The Multifaceted Nature of Sustainability Challenges: An Engineering Perspective

The Multifaceted Nature of Sustainability Challenges

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ABSTRACT

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Acknowledgments

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CHAPTER 1

Foundational concepts related to sustainability (JVA 1)

Are humans living "sustainably?" If not, then humanity will, at some point, either cease to exist as a species or experience drastic reductions in our standard of living. Thus, the question of whether human society is living in a sustainable manner is a question of utmost importance. The purpose of this book is to summarize the evidence that humans are not living sustainably and to show the characteristics of sustainable societies. The challenges associated with transitioning to a sustainable existence are complex and interconnected.

1.1 DEFINITIONS OF SUSTAINABILITY

Sustain means to endure, to continue, and to last. Many authors have written about sustainability and it may seem that each has a unique definition of sustainability. The most commonly cited definition of sustainability is that sustainability means meeting "the needs of the present without compromising the ability of future generations to meet their own needs" [1]. Sustainability has three components, called the three pillars of sustainability (see Figure 1.1), which are environmental sustainability, economic sustainability, and social sustainability. Environmental sustainability inlcudes issues such as pollution, resource depletion, habitat loss, and biodiversity. Economic sustainability involves questions of profit and loss, wealth management, and macroeconomic policy. Social sustainbility comprises human and civil rights, suffering, and personal freedom. This book will discuss issues associated with each of these three areas of sustainability.

1.1.1 THE SCOPE OF SUSTAINABILITY

When considering the meaning of sustainability, the two most important questions are "sustaining what?" and "for how long?" The second of these question is perhaps easier to answer. While humans seem to have difficulty planning for time scales significantly

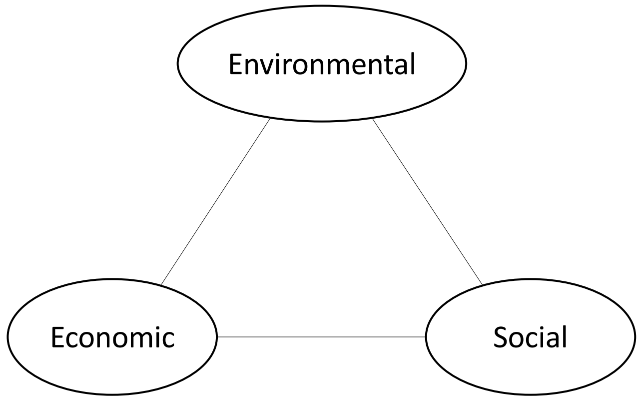


Figure 1.1: Three areas of sustainability.

longer than the human lifespan, true sustainaibilty is acheived only if the answer is "indefinitely" or "forever."

The narrowest answer for *what* needs sustaining is human life and society, which perforce entails those ecosystem services necessary for human health and wellbeing (see Figure 1.2). Beyond these basics, some people view the nonhuman world as having inherent worth or standing and, as such, to also be worth perserving, even if it has no (or negative, for example, smallpox) impact on human continuity. Unfortunately, humans don't know clearly what pieces of the ecosystem are, in the long run, necessary for survival and which aren't. For instance, would we be able to survive in a world without dandelions? Maybe. On the other hand, dandelions might be necessary for other organisms we depend on. Environmental science views the ecosystem in its entirety as a web, with all parts depending on all other parts. The ecosystem is viewed then, not as a individual components with binary "needed" "not needed" classifications but as a whole that exists on a continuum of "functional" to "nonfunctional."

In the outer ring is human-created devices and systems. Humanity could survive without the great pyramids of Giza, although we would have lost great cultural and historical artifacts. On the other hand, we may not survive if we don't give up coal-fired power plants.

Sustainability involves social and economic aspects as well as environmental (see Figure 1.1).

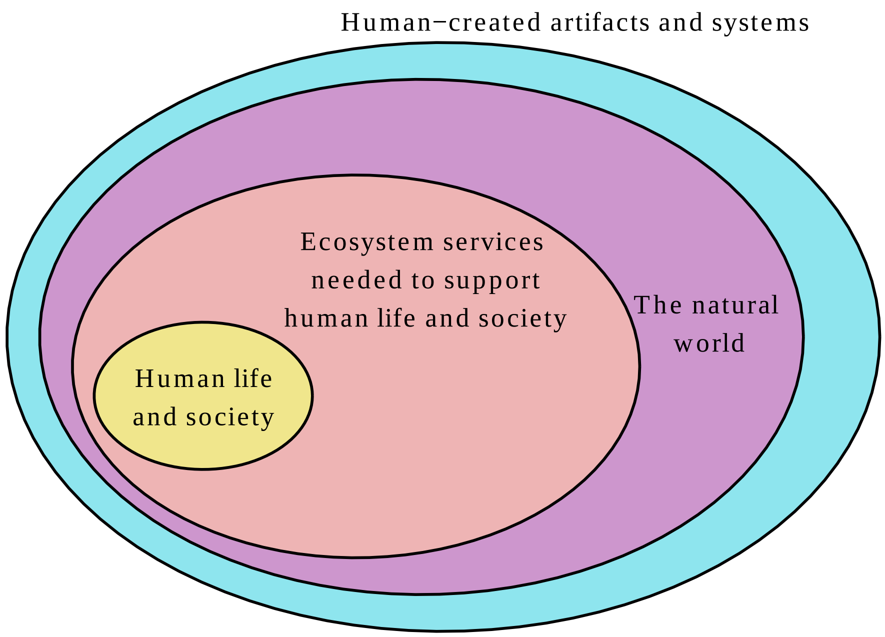


Figure 1.2: Sustainability hierachy.

1.2 HUMAN IMPACT ON THE ENVIRONMENT

The following identity, known as the IPAT equation, encapsulates a useful way to conceptualize the environmental impacts of human activity.

$$I = P \times A \times T$$

where P is human population, A is affluence, measured in per capita consumption, and T is technology, with units of environmental impact per unit of consumption. Although it is not commonly written in vector form, 1.2 could be written as a double summation of vector quantities.

$$\bar{I} = \Sigma_i \Sigma_j P_i \times A_{ij} \times \bar{T}_j$$

where index i refers to a country with population P_i and j refers to different categories of goods consumed. $\bar{T}_j$ is a vector of environmental impacts from producing/consuming good of type j and $\bar{I}$ is the vector of global environmental impacts, encompassing such things as global warming potential, aquifer depletion, and eutrophication.

The Kaya identity is similar to the IPAT equation but is specifically for greenhouse gases.

1.3 SOURCES AND SINKS

The IPAT equation works equally well for describing environmental *impacts* or the *resources* needed to support a certain level of consumption.

Human economic and social activity

1.4 MATHEMATICS OF SUSTAINABILITY

Both population (see Chapter 2) and affluence (see Chapter 3) have been growing exponentially. Economies are (typically) managed specifically for exponential growth by having a constant growth rate. Martingale rates and levels predictions and good enough

1.5 WHAT MAKES SUSTAINABILITY CHALLENGING

Complexity Our understanding of systems, natural as well as social, is limited.

Interconnectedness Everything relates to everything else.

Tradeoffs You can't ever do just one thing.

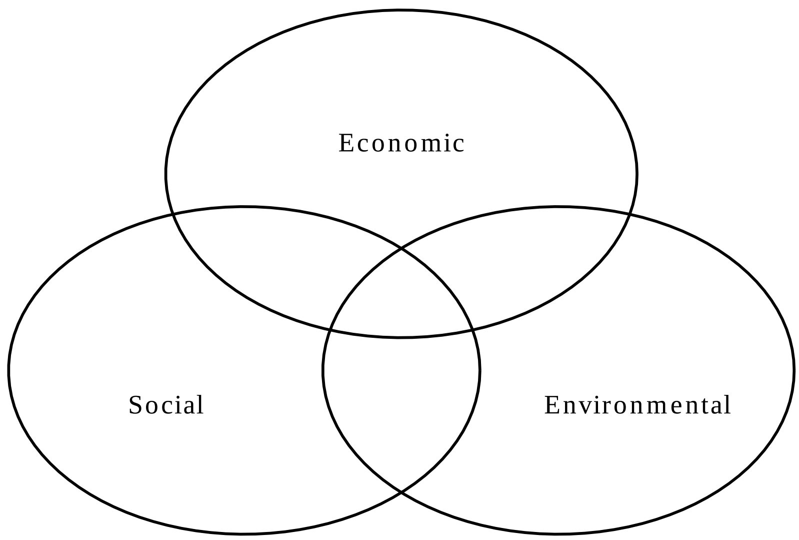


Figure 1.3: Three overlapping aspects of sustainability.

SUMMARY

In this chapter we have discussed very briefly some of the salient results from information theory and rate distortion theory and have indicated how these results can be used to bound communication system performance.

PROBLEMS

1.1. A random variable U has a sample space consisting of the set of all possible binary sequences of length N, denoted $\{u_j, j = 1, 2, \ldots, 2^N\}$.

1.2. Given a random variable U with the alphabet $\{u_1, u_2, u_3, u_4\}$ and probability assignments $P(u_1) = 0.8, P(u_2) = 0.1$, $P(u_3) = 0.05, P(u_4) = 0.05$, calculate the entropy of U. Compare your result to a random variable with equally likely values.

CHAPTER 2
Population

This chapter deals with human and nonhuman populations.

2.1 HUMAN POPULATION: PAST AND PRESENT

As shown in equation 1.2, human population has a major effect in determining our impact on the planet. It has been said, "It is difficult to make predictions, especially about the future." Predictions about future human popluations vary considerably. As it turns out, it is also difficult to make predictions about the past. Although scientists have estimated historical population levels, reliable data are limited. In April 2019, the population of humans was estimated to be 7,7 billion with a growth in 2019-2020 of 1.08%.

2.1.1 POPULATIONS OF THE PAST

Homo sapiens probably emerged as a species 100,000 to 200,00 years ago. In prehistoric times, the human population grew slowly. By 9000 BC there were 5 to 10 million humans. Around the year 1 AD there were around 300 million people, representing an average growth rate of about 0.1%. By 1650 AD, the world population was around 500 million. Average growth was slowed by trade and urbanization enabling infectious diseases to kill large numbers. For instance, the Black Death killed 75 to 200 million people in the 1300s. World population reached 1 billion (that is, 1,000 million) around 1800 AD. Over the couse of the twentieth century world population grew at an average rate of 1.55% per year with a peak growth rate of 2.1% between 1965 and 1970 (see Figure 2.1).

Population changes come from the birth rate and the death rate. Estimating the populations of antiquity is difficult because these rates are somewhat conjectural. However, estimates of the total number of humans to have lived are 100-110 billion.

2.1.2 WORLD POPULATION PROJECTIONS

Figure 2.2 shows projections made by the United Nations in 2010 about future human population. Future population depends on current population (known more-or-less accurately) and the birth rate and death rate. The wide range of uncertainty in the predicted population is indicative of the uncertainty surrounding future birth and

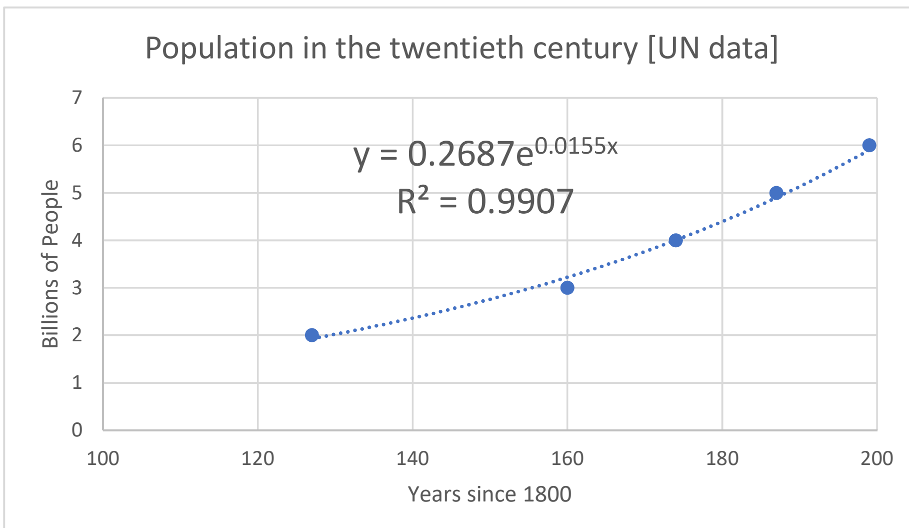


Figure 2.1: World population in the 20th century.

