CHAPTER 4
Energy

As demonstated in the previous chapter, energy is a major driver of the economy. Different sources of energy have different environmental impacts. Physical laws govern the conversion and use of energy. This chapter examines the role energy and energy systems play in sustainability.

4.1 DEMAND FOR ENERGY SERVICES

Modern life requires energy for everything. It runs the food and agricultural system (see Chapter 7), provides transportation for people and goods (see Chapter 8), enables habitable homes and buildings in adverse climates (see Chapter 9), and assists construction of urban and rural infrastructure (see Chapter 10). In short, energy runs economies (see Chapter 3).

But energy is not purchased for its own sake. Rather, energy is purchased for the services it provides when consumed in end use devices. Liquid fuels provide transportation when burned in automobiles, trucks, and planes. Electicity provides illumination when consumed by electric lights. Coal provides space heating when burned in a stove.

Energy is quantified in joules, which represent its heat equivalent.

4.2 ENERGY SUSTAINABILITY CHALLENGES

Providing energy for modern society is a significant sustainability challenge because of both resource depletion and emissions concerns. As discussed in Chapter 1, examination of sources and sinks is a helpful way to understand sustainability challenges, and the source/sink framework is applied in this chapter. Energy sources can be classified as renewable (solar, wind, hydro, and biomass) or nonrenewable (fossil fuels). Resource depletion and emissions concerns arise from the consumption of nonrenewable energy resources. (Energy sinks, or more precisely, sinks for products of combustion, will be discussed below.) This chapter discusses resource depletion and emissions in turn, with a focus on fossil fuel resource depletion and greenhouse gas (GHG) emissions.

4.2.1 RESOURCE DEPLETION

Depletion of nonrenewable natural resources is a complex processes, involving natural phenomena, human wants and needs, and technology. A calculus-based model can be used to describe depletion processes succinctly. All resources have a generation rate ($\dot{g}$), which is the speed with which the resource is re-created by natural or human processes. Natural resources can be consumed at a rate ($\dot{c}$), the speed with which the resource is removed from nature and consumed by human society or animals. The initial stock of a resource (s) at time t_0 is given by s_0. The stock level, the generation rate, and the consumption rate can be functions of time ($s(t)$, $\dot{g}(t)$, $\dot{c}(t)$) such that the remaining stock can be calculated at any time t by

$$s(t) = s_0 + \int_{t=0}^{t=t} \left[\dot{g}(t) - \dot{c}(t)\right] \, \mathrm{d}t \, . \tag{4.1}$$

When $\dot{g} < \dot{c}$, a resource is being depleted When $\dot{g} > \dot{c}$, a resource is recovering. For some renewable energy resources, such as solar and geothermal heat at some sites, $\dot{g} \gg \dot{c}$, and the resource is virtually limitless. Some energy resources are potentially renewable, such as biomass. For biomass, the relationship between $\dot{g}$ and $\dot{c}$ depends on local growing conditions and harvesting rates. Afforestation entails sustainable management of a forest such that $\dot{g} > \dot{c}$. Deforestation occurs when $\dot{g} < \dot{c}$. For nonrenewable energy resources, such as coal, oil, and natural gas, the natural rate of generation is very low ($\dot{c} \gg \dot{g} \approx 0$), so these resources are always being depleted by consumption.

For cost reasons, resources are extracted from the easiest sites first, such as oil from west Texas or coal from near-surface seams. All other things being equal, as the stock of nonrenewable resources declines, extraction costs are expected to rise when increasingly difficult sites are used. Examples include oil from offshore platforms and coal from kilometers-deep mines. On the other hand, technological advances (including new, efficient machines and techniques for resource extraction) put downward pressure on extraction costs, even as resources deplete. In the end, the extraction cost of nonrenewable energy resources is a race between depletion and technology.

On the other side of the supply–demand divide, continued demand for a depleting, nonrenewable resource will tend to push its unit price upward as the nonrenewable resouce becomes increasingly scarce.

If society continues to consume a nonrenewable energy resource at a constant rate $\dot{c}$ indefinately (remember that $\dot{c} \gg \dot{g}$ for a nonrenewable resource), its stock ($s(t)$) will eventually go to 0. But $s \to 0$ is not the expected long-run outcome for nonrenewable resources. Rather, extraction will cease (and $\dot{c} \to 0$) when the cost of extraction exceeds the market price for the nonrenewable energy resource. $\dot{c} \to 0$ will occur before $s \to 0$ as a resource becomes increasingly scarce, because the extraction cost will eventually exceed the price that consumers are willing or able to pay. The level of s at which production stops is the amount of the resource "left in the ground." The ultimately recoverable fraction (r) of initial resource stock (s_0) will be determined by the economic dynamics between market price and extraction costs. It is very likely that society will not extract ***all*** of any nonrenewable energy resource; the hardest-to-reach deposits will remain in the ground.

If sustainabilty is defined as continuing an activity indefinitely (see Chapter 1), $\dot{c} > 0$ is unsustainable for any nonrenewable resource for which $\dot{g} \approx 0$. Any consumption of nonrenewable resources is, by definition, unsustainable. Thus, ongoing consumption of the nonrenewable resources coal, oil, and natural gas is unsustainable. But given that modern society is thoroughly dependent upon those nonrenewable energy resources, a reasonable question arises: how long can society maintain its current consumption rates of nonsustainable energy resources? To answer that question, s must be calculated, implying that s_0 must be determined at some time t_0. Furthermore, extraction costs as a function of $s(t)$ must be predictable, meaning that price and technology forecasts are needed. And demand for an increasingly scarce resource must be estimable. Predicting the future is a tricky business indeed.

The economic dynamics among supply, demand, technology, scarcity, prices and extraction costs are complex. But simple calculations which ignore the economic dynamics can be performed to obtain estimates of remaining time available for various resources.

Using coal as an example, Rutledge [2, p. 22] estimates the initial stock of coal to be $s_0 = 784$ Gt[a] and the amount of coal consumed to 2017 to be 400 Gt, leaving 384 Gt in the ground as of 2018. The world consumption rate for coal in 2017 was $\dot{c} = 7549$ Mt/year [4, p. 7]. Dividing the remaining coal by today's extraction rate gives the years of coal extraction remaining (Δt).

$$\Delta t = \frac{384 \text{ Gt}}{7549 \text{ Mt/year}} \frac{1000 \text{ Mt}}{1 \text{ Gt}} = 50.9 \text{ years} \tag{4.2}$$

This simple calculation indicates that the world would "run out" of coal in 2070, neglecting economic dynamics. In fact, extraction rates are expected to decline as nonrenewable resources are depleted, so the date at which $\dot{c} \to 0$ is likely sooner.

Rutledge [2, p. 22] used an analysis method that accounts for declining exraction rates as resources deplete. His more-detailed analysis puts the "end of coal" at 2066. Despite its obvious shortcoming, the result

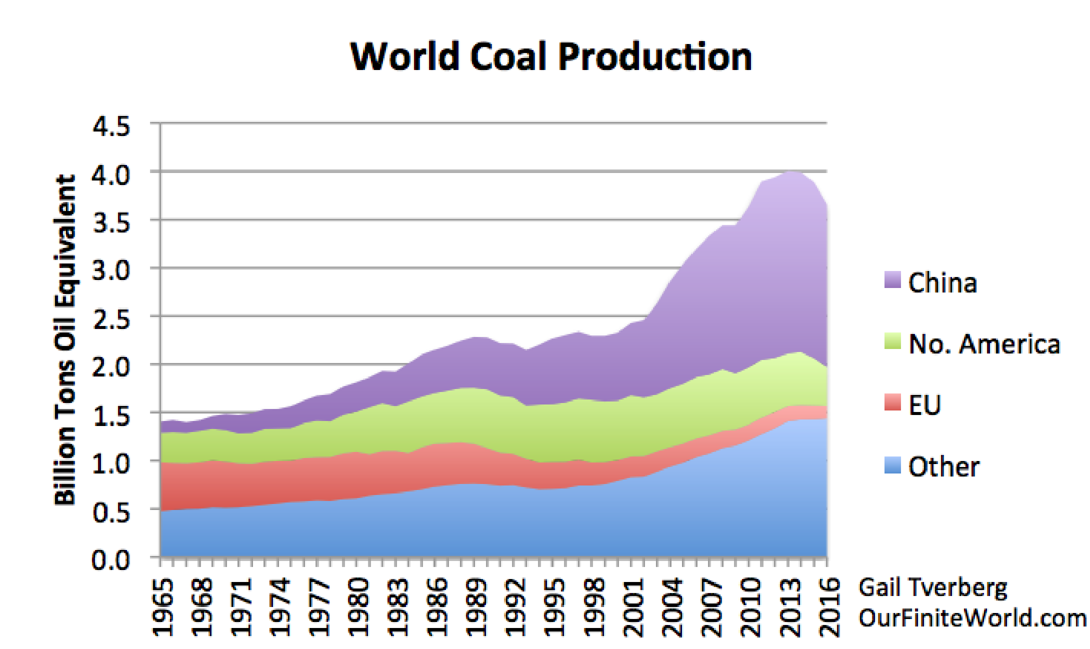

Figure 4.1: World coal production.

of the simple calculation shown above (2070) is quite close to the result of the detailed analysis (2066).

Indeed, this simple method can yield helpful insights when a resource extraction rate is in decline, as coal is today. (See Figure 4.1.) In particular, the simple method can provide an estimate for a timeframe for planning a transition away from nonrenewable resources prior to their depletion.

[a]Rutledge's estimation approach assumes that nonrenewable resource production follows a logistic curve through time. See Rutledge [3] for a description of the method. The estimate of $s_0 = 784$ Gt is from a 2018 presentation [2, p. 22] by the same author.

4.2.2 EMISSIONS

Emissions from fossil fuel consumption include greenhouse gases, primarily CO_2. In the Earth's atmosphere, accumulation of all types of greenhouse gases (CH_4, N_2O, HFCs, and PFCs in addition to CO_2) warms the Earth and disrupts natural climate systems that were in balance for millennia before the industrial revolution. Table 4.1

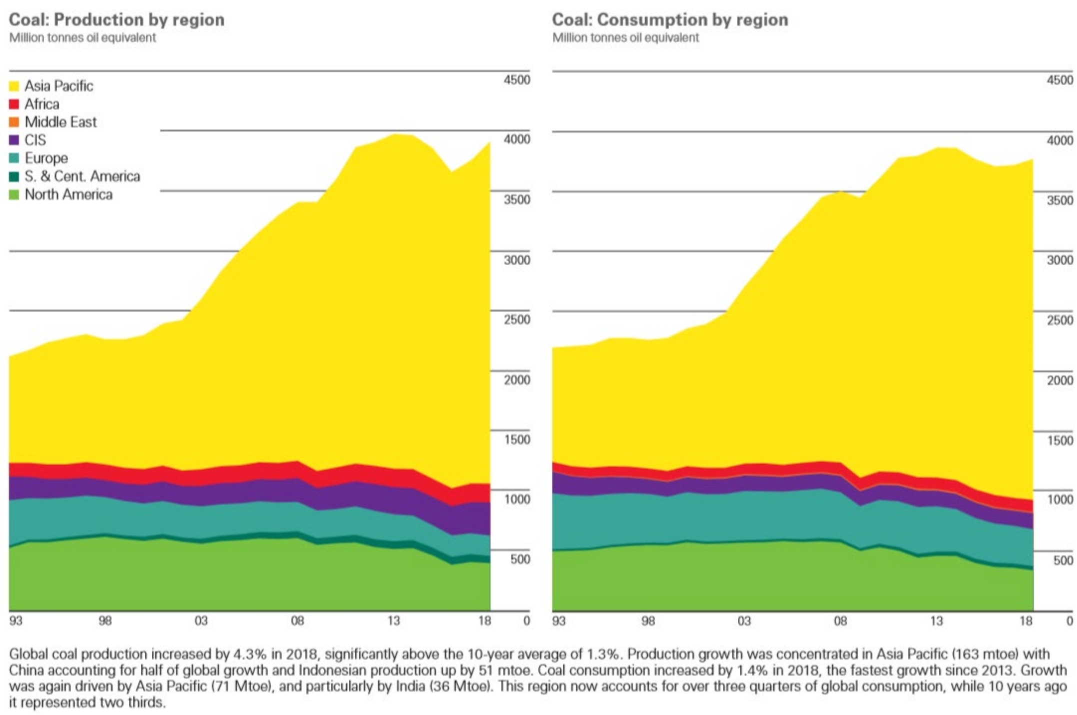

Figure 4.2: World coal production 1993-2019.

Table 4.1: Global warming potential (GWP) of various atmospheric gases [5, Table 8.7, p. 714]

	GWP (100 years)
CO_2	1
CH_4	34
HCFC-134a	1550
CFC-11	5350
N_2O	298
CF_4	7350

shows the global warming potential[1] for several greenhouse gases. To avoid irreversible effects of climate change, climate scientists say that global average temperature increase relative to pre-industrial times should be limited to 1.5 °C or less.

Figure 4.3 shows a Sankey diagram the proportions of GHG emissions from several *sources*. In the source/sink framework, GHG emissions from fossil fuel combustion are a significant source. Other sources include agricultural activity (especially livestock farming, which emits CH_4 in copious amounts) and decomposition of landfill waste (especially organic matter, which releases methane and nitrous oxide into the atmosphere).

Sinks for products of combustion include the atmosphere, the Earth's crust, and bodies of water. Sinks absorb the wastes from fossil fuel consumption, including gases (CO_2 and H_2O), lightweight solids (particulate matter), and heavy solids (ash and heavy metals).

Another important sink for GHGs is plants and trees, which absorb CO_2 to support their growth. (See Chapter 10.) However, land use changes (especially deforestation) reduce the number of trees, thereby reducing the planet's CO_2 sequestration capability. Furthermore, energy, especially diesel to operate heavy equipment, is required to cut down trees. Thus, deforestation both (a) reduces GHG sequestration and (b) contributes to GHG emissions. (Afforestation, on the other hand, enhances the planet's capacity to remove CO_2 from the atmosphere.) Taken together, the continuous rise of fossil fuel consumption and the steady pace of deforestation have amplified the sources and diminished the sinks of atmospheric GHGs, leading to annual increases in CO_2 concentration since measurements began in the late 1950s. (See the Keeling curve, Figure 4.4 [7].) The latest climate science [8, Fig. SPM.1]

[1] Global warming potential is "the total energy added to the climate system by a component in question relative to that added by CO_2" [5, p. 711].

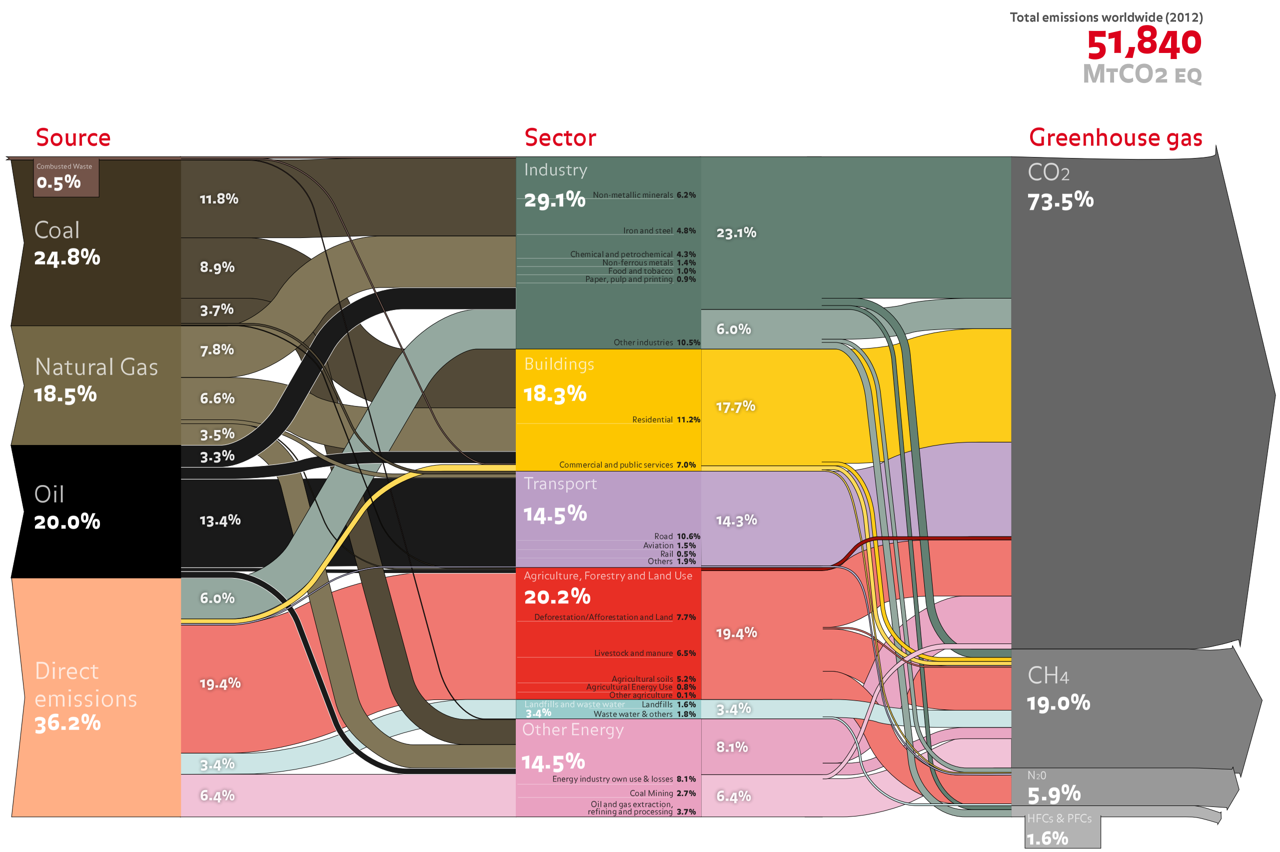

Figure 4.3: World greenhouse gas emissions, 2012 [6].

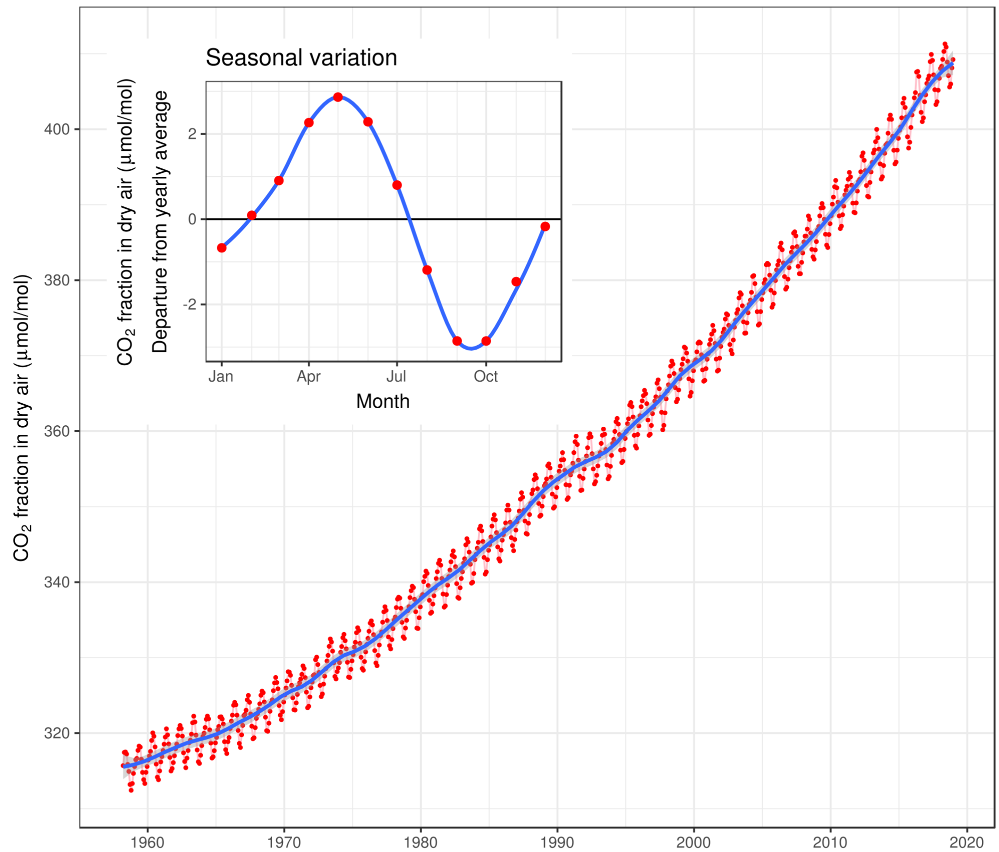

Figure 4.4: Monthly mean CO_2 concentration measured in-situ at Mauna Loa, Hawaii, 1958–2018 [7]. Data from Keeling et al. [9].

indicates that humanity has only 1–2 decades before reaching the dangerous 1.5 °C warming level.

Economic activity (see Chapter 3) drives energy consumption, the largest source of GHG emissions. So it is not a stretch to say that the global economy drives energy demand and serves as the ultimate cause of GHG emissions. Figure 4.5 is a Sankey diagram that shows the economic sources of energy demand in the U.S. Transport is largest single source of demand, followed by the industrial sector, the residential sector, and the commercial sector.

Figure 4.5 provides data to calculate the energy efficiency of each sector, because it shows the amount of energy that provides useful service to society relative to the amount of energy that is wasted. For example, the efficiency (η) of the U.S. electricity

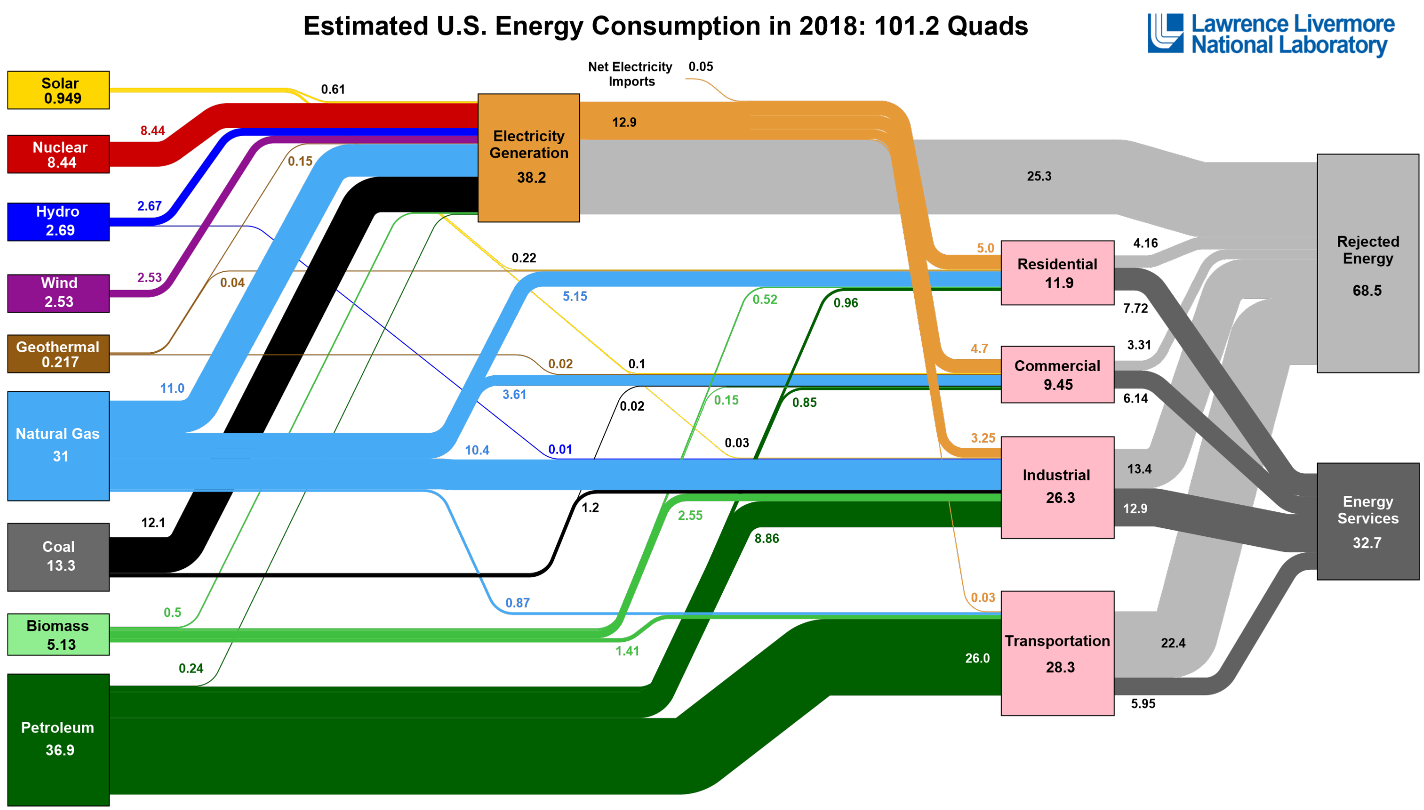

Figure 4.5: U.S. energy flows Sankey diagram, 2018 [10].

generation sector is

$$\eta = \frac{12.9 \text{ quads}}{38.2 \text{ quads}} = 34\ \% \ . \tag{4.3}$$

(A quad is 1 short quadrillion BTUs, or 10^{15} BTU.)

4.3 ENERGY TRANSITIONS

A transition to renewable primary energy sources and away from unsustainable fossil fuels (natural gas, coal, and petroleum) could eliminate GHG emissions from fossil fuel consumption, while still meeting the energy needs of society and the economy. A fossil-to-renewable energy transition would help to put the world on a sustinable energy trajectory. Figure 4.5 shows how little U.S. energy is supplied (at present) by renewable sources (solar, hydro, wind, geothermal, and biomass). There is a long way to go, and a fossil-to-renewables transition faces several challenges, three of which are time, money, and backfire.

Time Throughout history, societies have used different primary energy sources in varying proportions. Longitudinal analysis of those proportions reveals the speed of past energy transitions and may suggest the time needed for a future fossil-to-renewables transition. Figure 4.6 shows a longitudinal analysis of United Kingdom primary energy transitions from 1500–2000. The figure shows that the UK's transition from food, feed, and biomass to coal took many centuries. The ongoing transition from coal to petroleum (liquid fuels) and natural gas will take at least a century. The depletion and emissions timeframes (51 years and 10–20 years, respectively) can be compared to find that the emissions timeframe is more challenging than the depletion timeframe. A two-decade transition from fossil fuels to renewables driven by emissions concerns would be unprecedented. The time challenge is this: can society effect a worldwide fossil-to-renewables transition in one or two decades to limit global warming to less than 1.5 °C?

Money An optimistic (and much-criticized) analysis of the requirements for a fossil-to-renewables (wind, water, and solar, or WWS) transition was provided by Jacobson and Delucchi [2011, 2011]. They estimated that "construction cost for a WWS system might be on the order of $100 trillion worldwide, over 20 years, not including transmission" [14, p. 64]. For context, the $5 trillion annual cost is 7.2 % of world GDP ($69 trillion/year). The money challenge is this: what funding source will provide the necessary monetary resources for a fossil-to-renewables transition in the timeframe of a decade or two? (See Chapter 11.)

Backfire Many suggest that investing in technical efficiency improvements for energy conversion machines (such as power plants, automobiles, and lights) will reduce

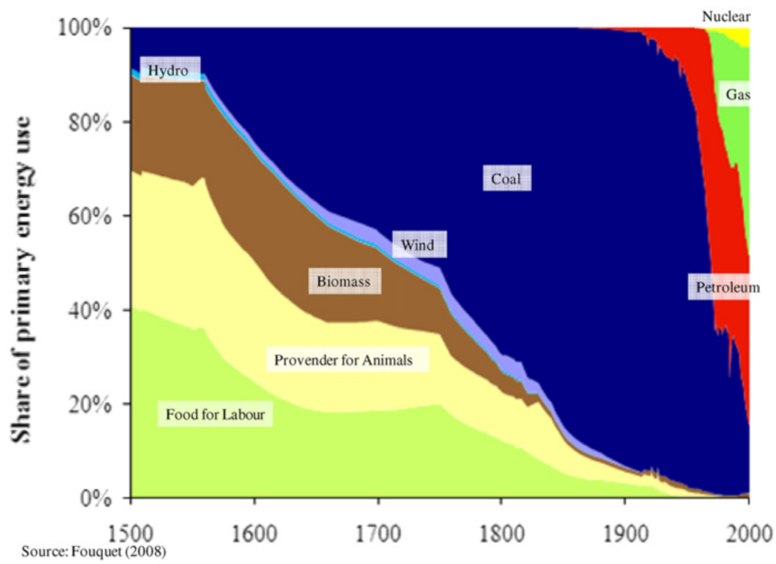

Figure 4.6: UK primary energy transitions, 1500–2000 [11, Fig. 5].

primary energy consumption and GHG emissions, while continuing to supply the end-use energy needed for the economy. However, rising energy efficiency is correlated with increased GDP, and rising GDP is correlated with increased primary energy consumption [15]. The relationship between efficiency and economic growth is complex and dynamic, but at least two mechanisms are involved: (a) rising GDP means more money available to invest in new machines and equipment with higher energy efficiency, thereby increasing the aggregate energy efficiency of the economy over time, and (b) rising aggregate energy efficiency means that less money is spent to obtain energy, more money is available for other economic activity, and the economy expands as a result. That is, energy efficiency–GDP feedback through the wider economy "takes back" efficiency-driven reductions in energy consumption (and associated CO_2 emissions), a phenomenon known as the "rebound effect" [16, 17]. In the extreme, increases in energy efficiency can lead, counterintuitively and perversely, to *increased* energy consumption, a phenomenon known as "backfire." (Increases in steam engine efficiency led to dramatically increased coal consumption in the UK at the dawn of the industrial revolution; see Sorrell [18, p. 1787].) The efficiency backfire challenge is this: can energy efficiency be deployed to reduce energy-related GHG emissions *without* inadvertantly stimulating the economy, thereby increasing energy consumption and GHG emissions?

QUESTIONS

4.1. Choose another nonrenewable resource besides coal. Perform your own research to find (a) estimates of the remaining stock of that resource and (b) the world's present consumption rate. Perform a simple calculation to estimate the remaining years of the nonrenewable resource. Can you envision a transition away from reliance upon this nonrenewable resource in the timeframe available? What would be required for such a transition?

4.2. What is the energy efficiency of each economic sector in Figure 4.5? Are the efficiencies larger or smaller than expected? Compare the efficiency of the electricity generation sector to the Carnot efficiency of a heat engine operating between a typical coal combustion temperature and atmospheric temperature.

4.3. The cost of the WWS fossil-to-renewable transition proposed by Jacobson and Delucchi is very large. ($100 trillion over 20 years.) Compare the estimated cost for the fossil-to-WWS transition to costs for other large programs such as

- the U.S. Apollo program,
- the worldwide fight against HIV/AIDS,
- President Lyndon B. Johnson's Great Society program,

- President Ronald Reagan's Strategic Defense Initiative (SDI), and
- the U.S.' post September 11, 2001 wars in Iraq and Afghanistan.

4.4. Find several critiques of the WWS proposal. Find at least three costs that the WWS proposal neglected. Given the critiques and the additional costs, what is an updated estimate for the cost of the fossil-to-WWS transition? On annual basis, what percentage of world GDP does the updated cost of the transition represent?

4.5. How much is spent annually on the fossil-to-renewable transition worldwide? Is the spending commensurate with the investment needed for a complete transition in the timeframe available before reaching 1.5 °C climate warming?

4.6. The source of money for a WWS transition was discussed the chapter. But the source of energy for a fossil-to-renewables transition must also be considered. What will be the source of the energy to develop and emplace renewable energy systems on a worldwide scale? Depending on the speed of a fossil-to-energy transition the renewable energy sector might not serve as a net energy provider for a time! Read Dale and Benson [19] and provide an assessment of whether the solar PV industry is a net energy provider or a net energy consumer today. What are the sustainability implications of your findings?