CHAPTER 1

Energy, economics, and climate change

We can't engage in a serious examination of climate change without considering its strong ties to energy. More than any other factor, anthropogenic contributions to climate depend on how energy is produced and used.

Over his illustrious career, Richard Smalley (1943–2005), a Nobel Laureate and pioneer in the field of nanoscience and technology, was invited to give many lectures on his work. However, in the last few years of his life, he felt compelled to use the lectures as a vehicle for sharing his concerns about the world's energy future. In one of his slides he presented his views on humanity's top ten problems of the next fifty years. His list included food, water, the environment, poverty, war, disease, education, democracy, and population. While we might attach different weights to the significance of each concern, we would probably agree that all are to be taken seriously. However, for Smalley, there was no equivocation on what belonged at the top of the list. Meeting the world's energy needs was paramount and linked, to varying degree, with the other nine.

1.1 Energy: an indispensable resource

It would be difficult to overstate the importance of energy to the well-being of humankind. It is the resource that sustains all life and economic activity. It enables the production and distribution of all manner of goods and services, as well as human mobility on the ground and in the air. It is absolutely essential to achieving an acceptable standard of living, and in the words of Paul Roberts (2004, p. 6), "Access to energy has emerged as the overwhelming imperative of the twenty-first century."

While preindustrial societies functioned entirely on energy derived from the Sun, the Industrial Revolution marked a transition to the use of fossil fuels and by the mid-twentieth century to nuclear energy. It is difficult to appreciate the enormity of today's global energy supply chain. In 2013, humankind consumed approximately 505 quadrillion (505,000 trillion) British thermal units (Btu) of energy, or simply 505 quads (BP, 2014a).[1] The amount is staggering, and trillions of dollars are spent annually to produce and distribute this energy. That said, about one-third of the world's population still live in or near poverty, with many lacking the energy required to meet the most basic human needs. Movement of people from poverty to a decent standard of living, along with a growing world population, guarantees continued growth in the demand for energy. But generally energy production and consumption do not occur without adverse environmental effects, and some forms of energy are more benign than others.

1.2 Energy 101: a taxonomy

Forms of energy are diverse, and any taxonomy should include a distinction between primary sources of energy and energy carriers. Primary sources can be characterized as renewable or nonrenewable and as carbon-free or carbonaceous. A primary source of energy is simply one that exists naturally. In contrast, an energy carrier does not exist in a natural form and can only be produced by converting the energy associated with a primary source.

There are two major energy carriers: electricity and hydrogen. Electricity has been vital to human advancement for more than a century and will become even more important in the years ahead. Although hydrogen is, at best, a bit player in today's energy supply chain, it could one day play a more prominent role. But for human consumption, electricity and hydrogen are not inherent gifts of nature. Some artifact of human innovation must be used to convert a primary energy source to electrical energy or hydrogen.

Primary sources of energy are highlighted in Figure 1.1. Once used, a nonrenewable source of energy is not replenished. It is simply depleted. One can think of these sources as stored within the Earth and consisting of fossil and nuclear fuels. There is only so much, and when a nonrenewable resource is used, it reduces the amount left in storage. Continued withdrawal leads to depletion or to a point where reserves are so diminished that further withdrawal is impractical.

Fossil fuels (coal, natural gas, and petroleum) consist of hydrocarbon molecules, and the chemical energy associated with the bonds between carbon and hydrogen atoms can be released by chemical reactions,