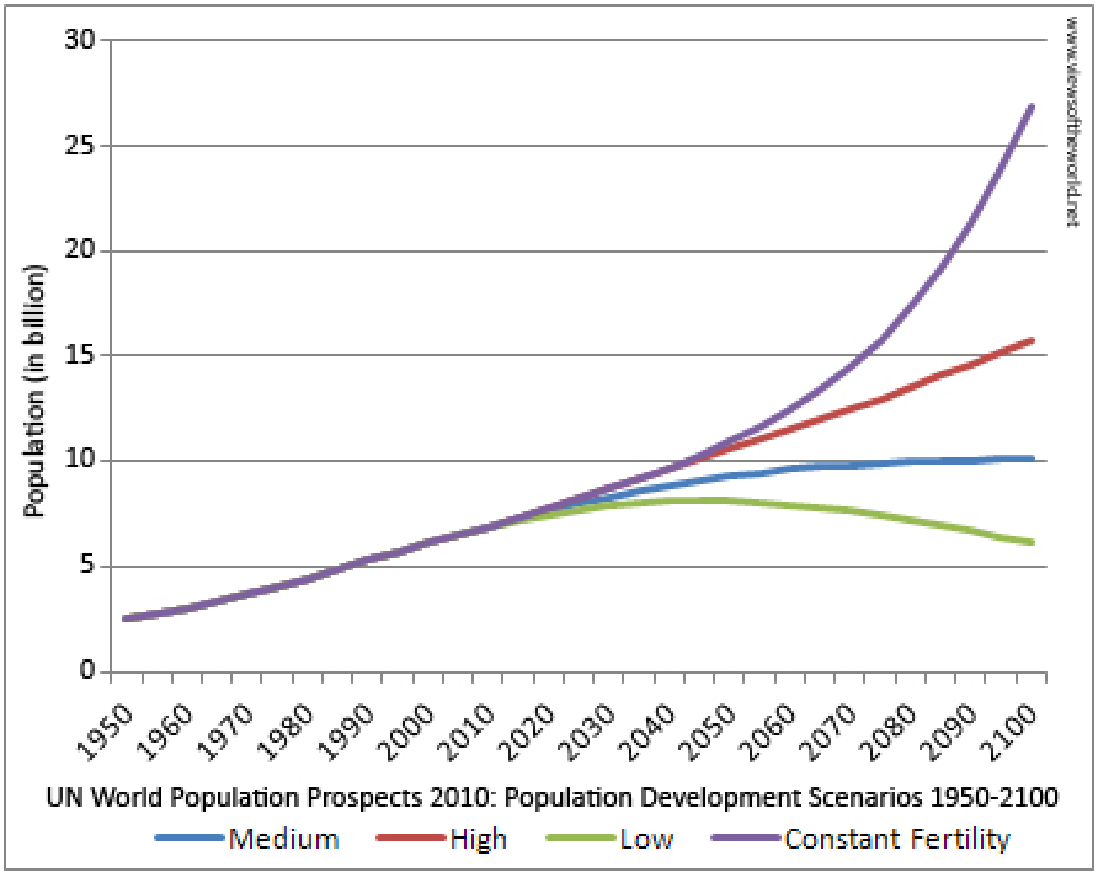


Figure 2.2: UN World Population Prospects 2010: Population Development Scenarios: 1950-2100.

death rates. Birth and death rates are dependent on many other variables. Figure 2.3 shows a schematic of the causal loops used in the World3 population model. Notice the number of variables (24!) and the many ways those variables (are thought to) interact. No model is perfact and, indeed, the World3 model is controversial (all predictions are). The point isn't to say that one model is right and another is wrong, but instead to point out the many variables that effect population. In fact, another population model produced around the same time used 200,000 equations.

2.1.3 DEMOGRAPHIC TRANSITION THEORY

In an undeveloped society, both birth rates and death rates are high, resulting in a low population growth rate. Demographic transition theory says that development leads

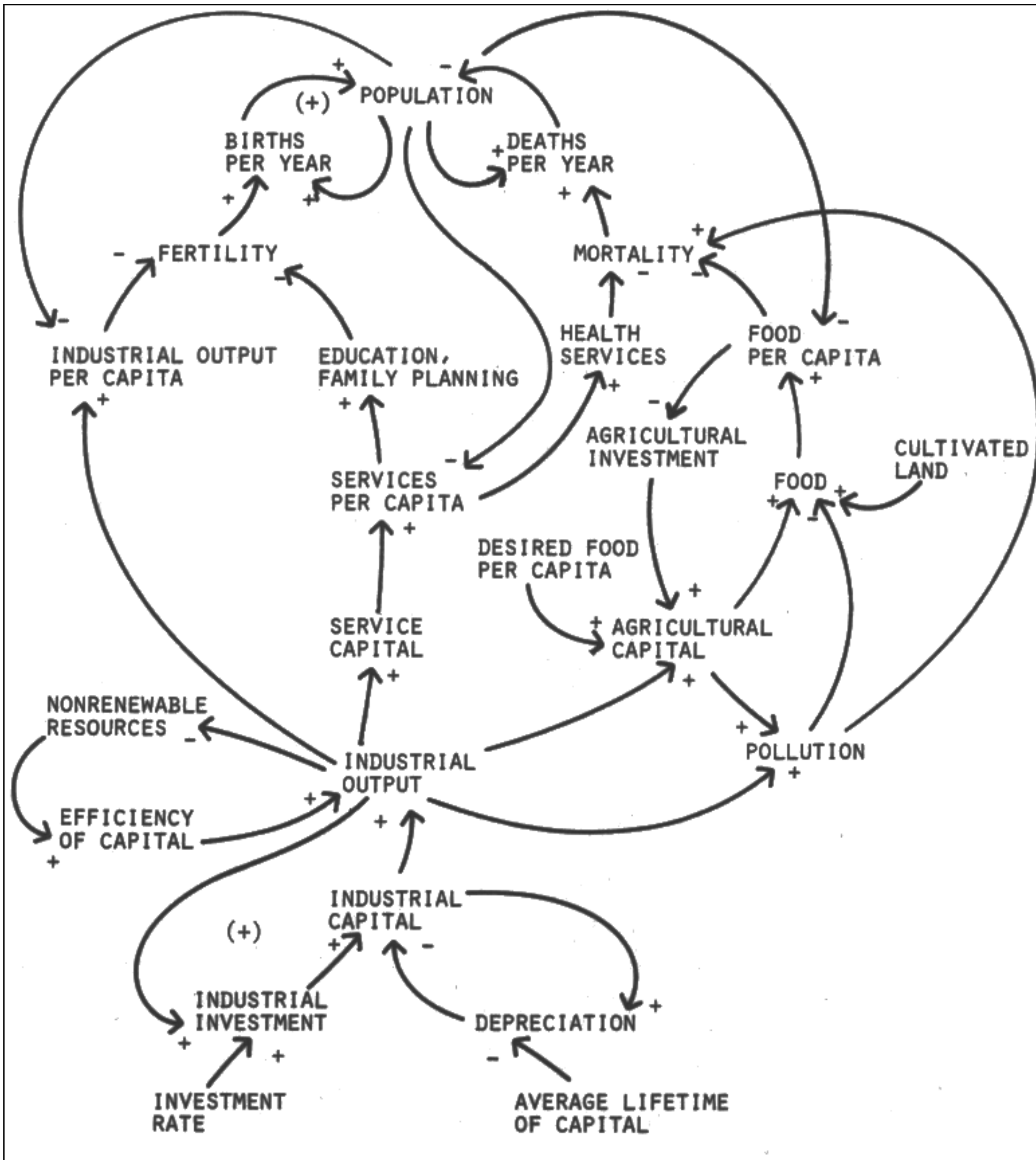


Figure 1-3 Causal-loop diagram of several important feedback loops in World3

Figure 2.3: Causal loop diagram of several important feedback loops in the World3 population model.

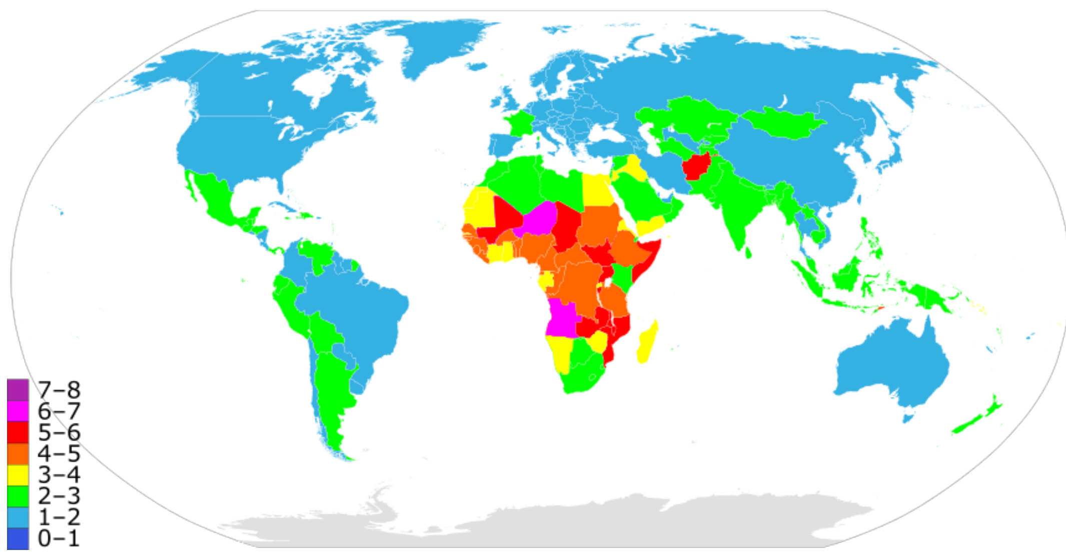


Figure 2.4: Map of countries by fertility rate (2018), according to CIA World Factbook.

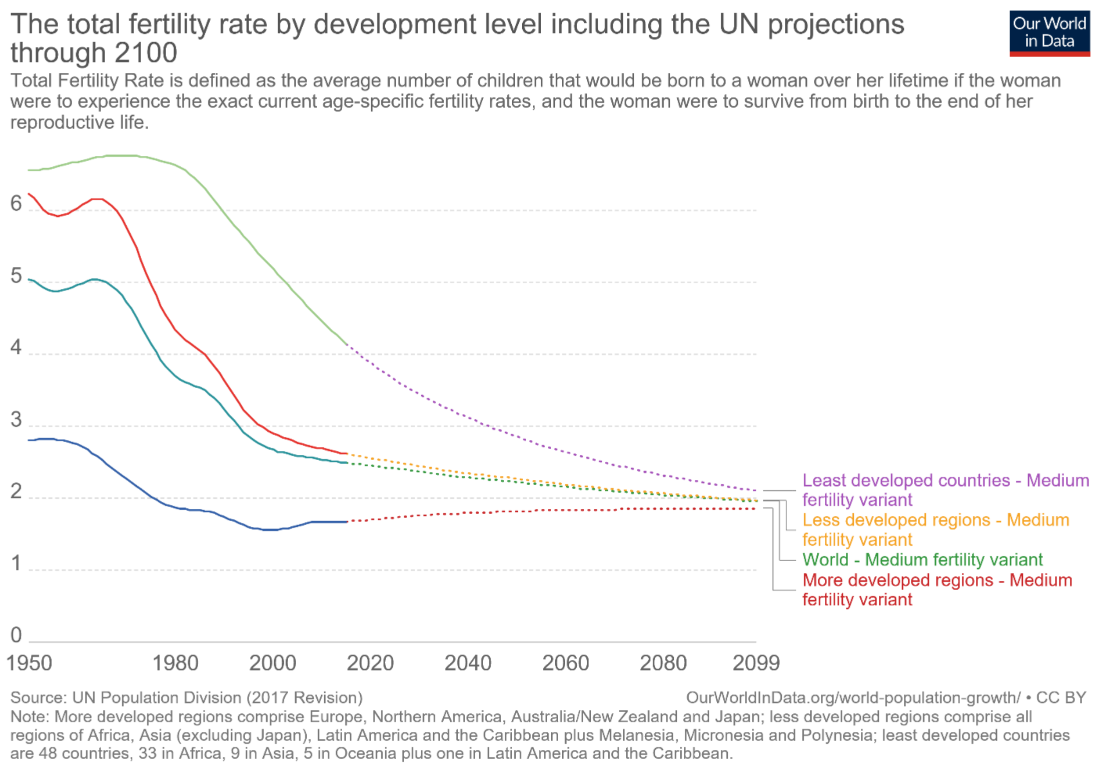


Figure 2.5: Total fertility rate by development level, including the UN projections through 2100.

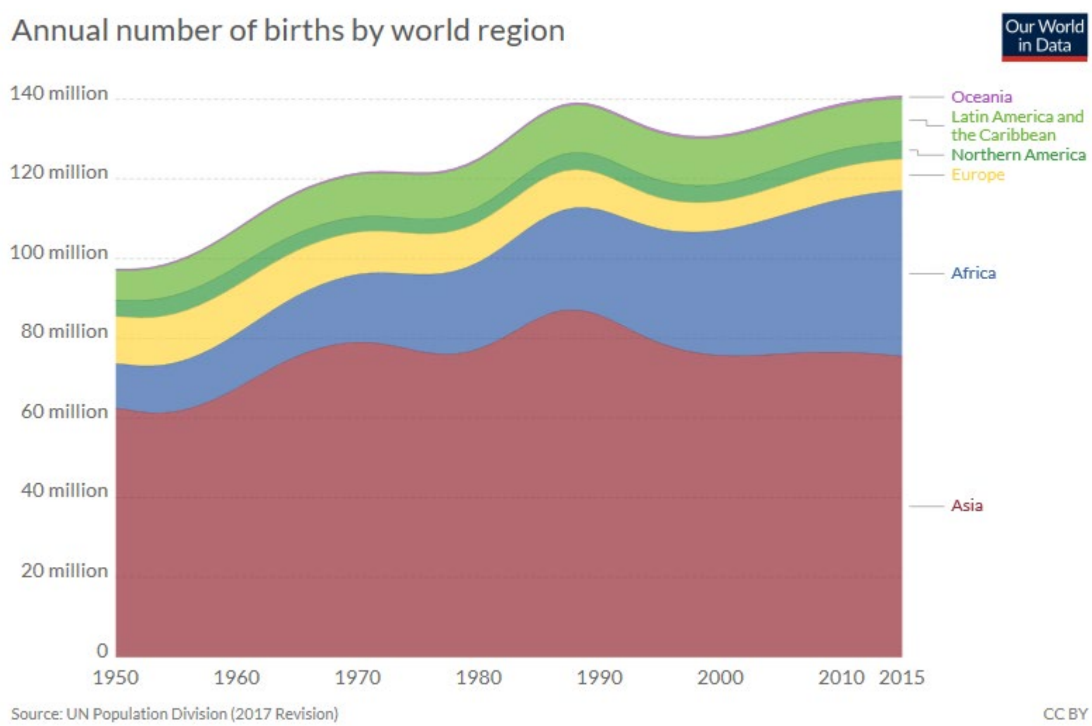


Figure 2.6: Annual number of births by world region, 1950-2015.

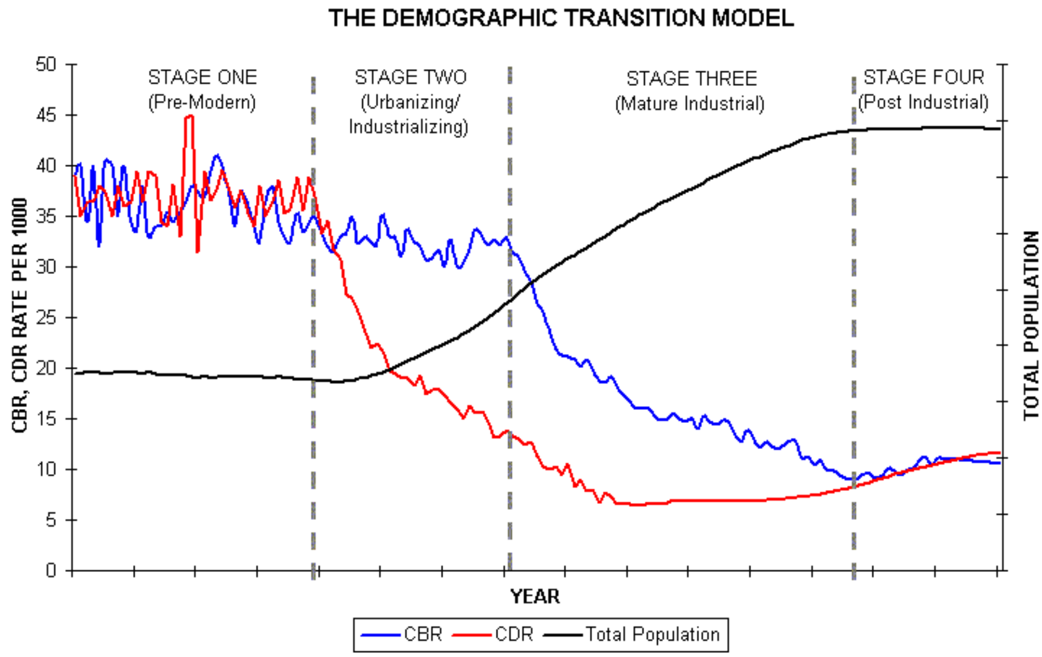


Figure 2.7: Schematic of demographic transition theory. Crude birth rate (CBR) and crude death rate (CDR) are defined as births or deaths per year per 1000 people in the total population (uncorrected for sex or age cohorts).

to a decrease in mortality followed some time later by a falling birth rate. Thus, the population will grow rapidly and then stabilize. Figure 2.7 illustrates schematically demographic transition theory.

2.1.4 DISTRIBUTION OF POPULATION

Where do people live? Given our goal of a sustainable society, where do we *want* people to live? In 2015, about half of the world's people live in an area, shown in Figure 2.8, known as the Valeriepieris circle. This circle has a radius of about 4,000km. Other researchers have since defined a more compact region (radius 3300km) with the same fraction of Earth's population.

Since the industrial revolution, humans have been increasinly living in urban environments. In 1973 there were only 3 cities (Mexico City, Tokyo, and New York City) with populations of more than 10 million people (megacities). Since 2005-2006 more than half of the world's population live in urban areas. Now there are 21 cities

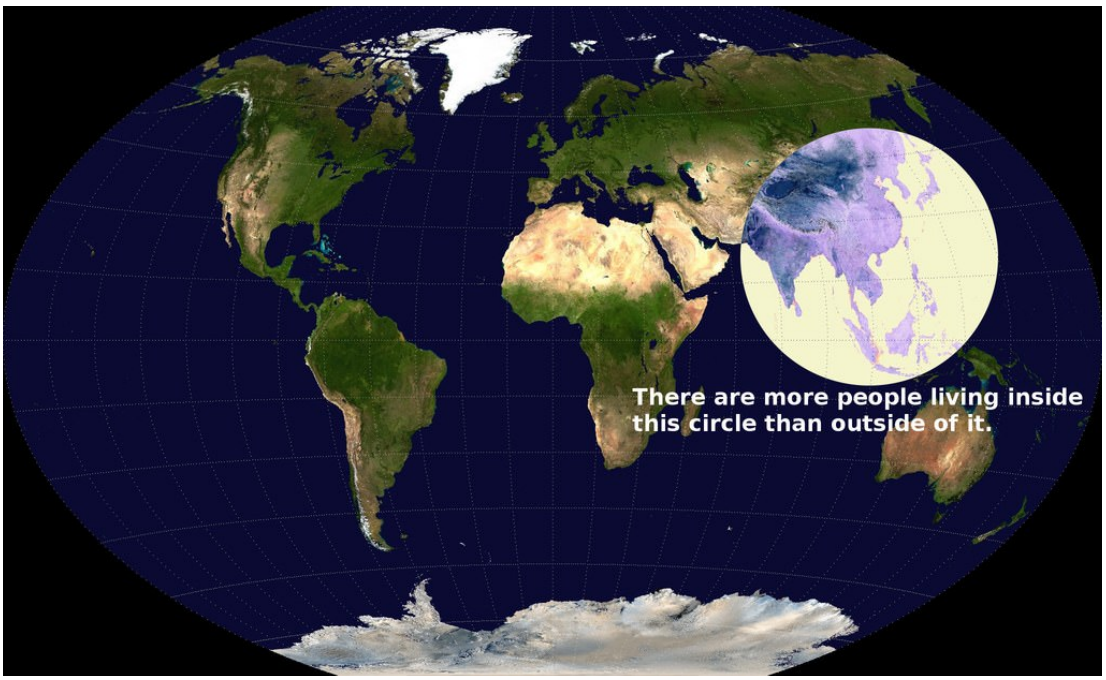


Figure 2.8: As of 2015, more than half the world's population lives in the Valeriepieris circle, a circular region centered in the South China Sea.

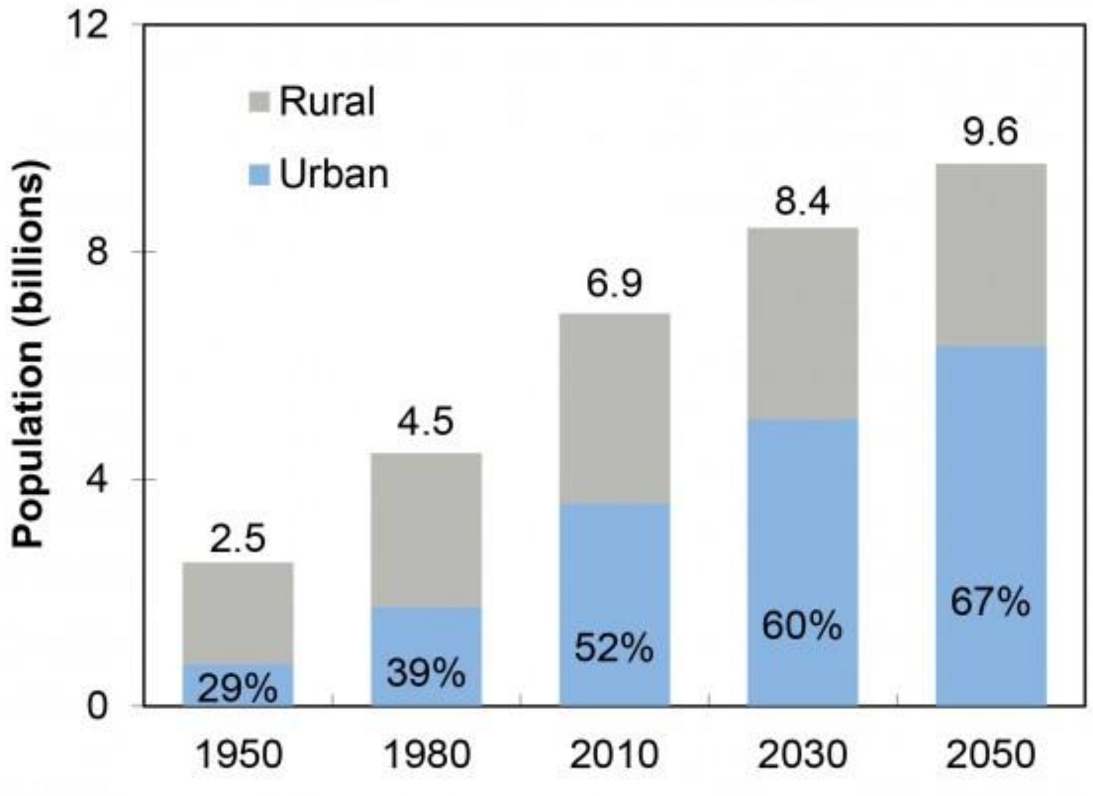


Figure 2.9: World Population Urban and Rural 1950-2050.

with populations of 10 million or more (see Figure 2.10 for more detail). The percent living in urban areas is projected to grow to 68% by 2050.

Urban living is correlated with wealth and higher GDP. High population density means mass transit is practical and, in fact, widely used. David Owens argues that Manhattan, being very dense, is the most ecological place to live. However, higher wealth partially offsets this.

> Cities are one of the big issues facing the planet. Hundreds of new cities are expected to be created across Africa and Asia in the course of the next century. Researchers believe that, if current population trends continue, Lagos, the largest city in Nigeria, could develop into a vast, sprawling metropolis of over eighty-five million people. Niger has the highest birth rate in Africa; Niamey, its capital, is expected to explode in size, from less than one million people to forty-six million by 2100. Unfortunately, the urban

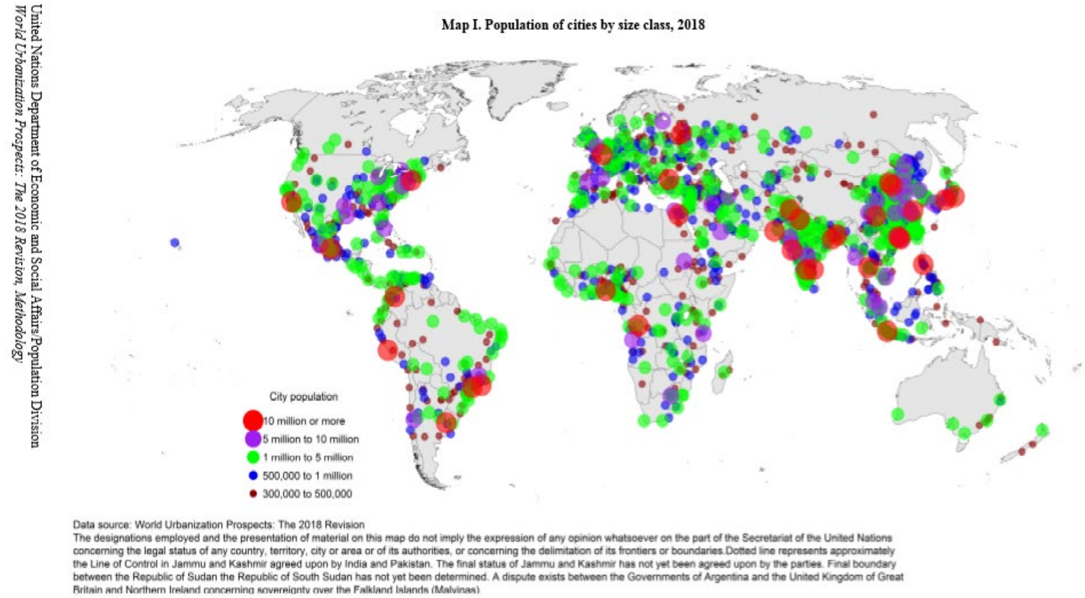


Figure 2.10: Population of cities by size class, 2018.

> expansion that has already taken place across the developing world has been ramshackle. Much of it has taken the form of shanty towns, where groups of shacks are crowded together with little sanitation or governance. This is brewing an obvious problem. The example of the West is, alas, little more encouraging. Much new development takes the form of suburban sprawl, which is wasteful of precious land, and has little character of its own. Young people are frustrated because they cannot break out of parental nests; the elderly feel isolated. And yet the pressure to build more housing—for reasons of immigration, increased life expectancy, and the creation of more households due to divorce—will increase, not abate. The need for master-planning has never been greater.

2.2 ANIMAL POPULATIONS

Populations of insects are down 80% in the last 30-40 years. Pollution plays a role. Pesticides have been hard on insects. Mostly these losses seem to be due to habitat loss and growing human populations. Where do we put the wilderness? The United Nations Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services summary report says 1 million animal and plant species are threatened with extinction. "In 2015, 33% of marine fish stocks were being harvested at unsustainable levels; 60% were maximally sustainably fished, with just 7% harvested at levels lower than what can be sustainably fished."

> In "The Once and Future World," the journalist J.B. MacKinnon cites records from recent centuries that hint at what has only just been lost: "In the North Atlantic, a school of cod stalls a tall ship in midocean; off Sydney, Australia, a ship's captain sails from noon until sunset through pods of sperm whales as far as the eye can see. ... Pacific pioneers complain to the authorities that splashing salmon threaten to swamp their canoes." There were reports of lions in the south of France, walruses at the mouth of the Thames, flocks of birds that took three days to fly overhead, as many as 100 blue whales in the Southern Ocean for every one that's there now. "These are not sights from some ancient age of fire and ice," MacKinnon writes. "We are talking about things seen by human eyes, recalled in human memory."
>
> What we're losing is not just the diversity part of biodiversity, but the bio part: life in sheer quantity. While I was writing this article, scientists learned that the world's largest king penguin colony shrank by 88 percent in 35 years, that more than 97 percent of the bluefin tuna that once lived in the

> ocean are gone. The number of Sophie the Giraffe toys sold in France in a single year is nine times the number of all the giraffes that still live in Africa.
>
> Scientists have begun to speak of functional extinction (as opposed to the more familiar kind, numerical extinction). Functionally extinct animals and plants are still present but no longer prevalent enough to affect how an ecosystem works. Some phrase this as the extinction not of a species but of all its former interactions with its environment — an extinction of seed dispersal and predation and pollination and all the other ecological functions an animal once had, which can be devastating even if some individuals still persist. The more interactions are lost, the more disordered the ecosystem becomes.
>
> It is estimated that, since 1970, Earth's various populations of wild land animals have lost, on average, 60 percent of their members. Zeroing in on the category we most relate to, mammals, scientists believe that for every six wild creatures that once ate and burrowed and raised young, only one remains. What we have instead is ourselves. A study published this year in the Proceedings of the National Academy of Sciences found that if you look at the world's mammals by weight, 96 percent of that biomass is humans and livestock; just 4 percent is wild animals.

(from the New York times https://www.nytimes.com/2018/11/27/magazine/insect-apocalypse.html)

University of Cincinnati geographers used satellite images to show that "22 percent of the Earth's habitable surface has been altered in measurable ways, primarily from forest to agriculture, between 1992 and 2015."

2.3 DISCUSSION QUESTIONS

1. How does wealth influence birth and death rates? Do different forms of wealth have different effects?
2. Why are birth rates falling? Falling birthrates are correlated with economic development. Attempt to explain the mechanism.
3. what things have a *higher* environmental impact as populations urbanize?
4. What do you like about living in "the city" or "the country?"
5. How do we manage Earth's total population? Is it feasible to do so? Ethical?
6. Migration of people from rural to urban environments and especially across national borders is an emotionally charged political issue. How does it look in terms of long-term sustainability?

7. What is a socially equitable way to allocate access to wilderness areas and experiences?

CHAPTER 3

Economy (JVA 3)

The navigation oriented heuristic ($h3$) considers the site topology. Accesses to cached pages are not recorded in the Web log due to the browser or proxy cache. Therefore, references to those pages are missed. The missing references in the log file can be found using a set of assumptions. The referrer field of the Web log or the Web site structure can be used to infer cached pages. If a requested Web page p_i is not reachable from previously visited pages in a session, then a new session is constructed starting with page p_i.

Algorithm 3.1 Construction of user sessions from Web server logs using $h1$ heuristic

Input : Web server logs
Output : set of user sessions $\mathcal{S} = \{s_1, ..., s_M\}$

$\mathcal{S} = \{\emptyset\}$
Order all Web logs by user IDs (u_k) and time increasingly
for all user ID u_k **do**
    Create a new user session in $\mathcal{S}$ for user u_k
    for i=1 to the number of records of this u_k **do**
        if $t_{i+1} - t_i < \triangle t$ **then**
            insert this record into user session
        else
            Create a new user session in $\mathcal{S}$ for user u_k
        end if
    end for
end for

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

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

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 $s_0 = 784\ \text{Gt}$[a] and the amount of coal consumed to 2017 to be $400\ \text{Gt}$, leaving $384\ \text{Gt}$ in the ground as of 2018. The world consumption rate for coal in 2017 was $\dot{c} = 7549\ \text{Mt/year}$ [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

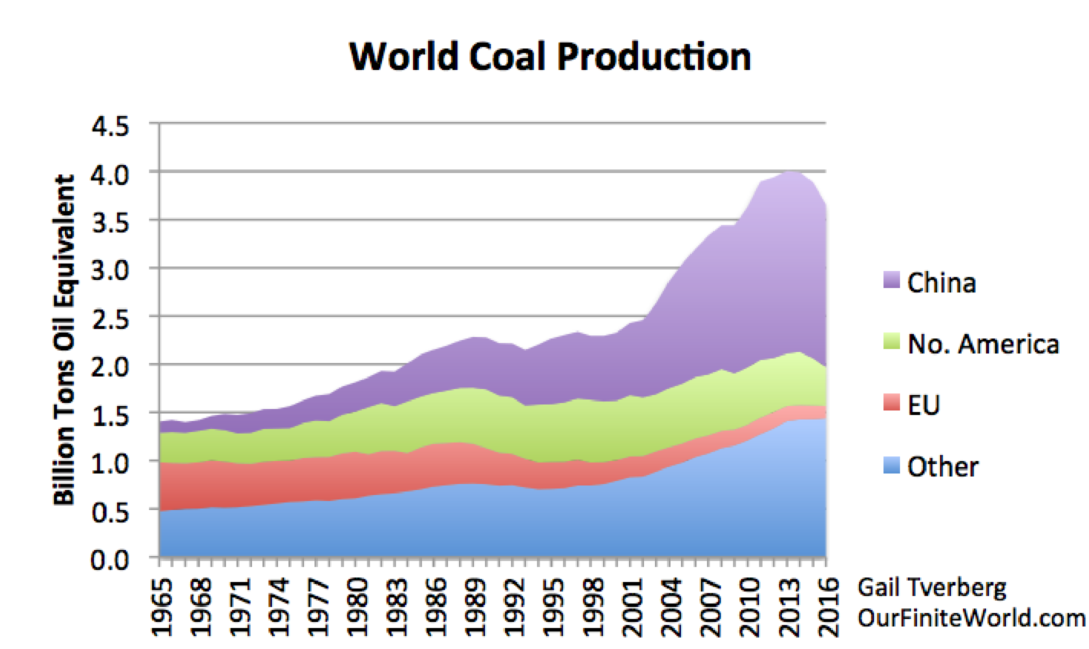


Figure 4.1: World coal production.

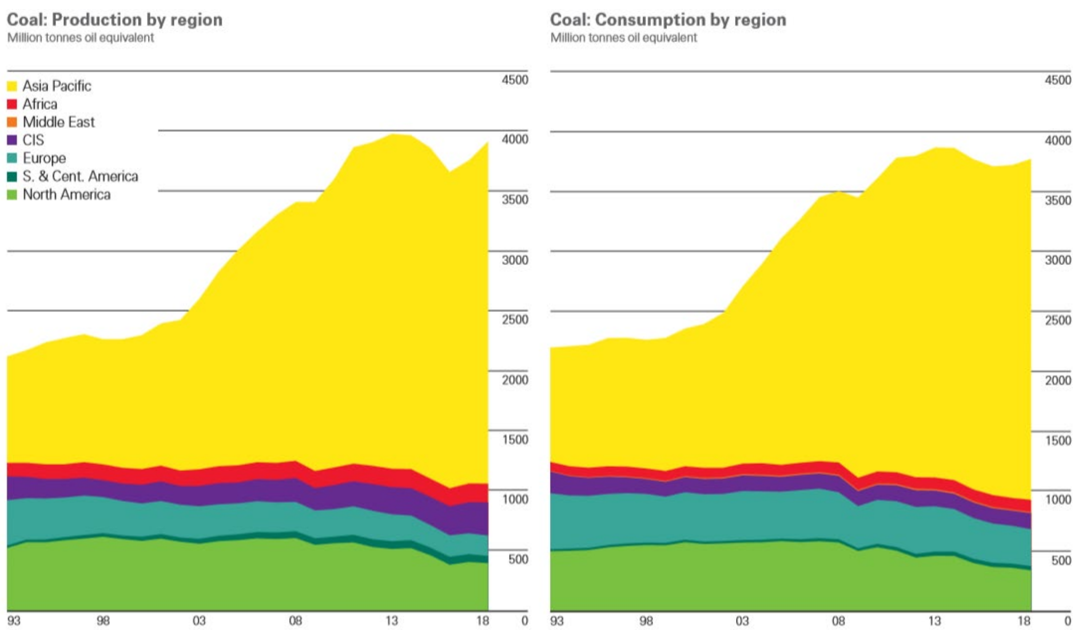
of the simple calculation shown above (2070) is quite close to the result of the detailed analysis (2066).

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



Global coal production increased by 4.3% in 2018, significantly above the 10-year average of 1.3%. Production growth was concentrated in Asia Pacific (163 mtoe) with China accounting for half of global growth and Indonesian production up by 51 mtoe. Coal consumption increased by 1.4% in 2018, the fastest growth since 2013. Growth was again driven by Asia Pacific (71 Mtoe), and particularly by India (36 Mtoe). This region now accounts for over three quarters of global consumption, while 10 years ago it represented two thirds.

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].

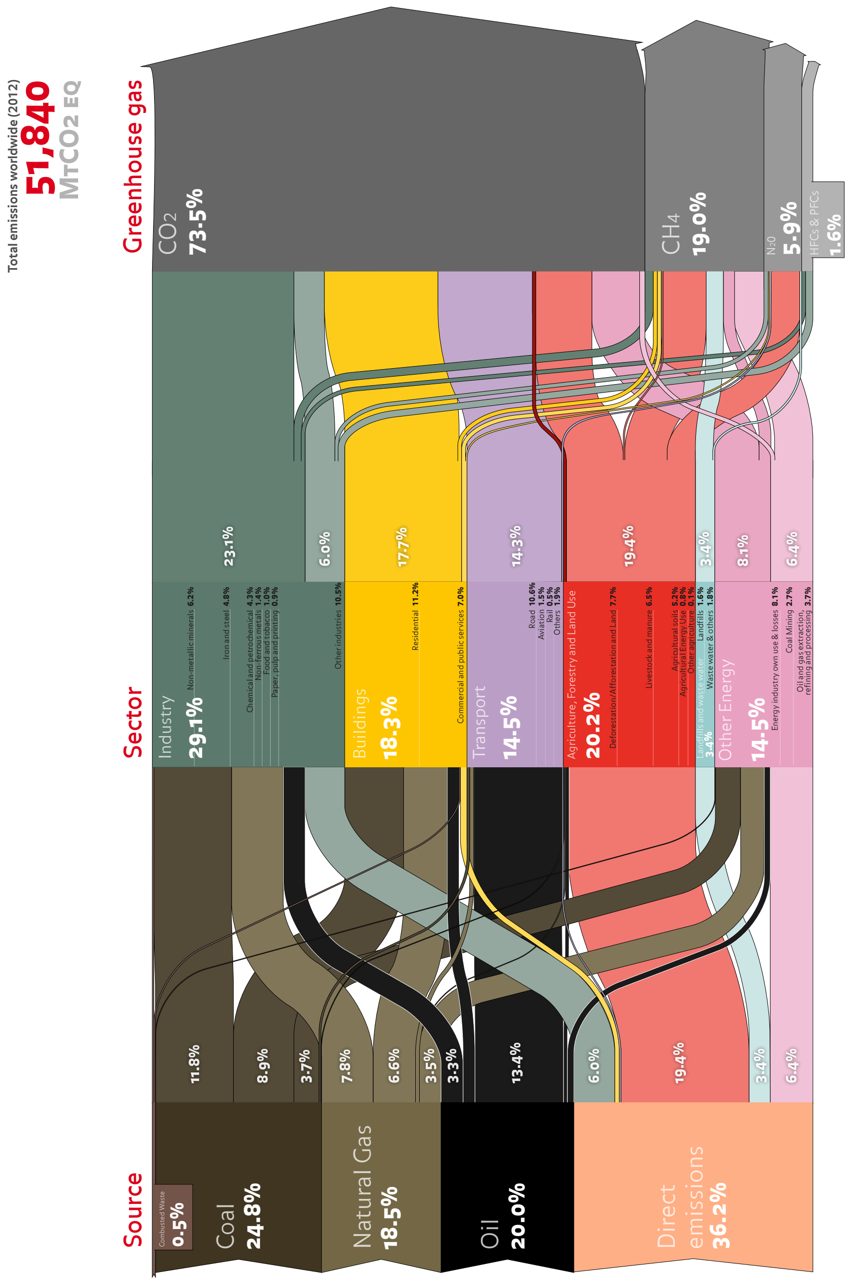


Figure 4.3: World greenhouse gas emissions, 2012 [6].

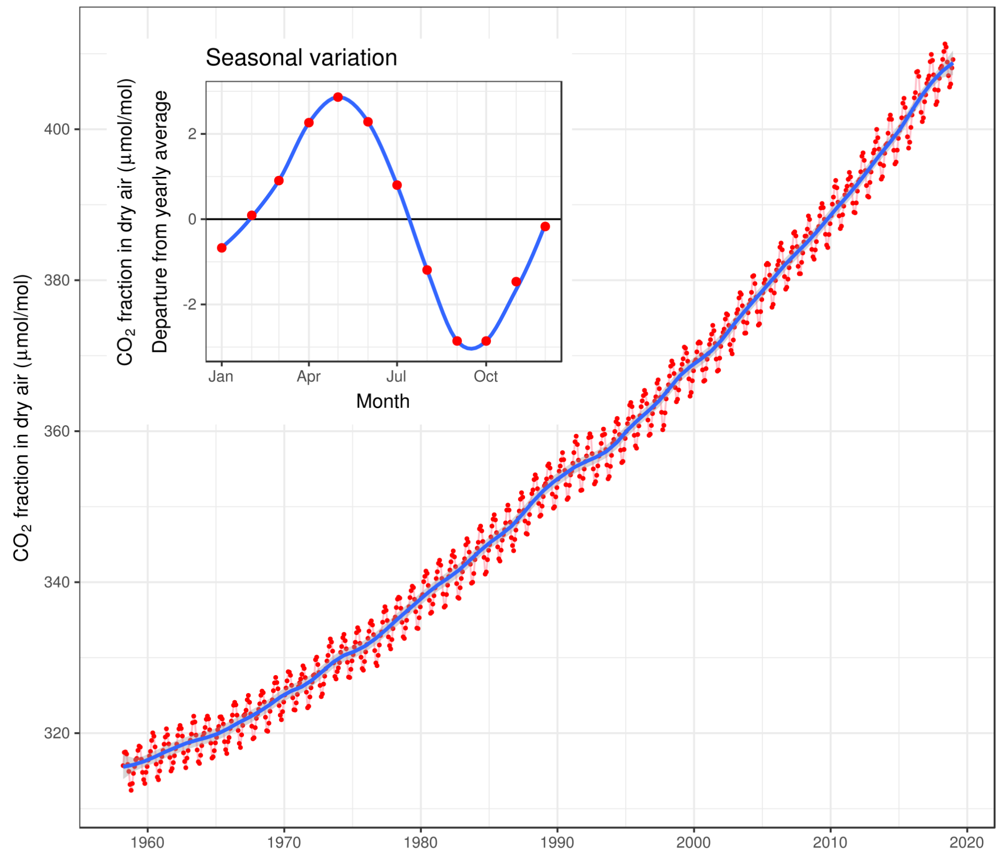


Figure 4.4: Monthly mean CO_2 concentration measured in-situ at Mauna Loa, Hawaii, 1958–2018 [7]. Data from Keeling et al. [9].

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

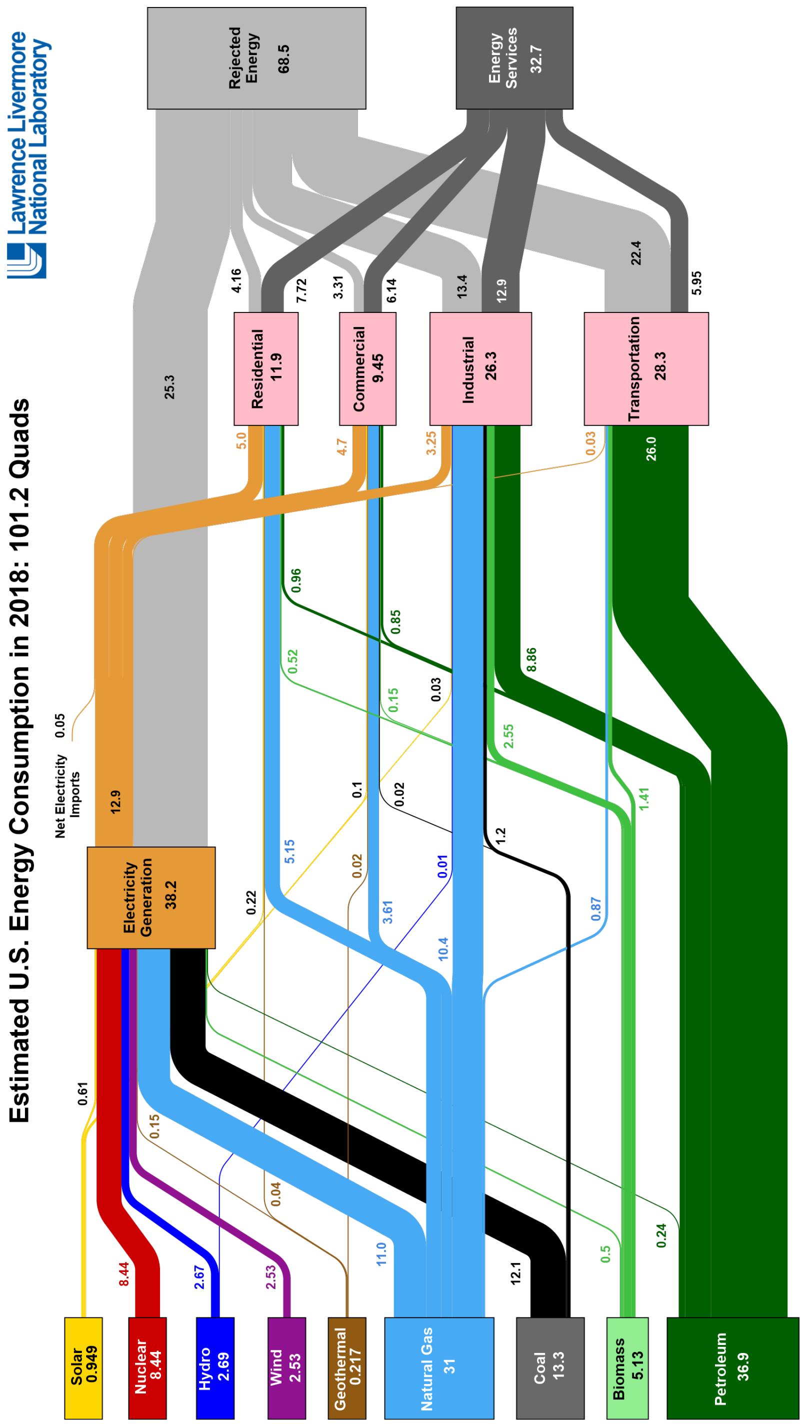


Figure 4.5: U.S. energy flows Sankey diagram, 2018 [10].

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

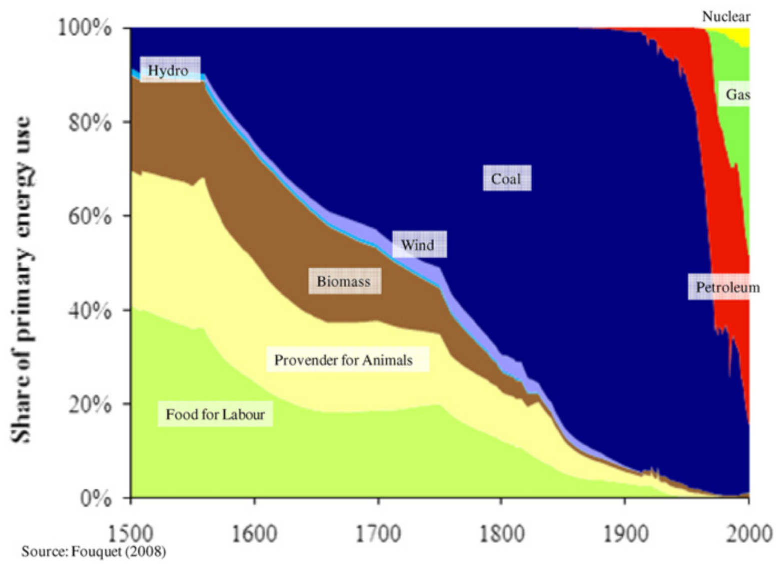


Figure 4.6: UK primary energy transitions, 1500–2000 [11, Fig. 5].

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?

CHAPTER 5

Air and Water (JVA 6)

5.1 BOLD MATH

Sometimes you have a math symbol in bold to indicate, for example, a vector or special functions. Use `\mathbf{x}` for letters and `\bm{\Phi}` for Greek letters.
…$\boldsymbol{\Phi}$ and $\boldsymbol{\Theta}$ are the distribution functions governing the likelihood of $\mathcal{X}$ and $\mathbf{Z}$ …

Some notes:

- use `\bm{\Phi}` to produce a bold Greek symbol Phi.
- use `\mathcal{X}` to display the caligraphic letter X
- use `\mathbf{Z}` to dispaly bold non-Greek symbols

If you plan to use Greek symbols to identify, for example, vectors, you could create a macro, like

```
\newcommand{\vect}[1]{\bm{#1}}
```

and then use

```
\ldots the vectors are $\vect{\Phi}$ and $\vect{\Theta}$ \ldots
```

to produce
…the vectors are $\boldsymbol{\Phi}$ and $\boldsymbol{\Theta}$ …

The idea is to have macro names for different constructs. If you chose to use a different representation for vectors, you change the macro and rerun your manuscript.

5.2 MATH VARIABLES

When we have a math variable with more than one character, like *abcd*, LaTeX treats each character as a separate variable. With Caslon fonts, that we use to produce your book, that space is noticeable.

We eliminat the extra space using `\mathit`:

```
\mathit{abcd} = 3.
```

$$abcd = 3.$$

If we use the variable *abcd* often, as in

```
\mathit{abcd} = \mathit{abcd}^2 - \sqrt{\mathit{abcd}} + \mathit{abcd},
```

$$abcd = abcd^2 - \sqrt{abcd} + abcd,$$

we can create a separate macro for the variable:

```
\newcommand{\abcd}{\mathit{abcd}}
```

Then we can use `\abcd` in the expressions:

```
\abcd = \abcd^2 - \sqrt{\abcd} + \abcd,
```

$$abcd = abcd^2 - \sqrt{abcd} + abcd,$$

If there is already a predefined command with the same name, we use instead something like `Abcd`:

```
\newcommand{\Abcd}{\mathit{abcd}}
```

Then we can use `\Abcd` in the expressions:

```
\Abcd = \Abcd^2 - \sqrt{\Abcd} + \Abcd.
```

$$abcd = abcd^2 - \sqrt{abcd} + abcd.$$

CHAPTER 6

Plants and Animals (JVA 5)

CHAPTER 7

Food and Agriculture (MKH 3)

Food provides energy for humans to pursue lives of work, service, and play with family, friends, and co-workers. Food consumption is rather predictable, because food energy intake (measured in food calories) scales linearly with population. Each healthy individual consumes about 2000 food calories per day, more for teens and active people, slightly less for women than men.

But food doesn't appear on plates magically, out of nowhere. Food arrives on plates through a network of natural and human-created transformation processes that convert solar energy into available, ingestible energy. This network is often called "agriculture." The economic value added of the Agriculture, forestry, and fishing industry is only 1 % of GDP for the U.S. and about 3.5 % of GDP worldwide [20]. But its importance goes far beyond its economic value. Without agriculture, none of us would be here today! This chapter presents key information about the food system and explores its sustainability challenges.

7.1 FEATURES OF THE FOOD AND AGRICULTURE SYSTEM

Figure 7.1 shows a Sankey diagram of material flows in the U.S. agriculture system [21, Fig. 1]. Several observations can be made.

First, the mass efficiency of the agriculture system is low. Consumed food (259,610 million pounds) is a very small fraction of the total input to the system (1,636,360 million pounds), yielding a mass-based efficiency of 15.9 %.

Second, animal-based food production comprises a large and important intermediate processing stage. Animal-based food production is less efficient than the overall food system with 9.64×10^5 million pounds as input and only 10.3 % efficiency on a mass basis.

Third, losses (wastage) at the final stages reduce the efficiency of the entire food system. In fact, final stage mass-based efficiency is only 72.9 %.

Fourth, imports are relatively small compared to domestic production and consumption. Thus, the U.S. is reasonably self-sufficient regarding food supply. However,

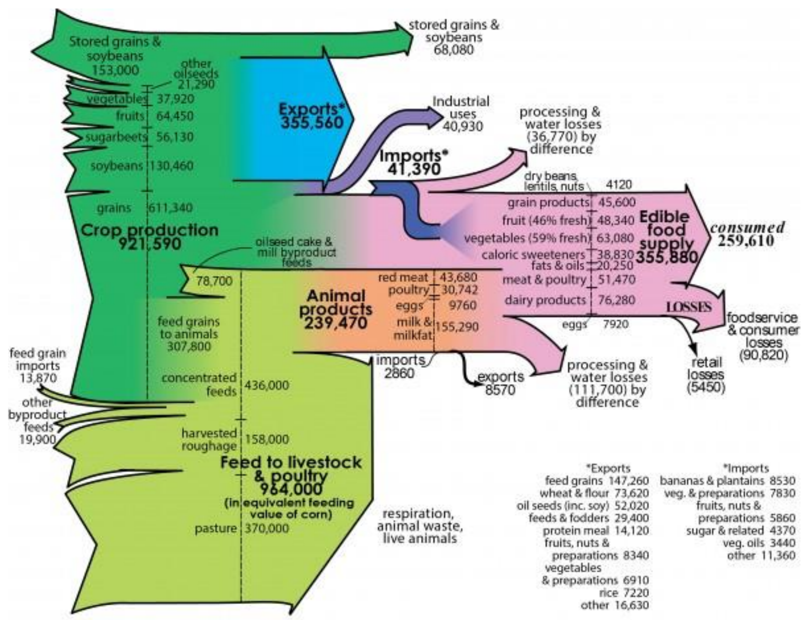


Figure 7.1: Material flow in the U.S. food system (1995, flows in million pounds) [21, Fig. 1].

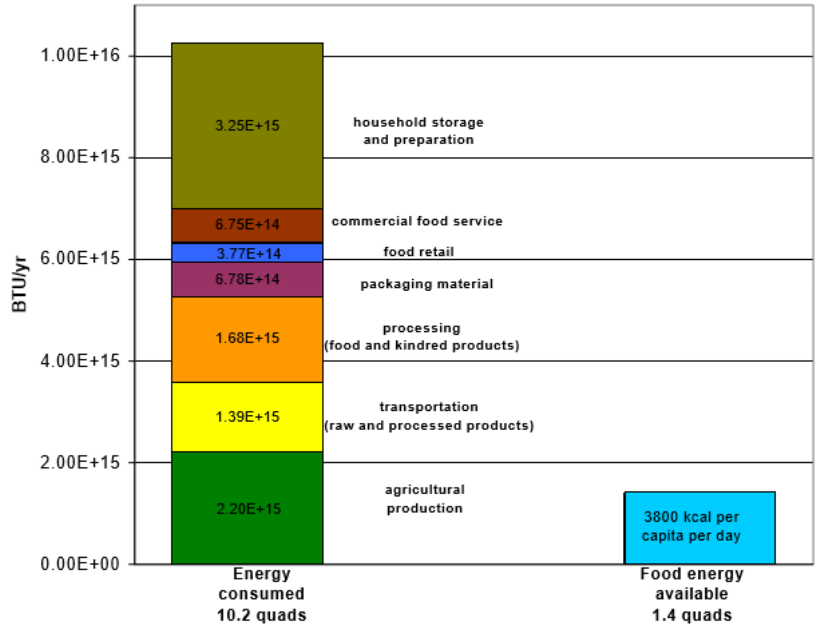


Figure 7.2: Percentages of energy consumed in different aspects of food delivery [21, Fig. 2]. **** Larisa: what year is this for? what country is this for? Can we make a ggplot version of this graph?

exports of crops (355,560 million pounds) are a significant source of demand for the U.S. agriculture system.

Finally, relative to annual worldwide consumption, there is little storage of food beyond what is needed to compensate for expected seasonal weather variations. I.e., the agriculture system produces what is needed now (or at least this year). Given that food demand scales with population, weather- and climate-related supply-side disruptions are more significant than demand-side disruptions for determining food prices.

7.2 FOOD AND AGRICULTURE SUSTAINABILITY CHALLENGES

The food system faces many sustainability challenges, including energy return ratios, CO_2 emissions, and justice issues.

7.2.1 ENERGY RETURN RATIOS

Because food is energy, the overall energy efficiency of the food delivery system can be calculated. Figure 7.2 shows the energy consumed and supplied by various aspects of the food delivery system [21, Fig. 2]. The energy efficiency of the food delivery system is 13.7 %. A good rule of thumb is that it takes roughly 7 calories of energy to provide 1 calorie of food energy. Thus, the energy return on investment (EROI) for the food system is only 1/7. The fact that the energy efficiency of the food delivery system is less than 1 means that the food delivery system is not a *source* of energy for society. Rather it is a *sink* of energy for society. Thus, today's food system is unsustainable from an energy point of view.

To put it another way, society spends more energy to *get* food than it *obtains* from food. Animals that spend more energy to obtain food than they gain from eating food ultimately die from lack of energy. Agrarian societies that spend more energy to obtain food than they gain from eating food ultimately cease to exist. But modern society remains viable because its food delivery system is supported by energy inputs from an external source: fossil fuels. Fossil fuels supply the energy for machines in agriculture, food transportation, food processing, food packaging, retail, food storage, and food preparation.

> A pithy way to summarize the sustainability challenge posed by today's food energy return ratios is: "We don't eat food; we eat oil."

7.2.2 CO_2 EMISSIONS

```
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```

A second sustainabiilty challenge that arises in food and agriculture is the greenhouse gas emissions whose origin is the food delivery system. Figure **??** shows the amount of CO_2 released from the production and distribution of one serving of several types of food [22, Fig. 2]. Figure **??** leads to two important observations: (a) animal-based foods have much more environmental impact than plant-based foods and (b) consuming food that is closer to the base of the food chain has environmental benefits.

> Convenient calculators for greenhouse emissions from food production can be found online [23]. Factors such as transport distance and wastage percentages are important for determining GHG emissions from food.

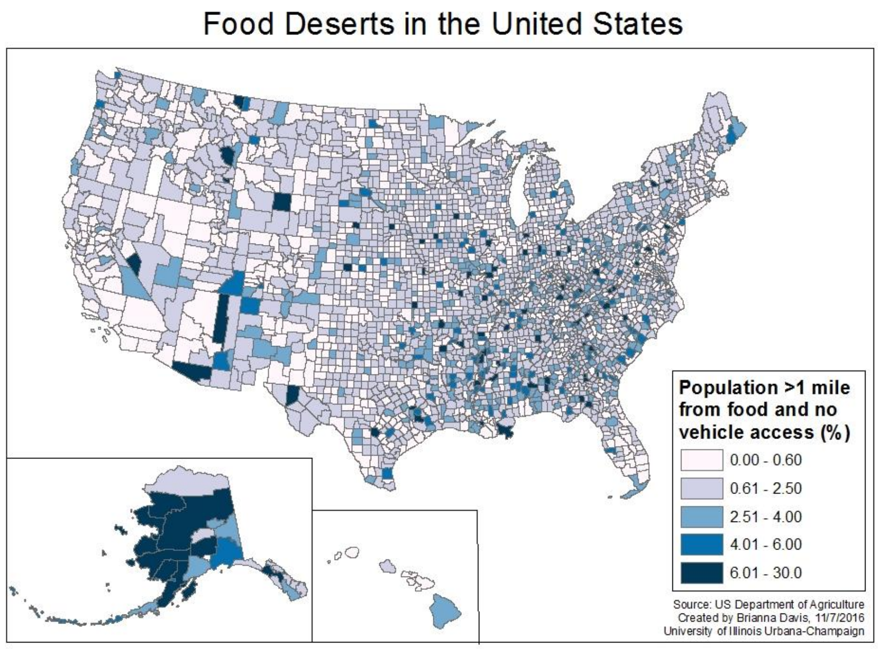

Figure 7.3: Food deserts in the U.S. **** Larisa: include reference here. ****

7.2.3 JUSTICE

Many justice issues arise when considering the sustainability of the food and agriculture system. One issue is the spatial distribution of food availability. "Food deserts" are places where fresh food is unavailable to people without access to transportation. Figure 7.3 shows, on a county-by-country basis in the U.S., the proportion of people who lack access to fresh food.

Lack of access to food tends to correlate with lack of access to money, so malnourishment tends to mirror poverty. Figure ?? shows the percentage of people in each country who are undernourished.

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## Error in loadNamespace(name): there is no package called 'rworldmap'
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7.3 FOOD AND AGRICULTURE TRANSITIONS

To achieve a more-sustainable food system, changes on many levels will be needed, from the personal to the global.

On the personal level, eating closer to the base of the food chain and pursuing vegetarian or vegan diets are among the most effective ways to reduce negative environmental impacts of the food supply system. Participating in the slow food movement can promote sustainability, as it seeks to promote traditional, regional cuisine, thereby reducing the distance from farm to plate.

At the global level, organic farming seeks to limit the use of synthetic fertilizers and pesticides by promoting the use of compost, manure, and natural practices. Practices such as crop rotation and biological (as opposed to chemical) past control are encouraged.

The growing problem of food waste spans the personal and global levels. **** Larisa: research food waste numbers over time. **** Actions and policies to minimize food waste provide benefits such as reducing inputs to the food system and strain on the biosphere.

QUESTIONS

7.1. Verify the efficiency values in Section 7.1. Use Figure 7.1 as the basis for your calculations.

7.2. Verify the efficiency values in Section 7.2.1. Then perform your own research to find the proportions of coal, oil, and natural gas consumed by the food and agriculture system. Are we eating coal? Are we eating oil? Or are we eating natural gas?

7.3. Use a food emissions calculator (such as the one suggested in this chapter [23]) to estimate the greenhouse emissions from your food choices over the course of a week. Compare to your peers. How do your food-related emissions compare to your emissions from transportation-related activities? Guided by the figures and advice in this chapter, develop an alternative diet and estimate its greenhouse gas emissions. What amount of GHG emissions reductions can you obtain by changing your diet?

7.4. Dig deeper into the problem of food deserts. Where are they most prevalent? What are their causes? What can be done to alleviate them?

CHAPTER 8

Transportation (MKH 2)

8.1 DEMAND FOR TRANSPORTATION SERVICES

Modern life requires transportation services: people need to move long and short distances for work and pleasure, and goods must be shipped from far and near to satisfy human wants and needs. Transport service levels are usually quantified in units of passenger-km and tonne-km for personal and freight transport, respectively. Provision of U.S. transportation service by various modes of travel is shown in Figures 8.1 and ??.

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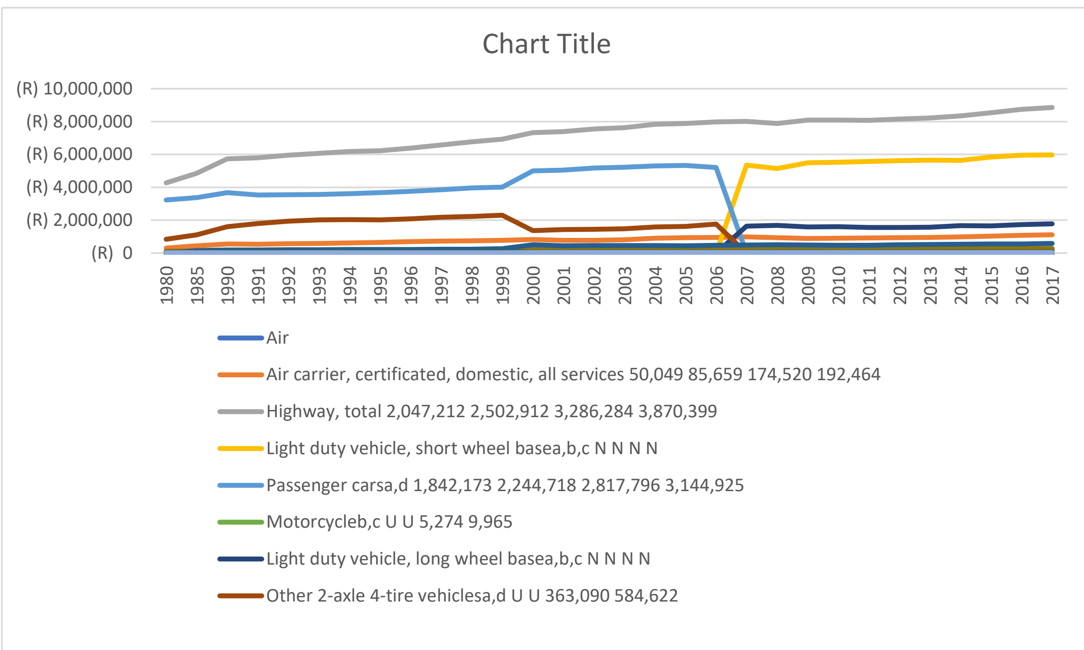

Figure 8.1: Passenger-km of personal transport by mode [24, Fig. 1].

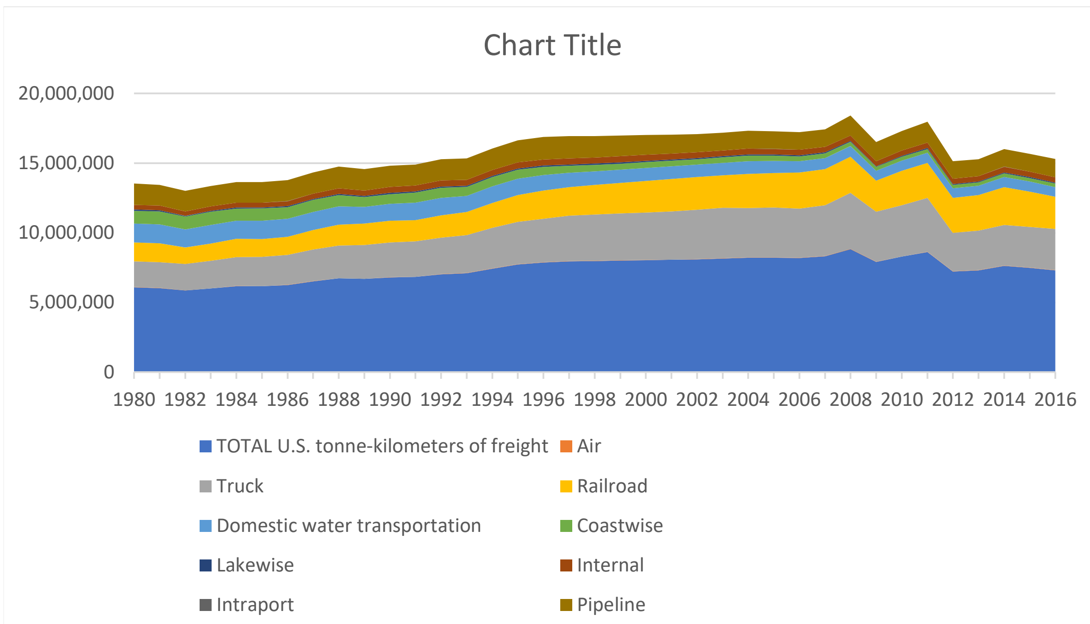

Figure 8.2: Tonne-kilometers of freight by transport mode [25, Fig. 1].

```
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```

******* Hi Professor Heun, Can you please check this one out? The graph is not very helpful, it only shows the highway line and the rest are too low.*********

```
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```

8.2 TRANSPORTATION SUSTAINABILITY CHALLENGES

Today, transportation services are provided by cars, trucks, trains, boats, and planes, powered almost exclusively by fossil fuels. Figure 4.5 shows that energy for transportation is supplied almost exclusively by fossil liquid petroleum fuels, because of their high energy densities as measured by both energy-to-mass and energy-to-volume ratios. Burning liquid fossil fuels to provide transportation services has global warming implications, and greenhouse gas (GHG) emissions from transportation are a significant sustainability concern. Indeed, Figure 4.3 shows that greenhouse gas emissions from transportation comprise 14.5 % of all greenhouse gas emissions worldwide. Figure 8.3 shows trends of CO_2 transportation emissions by mode over time. Passenger cars are the greatest single cause of CO_2 emissions from transportation.

```
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```

**** I added the reference for the graph above, if you want to use RStudio and redo the graph. The data is from the US. ****

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```

```
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```

Particulate matter emissions from combustion of transportation fuels raise significant health concerns as well. Furthermore, consumption of nonrenewable fossil fuels for transportation has implications for energy resource depletion. (See Chapter 4.)

8.3 DRIVERS OF TRANSPORTATION DEMAND

Activities that cause demand for transportation services include daily commuting to work and school, travel for business and pleasure, supply chain distribution, and

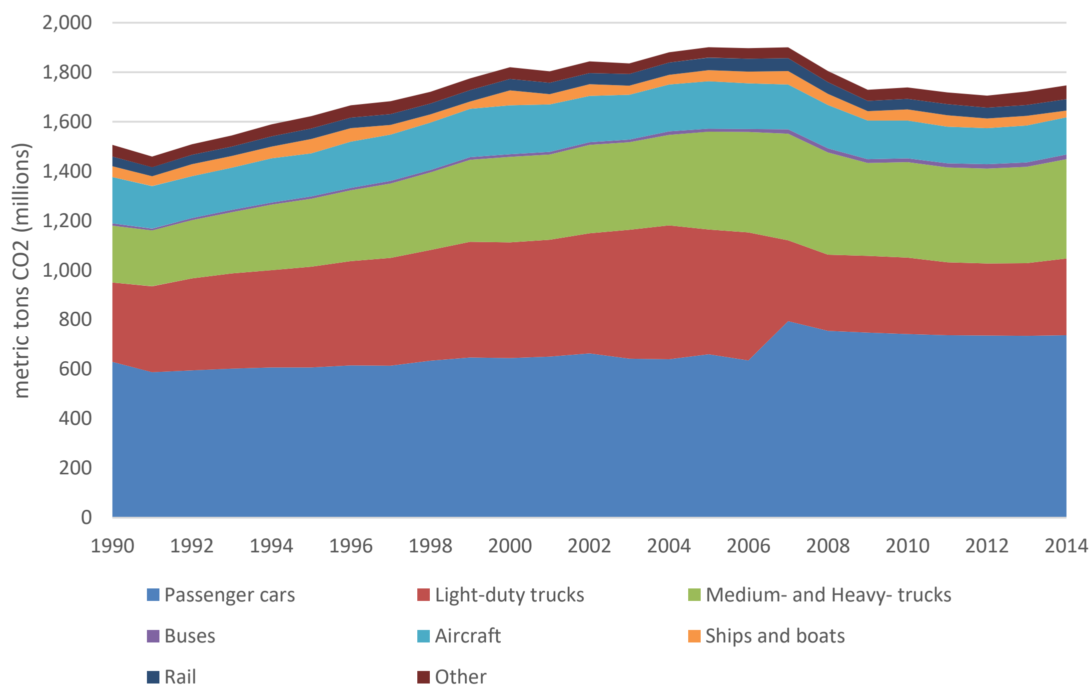

Figure 8.3: CO_2 emissions by transportation mode [? , Fig. 1].

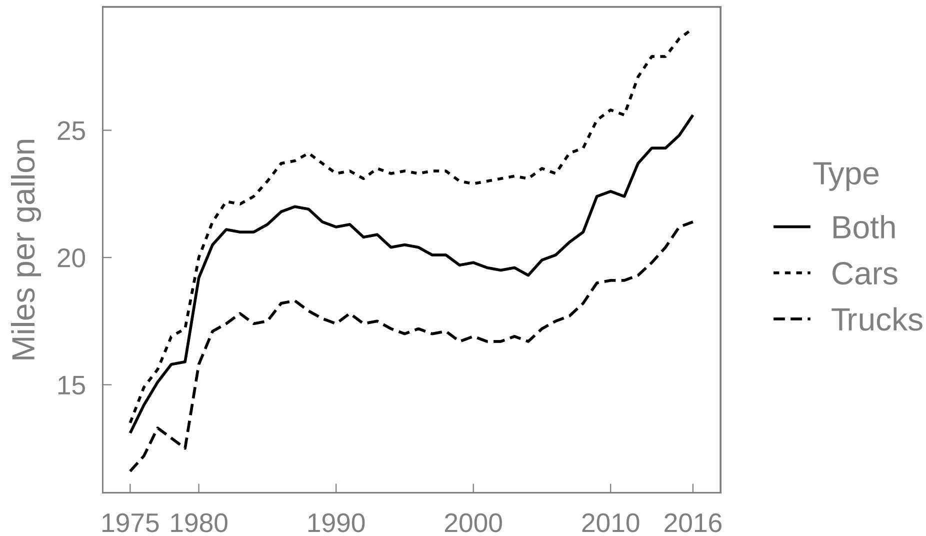

Figure 8.4: U.S. car and truck fuel efficiency

delivery of goods and services. Figure ?? shows the share of commuting distance by mode of transport.

Interestingly, Figures 8.1 and 8.2 both show distinctive declines in the demand for transport services from 2009 to 2010, an effect of the Great Recession. A reasonable conclusion is that demand for transportation services is caused, in large part, by economic activity.

Furthermore, Figures 8.1 and 8.2 show that the oil price spike in the runup to the Great Recession (2006–2008) caused drivers to move away from light-duty trucks toward passenger cars. Notably, drivers seek low-cost alternatives in the face of transportation fuel prices spikes.

8.4 TRANSPORTATION TRANSITIONS

To improve the sustainability of the modern transportation system, two broad options exist: (a) improve efficiency and (b) transition to sustainable fuels.

8.4.1 EFFICIENCY

Vehicle efficiency is usually quantified in distance travelled per volume of fuel consumed. Figure 8.4 shows U.S. fleet average fuel economy over time for cars, trucks, and the overall vehicle fleet. Truck efficiency has lagged car efficiency by 20–30%

for decades. In the 1970s, overall vehicle fleet efficiency was nearly the same as car efficiency, because most vehicles on the road were cars. However, the increasing popularity of light-duty trucks and sport utility vehicles in the U.S. means that the overall fleet efficiency is now about midway between car and truck efficiency. If the proportion of cars and trucks were the same today as it was in the early 1970s, overall vehicle fleet efficiency in the U.S. would be about 28 miles/gallon, or 16 % higher than the current value of 24 miles/gallon.

The most effective way for manufacturers to increase vehicle fuel efficiency is to reduce vehicle mass. Lighter vehicles can be achieved by replacing steel components with aluminum or carbon fiber alternatives. Other design considerations that affect fuel efficiency include aerodynamics and fuel type (diesel or regular).

In addition to vehicle design, driving habits influence fuel efficiency. Gentler driving (less acceleration, minimal dramatic braking) and constant speeds (using cruise control where appropriate) lead to improved vehicle efficiency as measured in distance per volume of fuel consumed..

Vehicle efficiency, by definition, focuses on the efficiency of the vehicle itself. But drivers don't buy fuel to move vehicles. They pay for fuel to move people and freight! So another way to measure vehicle efficiency is the ratio of transport service to fuel volume consumed. Transport service efficiency is quantified in units of passenger-km/liter or tonne-km/liter for passenger transport and freight transport, respectively. This simple shift from vehicle efficiency to transport service efficiency exposes the opportunity presented by Figure **??**. When 76.4 % of all communiting kilometers are taken in single-occupant vehicles, a simple way to improve transport service efficiency is to increase the occupancy rate of vehicles. Similarly for freight transport, the simplest way to increase transportation efficiency is to ensure that trucks and trains are filled to capacity when delivering freight.

> The viability of a "sustainability through services" strategy for the world economy is the subject of some debate. See Henriques and Kander [26] and Fix [27] and the references therein for a fuller discussion of the issues surrounding these concepts.

A significant challenge to higher occupancy cars and higher capacity trucks is known as the *last mile problem*, which refers to the difficulty of distributing goods and services the last mile to end users. Figure 8.5 shows percentages of total delivery cost for several parts of a delivery journey, and the largest portion is the last mile.

```
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```

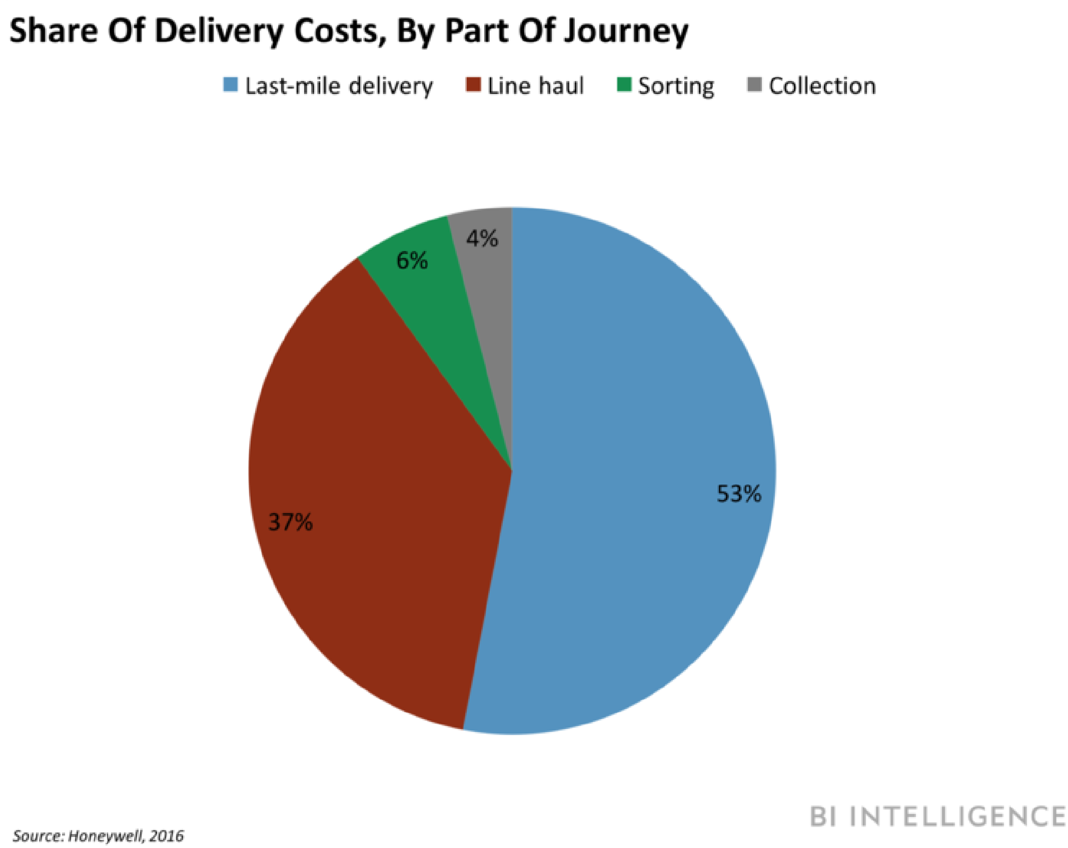

Figure 8.5: Percentage of delivery cost by part of journey [28, Fig. 1].

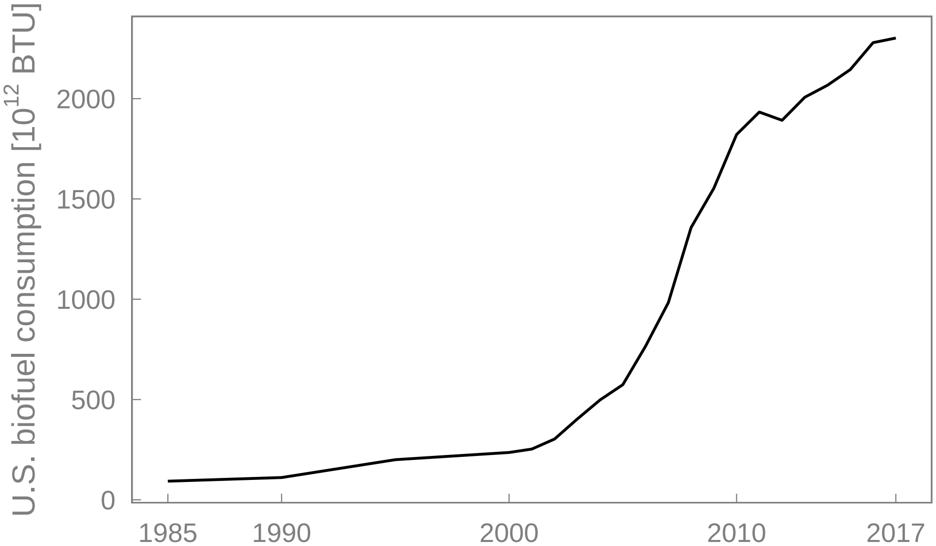

Figure 8.6: Biofuel consumption in the U.S., 1985–2017 [30, Table 10.1].

8.4.2 TRANSITION TO SUSTAINABLE FUELS

Another way to improve the sustainability of modern transportation is to transition away from fossil fuels toward sustainable fuels, thereby eliminating the negative environmental effects of fossil fuel combustion. Two solutions are often discussed: (a) widespread use of biofuels in internal combustion engine (ICE) vehicles and (b) widespread adoption of electric vehicle technology.

Biofuels Biofuels are liquid or gaseous hydrocarbon fuels produced from biomass material and used for transportation. Taking carbon neutrality as the indicator of sustainability, biofuels can be sustainable if they sequester more carbon than they emit across the full life cycle of a project, including land preparation, planting, harvesting, refining and processing, and direct combustion of the fuel itself. Perennial crops planted in low-carbon soils can be carbon negative, because GHG emissions from energy consumed for land preparation and planting can be allocated across several harvest years of the biofuel crop [29]. Biofuel consumption in the U.S. is shown in Figure 8.6.

Electric vehicles Figure ?? shows two types of environmental impact (global warming potenatial and mineral resource depletion) across the full life cycle of automobile use, from base vehicle manufacturing to end of life disposal, assuming 150,000 km service. Regular gasoline (gas) is consumed by internal combustion engine (ICE) vehicles. Electric vehicles (EVs) consume electricity with different primary fuel mixes: the European mix (Euro) or pure coal.

Figure ?? shows that EVs are clearly worse than ICE vehicles in terms of mineral resource depletion (MRD). The material demands for engine and battery fabrication are much higher for EVs than ICE vehicles. However, EVs provide benefits in terms of global warming potential (GWP) relative to ICE vehicles if the electricity source is the European mix of primary fuels and renewables, because of lower lifetime fuel/electricity emissions. In the case of the European electricity mix, the global warming benefits of EVs are achieved despite much larger emissions from battery manufacturing. The global warming benefits of ICE vehicles evaporate when coal electricity is consumed, because of higher electricity-related emissions. Hawkins et al. [31, p. 61] point out that "[e]nvironmental evaluations relying solely on fuel and powertrain efficiencies miss key differences associated with the production of different vehicle types and could lead to misguided comparisons across technologies."

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TRADEOFFS AND PROBLEM SHIFTING

Automobile technology is one of many arenas in which sustainability tradeoffs are observed. Under the right conditions, EVs can reduce global warming impact relative to ICE vehicles at the expense of depleting the stock of mineral resources, a phenemonon known as *problem shifting*.

The sustainabilty challenges of transportation transitions don't end with the GHG emissions/mineral resource depletion tradeoff discussed above. In fact, there is a temporal component that must be examined when comparing EVs against ICE vehicles. Whether or not GHG emissions are lower for an EV relative to an ICE vehicle depends upon the service lifetime of the vehicle. The benefits of EVs relative to ICE vehicles appear only after tens of thousands of kilometers of service, because manufacturing causes a larger fraction of lifetime GHG emissions for EVs than for ICE vehicles. Put another way, an EV that is totalled shortly after manufacture will never achieve its potential emissions reductions.

QUESTIONS

8.1. In Section 8.4.1, the move from machine efficiency (measured in miles/gallon) to service efficiency (measured in passenger-km/gallon) revealed insights about the transportation sustainability challenge, namely that filling empty seats in cars is a simple and effective form of increasing efficiency. Consider a different sustainability challenge besides transportation. Develop or find a machine efficiency for your challenge that is analogous to vehicle efficiency in miles/gallon. Develop or find a service efficiency for your challenge that is analogous to passenger-km/gallon. What changes when you move from machine efficiency to service effiency? How does the move from machine efficiency to service effiency affect the way you think about the sustainability challenge? Does the move from from machine efficiency to service effiency suggest new solutions to the sustainability challenge?

8.2. Research the term *problem shifting*. Identify at least three examples of problem shifting in which a "solution" to one sustainability challenge causes problems of a different sort.

8.3. Under the right conditions (European electricity mix, 150,000 km service life), Hawkins et al. [31] show that electric vehicles provide GHG emissions reductions relative to internal combustion engine vehicles at the expense of increased mineral resource depletion. The GHG emissions/mineral resource depletion tradeoff is an example of a tradeoff that is nearly impossible to decide on a quantitative or objective basis. Indeed, deciding this and similar tradeoffs cannot be divorced from human values and value judgments. Is it wise to trade reduced GHG emissions for increased mineral resource depletion? Why or why not? What values are guiding your decision?

CHAPTER 9

Housing and Households (MKH 6)

Households are sites of energy and material consumption. For example, Figure 4.5 shows that 11.9 quads of energy are consumed in U.S. residences[1], predominantly electricity, natural gas, and petroleum. This 11.9 quads represents 16% of final energy consumption. As Chapter 4 shows, energy consumption is the source of sustainability impacts (CO_2 emissions and resource depletion, for example) far beyond the site at which useable energy is converted to heat. In addition to energy, sustainability impacts arise from household decisions about food and material consumption, too. Thus, decisions made in households have sustainability implications far beyond the walls of each abode.

Often, people have little power to make decisions with sustainability implications at work, school, or church. Others (physical plant employees, custodial staff, or supervisors) control buildings and appliances that consume energy, material, and other resources. In contrast, households are the only place where some people have agency to make decisions that have sustainability implications.

> Households are ~~the~~ site where sustainability meets everyday life.

Figure 9.1 shows how the average U.S. resident exercises their agency in the realm of energy consumption, showing the percentages of energy consumption for several end uses [32, Fig. 3]. The end use categories in Figure 9.1 illustrate how choices made in households intersect with sustainability topics covered in other chapters, including energy (Chapter 4), water (Chapter 5), and food (Chapter 7). Clearly, population (Chapter 2), the economy (Chapter 3), land use and urban planning (Chapter 10), government and regulations (Chapter 11), values (Chapter 13), and personal action (Chapter 14) also affect household sustainability.

The end uses in Figure 9.1 can be aggregated to form fewer major categories of residential energy consumption. Space heating and cooling comprise 36.6% of all energy household energy consumption (including furnace fans). Hygeine (including

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

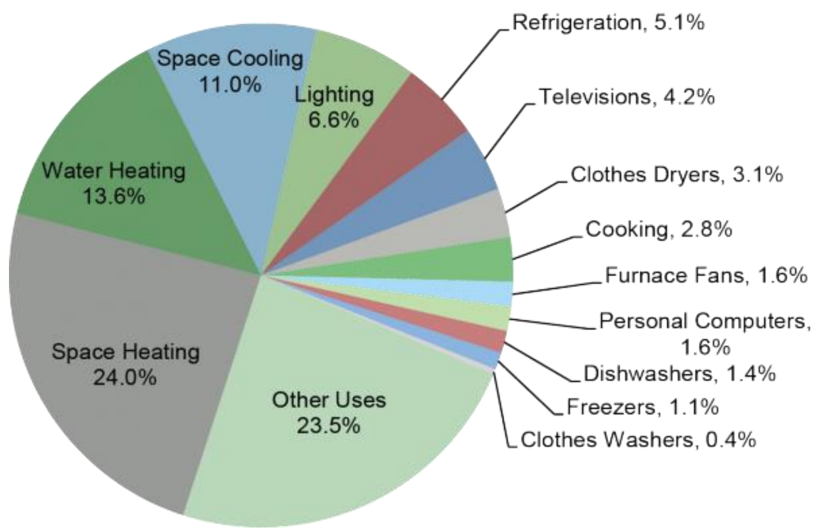

Figure 9.1: Average U.S. residential energy consumption by end use [32, Fig. 3].

water heaters, clothes dryers, dishwashers, and clothes washers) consumes 18.5% of household energy. Lighting consumes 6.6% of total household energy use.

Guided by the aggregation above, this chapter focuses attention on four important sustainability topics that intersect with household life, namely purchasing or renting a home or apartment, heating and cooling, hygeine, and lighting. This focus narrows the scope of this chapter and avoids repeating material from others.

9.1 PURCHASING AND RENTING

Many aspects of purchasing or renting a residence have sustainability implications, size and location chief among them.

9.1.1 SIZE

Figure 9.2 shows the trend of electricity consumption with respect to home size and confirms intuition that dwelling size is positively correlated with energy consumption. However, significant variation in annual electricity consumption is observed between the 20th and 80th percentiles at any home size. These variations indicate that decisions about *how* a dwelling is used are nearly important as the *size* of a dwelling for predicting residential electricity consumption.

**** Find data on natural gas consumption vs. size of home. 80–20 variations on that graph are likely due to climate and insulation differences. See the EIA's Residential Energy Consumption Survey (RECS), which may have the required information. May need to look at the "microdata" available from RECS. ****

Figure 9.3 shows the average floor space of new single family homes in the United States between 1970-2015 [33, Fig. 1]. Taken together, Figures 9.2 and 9.3 would suggest that residential energy consumption per dwellling is rising through time. However, per-dwelling energy consumption seems to be falling slowly in the U.S., with increased energy efficiency of appliances and building envelope improvements offsetting rising home sizes. However, total residential energy consumption is increasing, driven by increasing numbers of dwellings. Figures 9.4 and 9.5 show these trends.

One might think that increasing dwelling sizes are driven by more occupants per dwelling. However, Figure 9.6 shows that the percentage of single-person households is increasing through time [35, Fig. 2].

From a sustainability point of view, smaller, more-efficient homes with larger numbers of occupants are preferred. However, trends suggest that homes are becoming more efficient, but they are becoming larger and have fewer occupants through time.

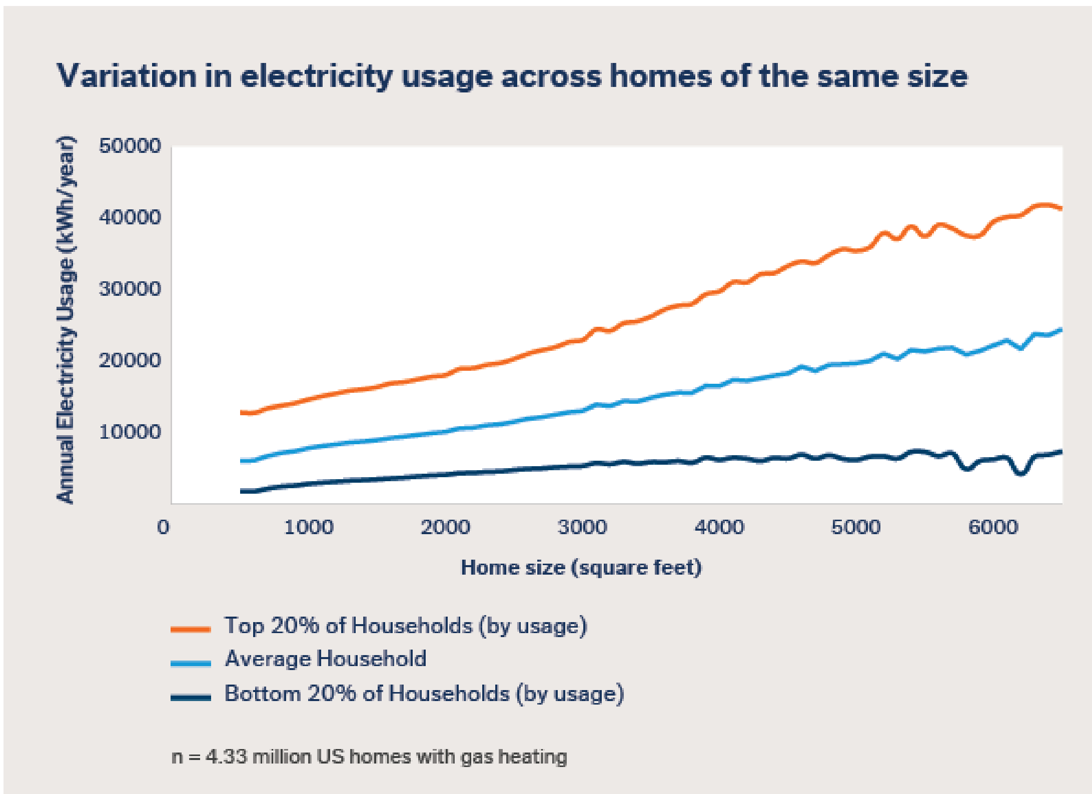

Figure 9.2: Annual electricity consumption vs. U.S. home size. **** Need to find reference. Found at http://www.doomsteaddiner.net/forum/index.php?topic=9830.0. ****

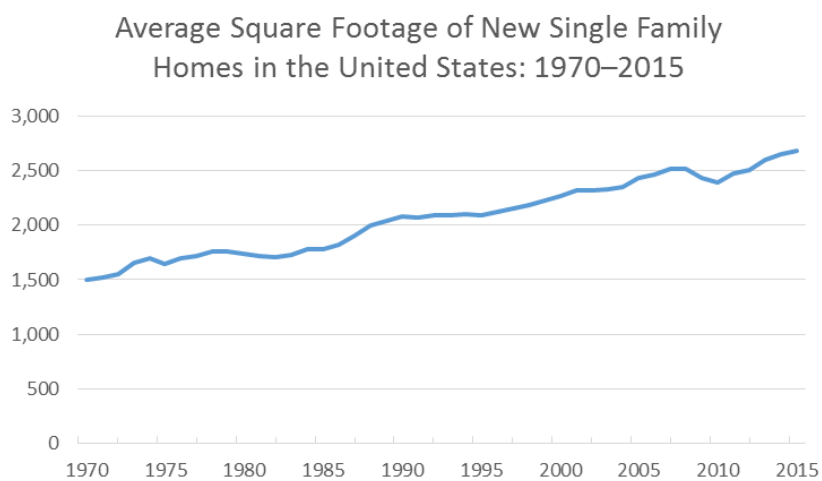

Figure 9.3: Average square footage of new single family homes [33, Fig. 1].

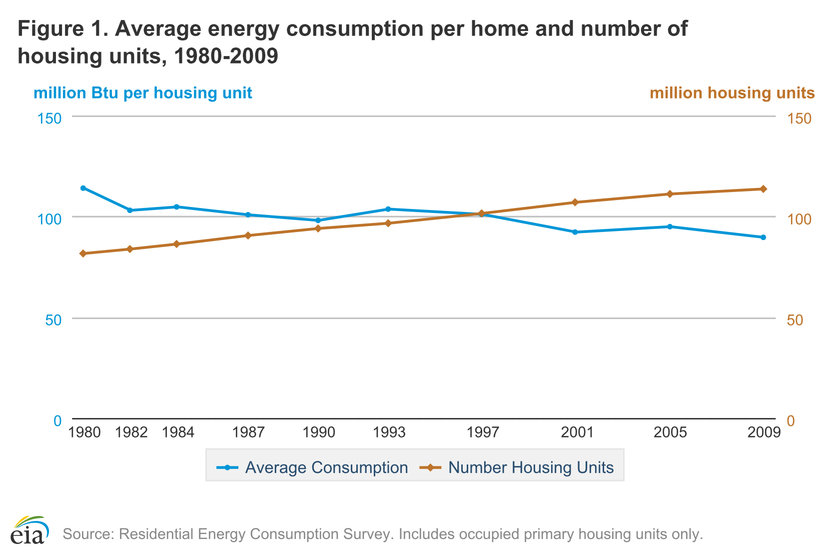

Figure 9.4: Average household energy consumption trend 1980–2009 [34, Fig. 1].

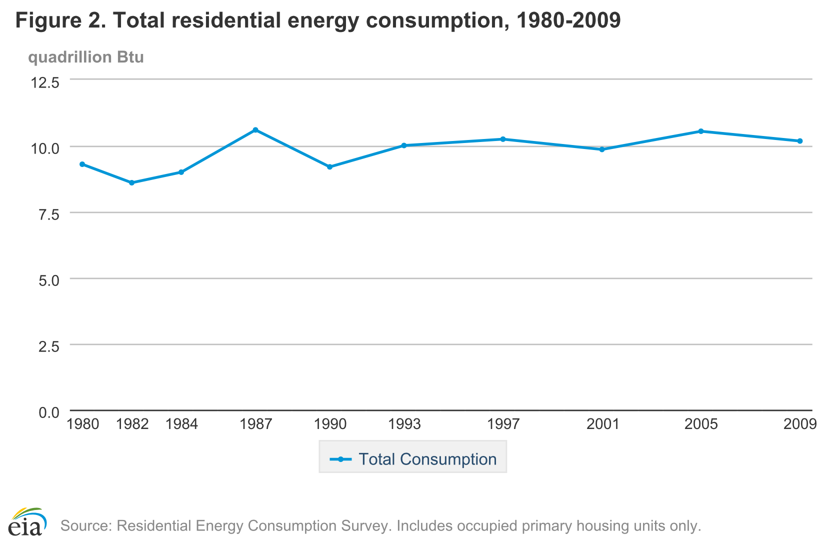

Figure 9.5: Total U.S. household energy consumption trend 1980–2009 [34, Fig. 2].

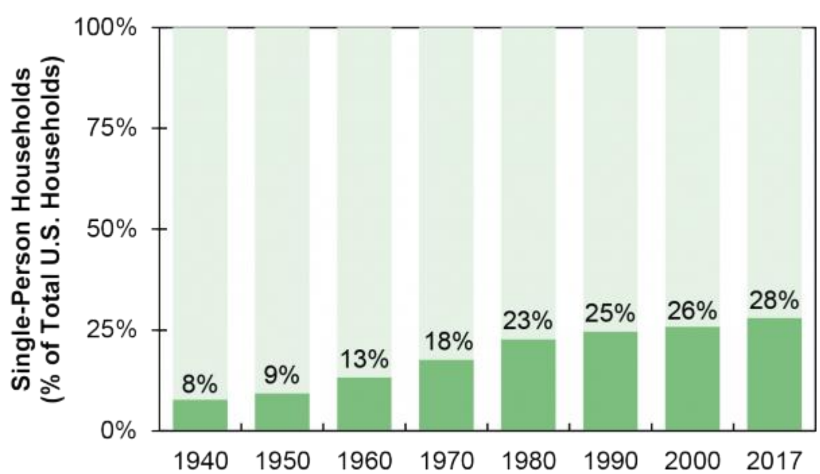

Figure 9.6: Percentage of single-person households 1940-2017 [35, