with electrical generation to 25% below 2005 levels by 2020 and 30% below by 2030. The regulation has since been rescinded, but the analysis of the regulation provides an example of the use of macroeconomic models to forecast the cost of reducing reliance on fossil fuels. The report used EIA's National Energy Modeling System (NEMS), "a modular economic modeling system used by EIA to develop long-term projections of the U.S. energy sector, currently through the year 2040." Data on existing energy costs, supply, and demand were taken from the *Annual Energy Outlook 2015,* a database maintained by EIA (EIA, 2015b).

The modeling exercise is complicated because CPP relied on states to implement emission reduction programs and gives them some latitude in the choice of tools to achieve the reductions. States did not need to begin to reduce CO_2 emissions until 2020 and were expected to reach performance goals, measured in pounds of CO_2 emitted per megawatthour of electricity generated from affected electric generating units, by 2030. Emission reduction targets and methods approved by the EPA to attain them are described in an EPA document titled "Best System of Emissions Reduction (BSER)." Those methods, which the EPA calls "building blocks," are:

1. Improving the thermal efficiency of individual affected sources (heat rate improvement);

2. Dispatching the generating fleet to substitute less-carbon-intensive affected sources for more-carbon-intensive affected sources (re-dispatch for reduced emissions);

3. Expanding the use of low- or zero-carbon generation in order to displace affected sources (low- and zero-carbon capacity expansion).

The modeling exercise is further complicated because Congress asked for consideration of nine scenarios (e.g., extension of the Clean Power Plan targets beyond 2030, treatment of future nuclear capacity similar to the treatment of renewable capacity, and sensitivities for expenditures and effectiveness of energy efficiency programs). It is not necessary for our purposes to review all of EIA's findings. Instead, we focus on what EIA calls its "Base Policy case." The agency found:

> Increased investment in new generating capacity as well as increased use of natural gas for generation lead to electricity prices that are 3% to 7% higher on average from 2020–25 in the Clean Power Plan cases, versus the respective baseline cases. … While prices return to near-baseline levels by 2030 in many regions, prices remain at elevated levels in some parts of the country. … Economic activity indicators, including real gross domestic product (GDP), industrial shipments, and consumption, are reduced relative to baseline under the Clean Power Plan. Across cases that start from the AEO2015 Reference case, the reduction in cumulative GDP over 2015–40 ranges from 0.17%–0.25%, with the high end reflecting a tighter policy beyond 2030.

EIA seemed to trivialize the impact of CPP on GDP in its summary by focusing on early years, before the costs are significant, and later years, when it claims (implausibly) that technological advances will lower the cost of alternative energies to below the cost of fossil fuels. Most other researchers use an electricity-GDP elasticity of around -0.13 and would say an increase in electricity prices of 3% to 7% would reduce annual GDP between 0.39% and 0.91% below baseline forecasts, between two and four times EIA's estimate, about \$69.8 billion to \$162.9 billion a year using an estimated U.S. 2015 GDP of $17.9 trillion.

Kevin D. Dayaratna, senior statistician and research programmer at The Heritage Foundation (Dayaratna, 2015), "unpacked" EIA's findings and produced a series of tables presenting the *annual* impact of CPP on manufacturing employment, overall employment, GDP, annual income for a family of four, and annual household electricity expenditures for four of EIA's nine cases. Two of his tables, for impacts on GDP and overall employment, appear below as Figures 3.6.2.5.1 and 3.6.2.5.2.

Dayaratna's tables show EIA's analysis found significant costs, but still less than previous methodologies would predict: more than $100 billion a year in GDP is lost in each of eight years (2021–2028), cumulative GDP loss amounts to $25 trillion to $30 trillion, and job losses total more than 100,000 in nine years (2021–2029). EIA's forecast of positive impacts beginning in 2031 are counterintuitive, to say the least, given the low learning rates and physical limitations confronting solar and wind power and the almost certain decrease in energy consumption due to the inability of alternatives to meet population-driven rising electricity demand.

One reason EIA's analysis finds relatively low costs is because it accepts the U.S. Environmental Protection Agency's assumption that energy conservation efforts will reduce the rate of increase in electricity consumption below historical levels without imposing costs on consumers. That assumption has been severely criticized by the Electric Reliability Coordinating Council (ERCC), a group of energy companies:

> There is no doubt that our economy is becoming more energy efficient, but EPA's claims about future improvements are simply wishful thinking. We are not aware of any serious analysis showing, as EPA claims, that it will save you money by increasing your electricity rates. The efficiency promises made by environmentalist groups such as the NRDC [who have led the call for this regulatory proposal] are beyond what any state, no matter how green, has achieved and are wholly unrealistic. Further, the economy remains in doldrums, with growth stunted over the last five years. If economic recovery picks up – which the Administration believes is likely – counting on appreciably less energy use will not be an option. What happens if policies rely on energy efficiency beyond what is viable given economic conditions? The result is energy rationing (ERCC, 2014).

Economic growth in the United States did in fact increase after 2014, validating the ERCC's concern.

References

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EIA. 2015a. U.S. Energy Information Administration. Analysis of the impacts of the Clean Power Plan. May.

EIA. 2015b. U.S. Energy Information Administration. *Annual Energy Outlook 2015*. Washington, DC: U.S. Department of Energy.

ERCC. 2014. Electric Reliability Coordinating Council. ERCC answers seven questions you should have about EPA's proposed rule on carbon emissions from existing power plants (website). June 2.

Figure 3.6.2.5.1
Impact of Clean Power Plan on U.S. GDP, 2015–2040

Year	Clean Power Plan (CPP)	CPP Policy Extension	CPP Policy with New Nuclear	CPP Policy with Biomass CO^2
2015	-$226,562,000	-$3,906,000	-$31,250,000	-$224,609,000
2016	-$3,052,735,000	-$4,857,422,000	-$2,546,875,000	-$3,001,954,000
2017	-$4,068,360,000	-$7,039,063,000	-$3,580,078,000	-$4,035,157,000
2018	-$3,375,000,000	-$5,656,250,000	-$4,134,766,000	-$3,210,937,000
2019	-$2,232,422,000	-$7,986,329,000	-$2,347,657,000	-$3,605,469,000
2020	-$61,351,563,000	-$68,333,985,000	-$57,271,485,000	-$69,414,063,000
2021	-$116,789,062,000	-$104,718,750,000	-$110,716,796,000	-$130,425,781,000
2022	-$106,982,422,000	-$95,548,828,000	-$99,708,985,000	-$122,193,359,000
2023	-$117,937,500,000	-$102,208,984,000	-$113,904,296,000	-$131,744,140,000
2024	-$134,919,922,000	-$129,205,078,000	-$133,191,407,000	-$145,988,281,000
2025	-$147,900,391,000	-$152,810,547,000	-$143,474,610,000	-$151,742,188,000
2026	-$131,402,344,000	-$140,197,266,000	-$124,250,000,000	-$132,585,937,000
2027	-$119,218,750,000	-$126,933,594,000	-$111,230,469,000	-$116,541,015,000
2028	-$101,009,766,000	-$102,050,781,000	-$101,613,281,000	-$91,500,000,000
2029	-$69,599,609,000	-$68,685,547,000	-$72,375,000,000	-$59,783,203,000
2030	-$28,572,266,000	-$38,830,078,000	-$32,189,453,000	-$18,908,203,000
2031	$4,818,359,000	-$24,000,000,000	$5,240,234,000	$12,169,922,000
2032	$25,599,609,000	-$6,478,516,000	$33,091,797,000	$35,785,156,000
2033	$42,017,578,000	$7,806,640,000	$52,261,719,000	$46,839,843,000
2034	$45,316,406,000	$3,943,359,000	$59,785,156,000	$45,500,000,000
2035	$32,140,625,000	-$17,144,531,000	$48,419,922,000	$41,345,703,000
2036	$15,488,281,000	-$36,867,188,000	$32,669,921,000	$20,746,093,000
2037	$6,117,187,000	-$49,640,625,000	$20,839,844,000	$5,699,219,000
2038	$1,623,047,000	-$58,640,625,000	$10,347,656,000	-$12,435,547,000
2039	-$7,621,093,000	-$68,392,578,000	$701,172,000	-$20,111,328,000
2040	-$12,064,453,000	-$66,421,874,000	$1,589,844,000	-$16,769,531,000

Source: Author's calculations based on U.S. Energy Information Administration, "Analysis of the Impacts of the Clean Power Plan: Macroeconomic," http://www.eia.gov/oiaf/aeo/tablebrowser/ (accessed June 22, 2015).

Figures in 2009 chain-weighted U.S. dollars (a method of adjusting real dollar amounts for inflation over time). CPP Policy Extension = a scenario in which the Clean Power Plan is extended after 2030 with additional targets. CPP Policy with New Nuclear = a scenario in which new nuclear power installations are accorded the same treatment as new eligible renewables in the compliance calculation. CPP Policy with Biomass CO^2 = a scenario assuming that the emission rate for biomass fuel is 195 pounds CO_2 per MMBtu in place of EIA's Reference case assumption that biomass is carbon-neutral. *Source*: Dayaratna, 2015, Table 3.

Figure 3.6.2.5.2
Impact of Clean Power Plan on overall employment, 2015–2040 (negative numbers represent lost jobs due to slower economic growth)

Year	Clean Power Plan (CPP)	CPP Policy Extension	CPP Policy with New Nuclear	CPP Policy with Biomass CO^2
2015	-1,206	351	213	-641
2016	-16,663	-26,886	-13,702	-16,388
2017	-25,772	-42,481	-22,476	-26,703
2018	-25,482	-44,403	-27,465	-28,061
2019	4,410	41,489	-3,067	1,725
2020	-57,755	-39,261	-46,097	-84,366
2021	-282,913	-183,823	-264,496	-350,708
2022	-234,329	-139,465	-206,054	-324,371
2023	-189,423	-114,548	-165,253	-258,331
2024	-211,365	-211,166	-189,392	-264,084
2025	-378,602	-452,668	-330,384	-390,458
2026	-453,460	-537,445	-399,994	-423,004
2027	-479,034	-536,194	-427,948	-425,873
2028	-422,989	-426,819	-423,660	-339,371
2029	-277,939	-264,175	-314,606	-192,703
2030	-78,506	-83,221	-121,551	9,964
2031	140,549	64,148	107,666	210,083
2032	293,762	187,958	295,578	345,978
2033	375,579	269,927	408,599	441,223
2034	387,955	281,433	449,509	439,117
2035	329,147	210,174	404,159	408,356
2036	254,502	113,861	313,233	305,390
2037	179,932	33,920	222,305	194,901
2038	147,323	1,251	163,421	111,572
2039	110,611	-15,183	122,604	58,762
2040	90,821	26,032	127,472	91,934

Source: Author's calculations based on U.S. Energy Information Administration, "Analysis of the Impacts of the Clean Power Plan: Macroeconomic," http://www.eia.gov/oiaf/aeo/tablebrowser/ (accessed June 22, 2015).

Figures in 2009 chain-weighted U.S. dollars (a method of adjusting real dollar amounts for inflation over time). CPP Policy Extension = a scenario in which the Clean Power Plan is extended after 2030 with additional targets. CPP Policy with New Nuclear = a scenario in which new nuclear power installations are accorded the same treatment as new eligible renewables in the compliance calculation. CPP Policy with Biomass CO^2 = a scenario assuming that the emission rate for biomass fuel is 195 pounds CO_2 per MMBtu in place of EIA's Reference case assumption that biomass is carbon-neutral. *Source*: Dayaratna, 2015, Table 2.

3.6.2.6 Modeled As a Tax Increase

The U.S. Environmental Protection Agency (EPA) estimated the Clean Power Plan (CPP) would reduce CO_2 emissions at an average cost of $30 a ton, "an average of the estimates for each building block, weighted by the total estimated cumulative CO_2 reductions for each of these building blocks over the 2022–2030 period" (EPA, 2014, p. 446). The EPA estimates the cost of "building block three," "Expanding the use of low- or zero-carbon generation in order to displace affected sources (low- and zero-carbon capacity expansion)," to be $37 per ton on average from 2022 to 2030 (p. 769). This latter figure is most salient to the current analysis.

Dayaratna *et al*. (2014) explained why CPP can be modeled as a tax increase: "Taxing CO_2-emitting energy incentivizes businesses and consumers to change production processes, technologies, and behavior in a manner comparable to the Clean Power Plan regulatory scheme. Modeling comparable tax changes as a substitute for estimating the macroeconomic impact of complex regulatory schemes is a widely accepted practice."

Dayaratna *et al.* go on to treat CPP as a $37/ton carbon dioxide tax. The authors "employed the Heritage Energy Model (HEM), a derivative of the [EIA's] National Energy Model System 2014 Full Release (NEMS). This model includes modules covering a variety of energy markets and integrates with the IHS Global Insight macroeconomic model. … We modeled the impact of a revenue-neutral carbon tax starting at $37 per ton in 2015 through 2030."

"The costs," Dayaratna *et al.* wrote, "turn out to be substantial." If implemented, CPP would reduce cumulative GDP "by more than $2.5 trillion between now and 2030. Employment would track nearly 300,000 jobs below the no-carbon-regulation baseline in an average year, with some years seeing an employment deficit of more than 1 million jobs." The researchers also found CPP, modeled as a tax on carbon dioxide emissions, would cause a peak employment shortfall of more than 1 million jobs and total income loss of more than $7,000 per person (inflation-adjusted) by the year 2030. They point out that EIA "analyzed the economic impact of a carbon tax using essentially the same model and found similarly devastating results. Comparing the EIA's $25-carbon-tax estimate with the baseline shows more than $2 trillion in lost GDP from 2014 to 2030 and a peak employment differential of 1 million lost jobs," referencing EIA's *Annual Energy Outlook 2014* (EIA, 2014).

The Heritage Foundation analysis is valuable, but like other methodologies described in this section it has drawbacks and limits. A carbon tax may be more efficient than the arbitrary caps, timelines, and technology mandates contained in CPP, so modeling CPP as a tax underestimates the cost of displacing fossil fuels and consequently their current value. The carbon tax in the model was assumed to be "revenue neutral," meaning its revenues would be offset by reductions in other tax collections, and consequently its impact on GDP would be less. Examples of new taxes that were "revenue neutral" are difficult to find in human history (see Chapter 1, Section 1.4 for some reasons why this is the case), so it is fair to guess that a new carbon tax would have a larger negative effect on economic growth than forecast by either EIA or Dayaratna *et al*.

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EIA. 2014. U.S. Energy Information Administration. *Annual Energy Outlook 2014*. Table labeled Macroeconomic Indicators.

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3.6.3 Comparison of Estimates

The six studies summarized in this section are difficult to compare or reconcile since they vary in what was measured and over what time periods. For example, the first estimate using LCOEs looked only at the case of replacing existing coal resources in the United States with new wind energy *ceteris paribus*, with no time frame and no consideration of the effects on other sources of electricity generation. Rose and Wei looked at only the lower-48 states and envisioned a ten-year transition (from 2006 to 2015) away from coal to natural gas, nuclear, and renewable fuels. Tverberg looked at global costs of reducing fossil fuel consumption by 80% and estimated effects in the year 2050. Figure 3.6.3.1 presents a summary of the findings in a table that makes the results easier to interpret.

Figure 3.6.3.1
Summary of six estimates of the cost of replacing fossil fuels with alternatives, measured as percentage of GDP, U.S.-only unless specified as global

Authors	Methodology	Time period	Current value of fossil fuels	Replace 20% by 2020 and 32% by 2025	Replace 33%	Replace 40%	Replace 66%	Replace 80% (global)
NIPCC (2018)	Comparison of LCOEs in the U.S.	2015	+$1.57 trillion GDP	-$307 billion GDP (20%) -$491 billion GDP (32%) (annual)	-$506 billion GDP (annual)	-$614 billion GDP (annual)	-$1.01 trillion GDP (annual)	--
Rose and Wei (2006)	Existence value of coal in the U.S.	2006–2015	+$1.275 trillion GDP (cumulative) +6.8 million jobs	--	-$166 billion GDP (annual) -1.2 million jobs	--	-$371 billion GDP (annual) -2.7 million jobs	--
Tverberg (2012) (global)	Historical relationship of energy consumption and global GDP	2012–2050	--	--	--	--	--	-$137.5 trillion global GDP (2050)
U.S. Chamber of Commerce (2014)	Cost of Clean Power Plan, bottom-up estimate	2015–2030	--	--	--	-$478 billion GDP (cumulative) -224,000 jobs per year (average)	--	--
EIA (2015)	Cost of Clean Power Plan, macroeconomic model	2015–2030	--	- $1.1 trillion GDP (cumulative) -196,00 jobs per year (average)	--	--	--	--
Davaratna, Loris, and Kreutzer (2014)	Cost of Clean Power Plan, modeled as a tax increase	2015–2030	--	-$2.5 trillion GDP (cumulative) - 300,000 jobs per year (average)	--	--	--	--

This table significantly simplifies the findings of six reports and therefore leaves out many caveats and other findings. In some cases these are static estimates that do not reflect the likely incremental cost of replacing fossil fuels over time. *Sources*: See References. NIPCC (2018) refers to this volume of *Climate Change Reconsidered II*s.

A few generalizations can be offered:

- Use of coal in the United States delivered economic benefits worth between $1.275 trillion and $1.57 trillion in 2015. Fossil fuels support approximately 6.8 million jobs in the United States.

- Replacing 20% of the energy produced with fossil fuels in the United States with wind power would cost approximately $300 billion and replacing 32% would cost approximately $491 billion. Achieving these reductions by 2020 and 2025, the stated goals of the Clean Power Plan (CPP), would cost between $1.1 trillion and $2.5 trillion in cumulative lost GDP and destroy between 196,000 and 300,000 jobs each year between 2015 and 2030.

- Replacing 33% of the energy produced by coal in the United States in 2006 with alternatives (including natural gas and nuclear power) by 2015 would have cost $166 billion a year and 1.2 million jobs. Replacing this same amount of coal generation with wind power would cost $506 billion a year.

- Replacing 40% of the energy produced by coal in the United States in 2012 with alternatives by 2030, the goal proposed by the Obama administration in 2010, would cost $478 billion and an average of 224,000 jobs each year. Replacing it with wind power would cost $614 billion a year.

- Replacing 66% of the energy produced by coal in the United States in 2006 with alternatives by 2015 would have cost $371 billion a year and 2.7 million jobs. Replacing it with wind power would have cost $1.0 trillion a year.

- Reducing global reliance on fossil fuels by 80% by 2050 would cause the loss of $137.5 trillion of global GDP in 2050.

Given the great variation in and independence of the methodologies used to reach these conclusions, as well as known and unknown limitations and flaws in several of the studies, it may be surprising the results are at least somewhat consistent. Fossil fuels deliver economic benefits to the United States of between $1.275 trillion (for coal alone) and $1.76 trillion (for all fossil fuels) a year in added GDP and some 6.8 million jobs (for coal alone). Continued reliance on fossil fuels in the year 2050 would be worth approximately 42% of global GDP, about $137.5 trillion in today's dollars.

Relying on fossil fuels and using alternative energies only as they become cost-competitive would *save* consumers the enormous expenses documented by these studies. Reducing our dependency on fossil fuels is costly, measured as hundreds of billions of dollars of GDP and hundreds of thousands of jobs annually. As the world's population continues to grow and billions of people rise out of poverty, using abundant and affordable fossil fuels is more important than ever.

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3.7 Conclusion

Despite much compelling evidence of the progress made in human well-being thanks to the use of fossil fuels, sometimes we wish for the "good old days." But our ancestors didn't think of horse-drawn carriages, open-hearth fires in homes, and stifling heat during warm summer nights that way. To them, safe and affordable transportation, clean and reliable home heating, and air conditioning would have been unmitigated blessings leading to tremendous improvements in their quality of life.

Fossil fuels make a dramatic contribution to public health by reducing poverty by supporting the technologies we rely on to keep us safe and well, making electrification of many processes possible, and helping to create a safe and plentiful food supply. Replacing fossil fuels with alternative energies that are more costly or less reliable would mean losing many of these benefits.

Fossil fuels created the modern era. They raised the standard of living, dramatically improved human health, increased human lifespan, and helped elevate billions of persons out of poverty. What we recognize today as modernity – modern cities, fast and affordable transportation, television and the Internet – are all products of fossil fuels. In the words of energy historian Vaclav Smil (2005), "The most fundamental attribute of modern society is simply this: Ours is a high energy civilization based largely on combustion of fossil fuels."

The research presented in this chapter supports Smil's observation. Renewable fuels such as wind turbines, solar PV cells, and ethanol cannot replace fossil fuels. None is sufficiently energy-dense, available in sufficient quantities, dispatchable (always available on demand), or affordable to play more than a small role in meeting the world's growing energy needs. Multiple methodologies aimed at monetizing the benefits of fossil fuels place their value at trillions of dollars a year.

In Chapter 1, "opportunity cost" was defined as the value of foregone uses of the funds or time spent following a choice. Every choice has an *apparent* cost, say the higher price of electricity produced by choosing to rely on wind or solar power instead of coal or natural gas. Research presented in Sections 3.4.4 and 3.4.5 found electricity generated by new wind capacity in the United States costs approximately 2.7 times as much as coal, 3 times as much as combined cycle gas, and nearly four times as much as nuclear power. This is the apparent cost of the choice, but the *opportunity* cost is far greater. The high prices and intermittency of alternative energies raise the cost of electricity, slowing economic growth, and their limited supply raises the prospect of living with much less energy. *What would that look like?*

Deming (2013) speculated about "what would happen to the U.S. today if the fossil fuel industry went on a strike of indefinite duration?" Some of the consequences he described include:

- "With no diesel fuel, the trucking industry would grind to a halt. Almost all retail goods in the U.S. are delivered by trucks. Grocery shelves would begin to empty. Food production at the most basic levels would also stop. Without gasoline, no farm machinery would function, nor could pesticides or fertilizers be produced on an industrial scale. The U.S. cannot feed 315 million people with an agricultural technology based on manure and horse-drawn plows. After two weeks mass starvation would begin.

- "Locomotives once ran on coal but today are powered by diesel engines. With no trains or trucks running there would be no way to deliver either raw materials or finished products. All industrial production and manufacturing would stop. Mass layoffs would ensue. At this point, it would hardly matter. With virtually all transportation systems out, the only people who could work would be those who owned horses or were capable of walking to their places of employment.

- "42% of electric power in the U.S. is produced by burning coal. With natural gas also out of the picture, we would lose another 25%. … With two-thirds of the electric power gone, the grid would shut down entirely. [Probably not entirely… electricity would still be available in some areas near dams and nuclear power plants.] No electricity also means no running water and no flush toilets. When the bottled water ran out, people would drink from streams and ponds and epidemic cholera would inevitably follow.

- "Hospitals could continue to function for a few days on backup generators. But with no diesel fuel being produced, the backups would also fail. Emergency surgeries would have to be conducted by daylight in rooms with windows. Because kerosene is a petroleum byproduct, lighting by kerosene lamps would not be an option. Even candles today are made of paraffin, another petroleum byproduct. It is doubtful if sufficient beeswax could be found to manufacture enough candles to light the 132 million homes in the U.S.

- "With no electricity, little to no fuel, and no way to transport either people or commodities, the U.S. would revert to the eighteenth century

> within a matter of days to weeks. The industrial revolution would be reversed. The gross domestic product would shrink by more than 95%. Depending on the season and location, people would begin to either freeze or swelter in their homes."

This dark tale of a future without fossil fuels may be easy to criticize, but it is hardly less scientific or less credible than the even darker predictions of a climate Armageddon coming from the United Nations' Intergovernmental Panel on Climate Change (IPCC) and many advocacy groups that echo its views. Deming's narrative has the virtue of relying on actual data consistent with what is reported in this chapter and the predictable consequences of abruptly ending the use of fossil fuels, whereas IPCC's forecasts rest on assumptions and computer models. Unlike the IPCC and its allies, Deming did not claim to be making a scientific forecast. If only for that reason, Deming seems to be the more trustworthy of the parties.

References

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