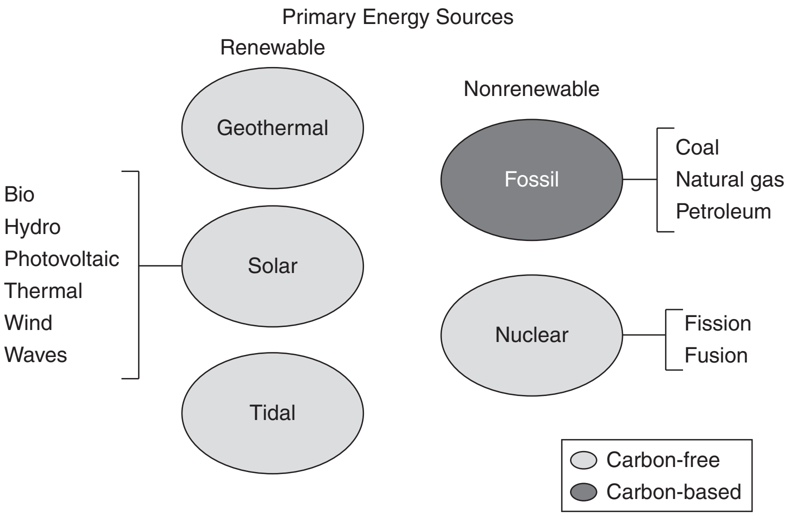

FIGURE 1.1. Primary sources of energy: renewable and nonrenewable, carbon-free and carbonaceous.

typically by burning the fuels. The chemical energy of the fuel is converted to thermal energy of the high-temperature products of combustion, which can then be used for space heating in homes and commercial buildings, for process heat in factories, to power automobiles and aircraft, and to produce electricity. Fossil fuels have several desirable attributes. They have large energy densities (energy content per unit mass or volume); they are abundant; and they can be produced and supplied to the consumer at comparatively low costs. Not surprisingly, they are widely used, and the global infrastructure and capital investments associated with producing, distributing, and using the fuels are enormous. Consider the vast array of oil and gas wells; coal mines; supertankers, pipelines, and freight trains; space and process heating systems; automobiles, trucks, boats, and aircraft; and electric power plants.

Fossil fuels have sustained economic growth since the eighteenth century and will remain important well into the twenty-first century. But there is a downside to burning the fuels. The products of combustion, which are discharged to the atmosphere, include constituents that contribute to atmospheric pollution and global warming. The challenge is one of using the fuels in an environmentally benign fashion.

Nuclear energy is highly concentrated and is also nonrenewable. It can be released by means of a fission or fusion reaction. Fission reactions entail splitting heavy atomic nuclei such as uranium-235 into fragments, thereby releasing large amounts of energy that can be harnessed for useful purposes. Fission reactors are widely used to produce electricity, but not without environmental issues related to reactor safety and disposal of radioactive wastes produced by the fission process.

A fusion reaction combines lighter nuclei to form a heavier nucleus, again with the release of a large amount of energy. Fusion is an attractive target for two reasons. Light nuclei required to fuel the reaction are abundant in the world's oceans, providing a nearly inexhaustible supply, and products of the reaction are benign. However, despite the billions of dollars that have been spent – and continue to be spent – on attempts to contain a fusion reaction, commercialization of the process is far from imminent. Even if the reaction can be sustained, the engineering problems associated with developing a viable power production system would be enormous and costly. Fusion technology is in some sense a Holy Grail, but one that is not likely to be achieved in this century, if ever.

Although fossil and nuclear fuels are both nonrenewable, they differ in one important way. Because fossil fuels are carbonaceous, their products of combustion include carbon dioxide, the largest contributor to global warming. In contrast, nuclear fuels are carbon-free.

Renewable forms of energy are also carbon-free and for all practical purposes can never be depleted. Geothermal energy is derived from energy that was stored within the Earth during its formation and energy that is continuously released by nuclear (fission) reactions. High temperatures within the Earth's core and mantle provide the driving potential for conduction of thermal energy to the Earth's crust, where pressurized steam or hot water are generated at depths accessible to drilling from the Earth's surface. Once accessed, thermal energy associated with the steam or hot water can be used for space and process heat or for power generation. Although geothermal energy is being harnessed throughout the world, its contribution to global energy consumption is well below 1%.

Solar energy is far and away the most abundant source of renewable energy. The rate at which the Earth intercepts solar radiation, commonly termed *insolation*, is enormous, amounting to approximately 165,000 terawatts (165,000 TW), or 11,000 times the average rate at which humans consumed energy from all sources in 2013. Through absorption by the Earth's land and oceans, solar radiation maintains temperatures conducive to plant and animal life. Through the process of photosynthesis, solar energy is converted to chemical energy in the form of biomass, which propagates through the food chain and can also be used as a biofuel.

Solar radiation is also responsible for temperature variations on land and sea. These variations sustain the Earth's hydrologic cycle and atmospheric winds, which can be tapped as sources of hydro, wind, and wave energy. Solar energy can also be converted directly to electricity by means of photovoltaic technologies and to space and process heat or indirectly to electricity by means of solar thermal technologies. Solar energy is the antithesis of fossil fuels. While fossil fuels are nonrenewable, concentrated (have a large energy density), and, to varying degrees, environmentally detrimental, solar energy is renewable, diffuse, and environmentally benign.

The distinction between renewable and nonrenewable forms of energy has an important bearing on the future of the human species. At some point, nonrenewable sources of energy will be depleted, and human innovation will have to achieve a sustainable energy future that relies exclusively on renewable sources.

1.3 Energy and economic growth

For centuries there has been a steady, seemingly inexorable increase in global energy consumption, and it is a sine qua non that economic growth is accompanied by increased energy consumption. Since the Industrial Revolution, living standards have been shaped by cheap and abundant energy. A huge global infrastructure has been created for the production and use of energy, enabled by capital markets, large corporations, and an abiding faith that it will have no end. Abundant and cheap energy has enabled globalization and has elevated expectations for higher living standards across the world.

In recent decades a nominal annual increase of 3% in gross world product (GWP) has been accompanied by an annual increase of about 2% in global energy consumption. The linkage between a nation's energy consumption and its economic activity is highlighted in Table 1.1 for representative nations at different stages of economic development. The first two columns of data provide energy consumption and gross domestic product (GDP) per capita, where the unit of energy (a gigajoule) is one billion joules and GDP is standardized on the basis of purchasing power parity (PPP).[2]

Several factors influence the relationship between a nation's economic output and its energy consumption. An economy relying heavily on manufacturing uses more energy than one based largely on services, while some nations simply use energy more efficiently than others. The third column of the table provides one measure of how effectively a nation uses

TABLE 1.1. *Circa 2011–12 primary energy consumption and GDP per capita and energy intensity for selected nations*

	Energy consumption (GJ/Person)[a]	GDP (PPP2012) (U.S.$/Person)[b]	Energy intensity (GJ/U.S.$1,000)
Group I			
Australia	271.5	43,300	6.27
Canada	418.4	43,400	9.64
Russia	242.6	18,000	13.5
Saudi Arabia	343.4	31,800	10.8
United States	330.0	50,700	6.17
Group II			
France	174.2	36,100	4.83
Germany	169.4	39,700	4.27
Japan	172.6	36,900	4.68
Switzerland	168.7	46,200	3.65
United Kingdom	143.3	37,500	3.82
Group III			
Brazil	62.2	12,100	5.14
Chile	84.7	18,700	4.53
China	86.5	9,300	9.30
India	21.0	3,900	5.38
Mexico	72.5	15,600	4.65
Group IV			
Bangladesh	6.8	2,100	3.24
Ethiopia	1.7	1,200	1.42
Haiti	3.2	1,300	2.46
Nigeria	4.7	2,800	1.68

[a] Data for 2011 from EIA (2013c).

[b] Data for 2012 from CIA (2013).

its energy. Termed energy intensity (EI), it provides the ratio of a nation's energy consumption to its GDP. A logical national goal would be to minimize the energy required to maintain a strong economy.

The selected nations are separated into four categories. Group I includes nations with large energy consumption and moderate to large GDP, while Group II embodies nations of comparable GDP and much lower energy consumption. With respect to economic output, Group II nations use energy more efficiently than those of Group I. Citizens of Group II enjoy living standards and a quality of life as good as or better than those of Group I while consuming much less energy per unit of economic output, and for Germany and Japan doing so with a large manufacturing base.

Group III consists of developing nations that have undergone rapid economic growth over the last two decades and, moving forward, are likely to grow more rapidly than the developed nations represented by Groups I and II. Two nations (Chile and Mexico) have energy intensities comparable to those of Group II; two nations (Brazil and India) lie between I and II; while China, a manufacturing juggernaut for which improving energy efficiency is a work in progress, is aligned with Group I. In contrast, Group IV represents some of the world's poorest nations for which both energy consumption and GDP are low.

Comprised largely of African, South American, and Asian nations, Groups III and IV are of special interest because they have the greatest potential for economic growth. But, as they grow, what trajectory of energy consumption will they follow? Will it be more closely aligned with Group I or II? Consider that from 2008 through 2013, primary energy consumption decreased by about 2.4% in the thirty-four developed nations of the Organisation for Economic Co-operation and Development (OECD),[3] while increasing by 24.2% in the largely developing non-OECD nations (BP, 2014a). In the context of climate change, why are these numbers important?

Economic activity is inextricably tied to energy consumption. But, when fossil fuels are burned, their carbon content is released to the atmosphere as carbon dioxide, where it becomes a major contributor to global warming. Although fossil fuels comprise only one of the five energy categories of Figure 1.1, they contribute disproportionately to meeting the world's needs for primary energy.

In 2011, fossil fuels provided about 82% of the world's total primary energy supply (TPES), with the remainder provided by nuclear (5%) and renewable (13%) energy (IEA, 2013a). Of the renewables, most of the energy was supplied by bio/hydro sources and about 1% from a combination of solar, wind, and geothermal energy. From 2011 through 2013, fossil fuels also accounted for about 82% of U.S. energy consumption, with nuclear and renewable energy each providing about 9% (EIA, 2014a). Fossil fuels also contribute significantly to generating the world's electricity, providing 68% of the primary energy used to produce 23,100 terawatt-hours (TWh) in 2013 (BP, 2014a). From 2011 through 2013, fossil fuels contributed 67% of the primary energy used to generate about 4,050 TWh per year in the United States (EIA, 2014a).

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The bottom line is that the primary energy sustaining the global economy involves huge amounts of fossil fuels. Even with annual growth of 30% or more in the production of carbon-free solar and wind energy, growth is from a small base, and it will be many years before these sources can provide energy comparable to the scales associated with fossil fuels. By all estimates, global energy demand will continue to grow, and the demand for fossil fuels shows no sign of abating. Annual growth in GWP and global energy consumption – occurring mostly in developing, non-OECD nations – is projected to be 3.6% and 1.5%, respectively, through 2040, when demand for energy is expected to reach 820 quads with more than 75% supplied by fossil fuels (EIA, 2013b).

1.4 Energy, greenhouse gases, and the environment

Largely through their impact on air, water and/or land pollution, energy production and utilization are inextricably linked to the natural environment. If an energy source is to be used responsibly, harmful environmental consequences must be identified and reduced to acceptable levels.

Environmental concerns are not new, and in the second half of the twentieth century, several large movements were launched to curb environmental degradation. In the 1950s and 1960s, the focus was on moderating the use of harmful herbicides and pesticides in agriculture and on curbing water pollution. The clean air initiatives of the 1970s were directed at reducing emissions of pollutants such as oxides of nitrogen and sulfur from automobiles, aircraft and power plants. In the 1970s and 1980s, concerns for radioactive wastes produced by nuclear power plants, along with accidents at the Three-Mile Island (USA) and Chernobyl (USSR) plants, put a damper on further development of nuclear power in many nations. In the late 1980s and early 1990s, concerns for the depletion of stratospheric ozone resulted in the replacement of chlorofluorocarbons (CFCs) by more benign fluids in refrigeration and air-conditioning systems.

By the turn of the millennium, however, few environmental issues were drawing more attention than climate change, or more specifically, climate change due to human (anthropogenic) activity. Grade school children and their parents were learning about the greenhouse effect, greenhouse gases (GHGs) and global warming, while scientists and politicians across the globe were debating the gravity of the problem. But there's an important distinction to be made between anthropogenic climate change and other environmental issues. Because GHGs do not pose an immediate threat to human health and welfare, it is more difficult to make the case for mitigation.

Harmful effects of discharging GHGs into the atmosphere are manifested slowly, and absent measures to reduce emissions, serious consequences would increasingly be felt by future generations. This tendency to defer mitigation measures finds sustenance in two premises. Because the measures have associated costs, why spend today's dollars to deal with a problem that is not at hand? We can deal with the problem if and when we have to. And, if there is a problem, it's global in nature, since all nations share the same atmosphere. Why should one nation or a group of nations step up and bear the costs of reducing GHG emissions if all nations aren't willing to do so? Today, there are those who believe that global warming and climate change represent serious threats to future generations, while others are inclined to discount their significance. What is it about this issue that we can claim with certainty?

We know with absolute certainty that some atmospheric gases absorb radiant energy emitted by the Earth's surface, energy that would otherwise be transmitted directly to outer space. By trapping this energy, the gases act much like the glass cover of a greenhouse, which transmits solar radiation into the greenhouse but restricts outflow of radiation emitted by contents of the greenhouse.

Greenhouse gases exist naturally in the atmosphere, largely in the form of carbon dioxide (CO_2) and water vapor $(H_2O)_{vapor}$. Without them the Earth would be a colder and less hospitable planet. But what happens when human activities release greenhouse gases to the atmosphere at a rate that exceeds the ability of the Earth's ecosystems to remove them? Few would dispute the contention that, as the concentrations of greenhouse gases increase, more of the Earth's emitted radiation is absorbed by the atmosphere and the Earth's temperature must increase. But by how much, and is the effect significant or negligible relative to changes driven by natural agents? If anthropogenic agents are significant, what effect would global warming have on the Earth's environmental, economic and social systems?

Those who express concern for anthropogenic climate change point to the steady increase in atmospheric GHG concentrations since the middle of the eighteenth century, which marks the onset of the Industrial Revolution. Although greenhouse gases come in many forms, such as methane (CH_4), nitrous oxide (N_2O) and numerous industrial chemicals, carbon dioxide receives the greatest attention. From 1760 to 2014, atmospheric concentrations of CO_2 increased from approximately 280 to 400 parts per million (ppm) by volume, largely due to the burning of fossil fuels and secondarily to deforestation and other land-use changes.

There are two onerous implications of using fossil fuels: (1) the store of highly concentrated and valuable forms of energy is irreversibly reduced, and (2) the natural environment is degraded by their use. In both cases, there is a depletion of natural capital, in one case manifested by loss of the fuels themselves and in the other by degradation of the environment into which their waste products are discarded. According to Daly (1996, p. 49), "The evolution of the human economy has passed from an era in which man-made capital was the limiting factor in economic development to an era in which remaining natural capital is the limiting factor." It is debatable whether that transition has already occurred, and whether it is imminent will depend a good deal on mankind's ability to innovate. Nevertheless, the point is well taken. There is an upper limit to the use of natural capital that is determined by the "regenerative or absorptive capacity" of the environment, a limit or "anthropogenic optimum" for which the "marginal benefit to human beings of additional man-made capital is just equal to the marginal cost to human beings of sacrificed natural capital." In the context of global warming, what is the absorptive capacity of the Earth's atmosphere – an important constituent of natural capital – for greenhouse gases?

Although the use of fossil fuels was virtually nonexistent before 1760, it has since grown exponentially, becoming a cornerstone of human economic activity. In the preceding section we noted that fossil fuels account for more than 80% of global energy consumption. In 2013, CO_2 emissions from fossil fuels reached a new high of 35.1 billion metric tons (35.1 Gt-CO_2), with contributions of approximately 43%, 37% and 20% from the combustion of coal, oil and natural gas, respectively (BP, 2014a). With rapid economic and population growth in developing nations more than offsetting recessionary effects in developed nations, emissions increased at an average annual rate of 2.1% from 2008 to 2013. And with sustained economic and population growth in developing regions of the world, as well as continued high demand in developed nations, fossil fuel consumption and CO_2 emissions will continue their upward trajectory for the foreseeable future.

A critical question concerns the extent to which the concentration of atmospheric carbon dioxide (and other GHGs) can increase and still remain at levels that allow for human adaptation to potential climate change. One view is that a CO_2 concentration of 450 ppm represents a threshold for which the increase in the global mean surface temperature above preindustrial levels would be limited to two degrees Celsius (2°C)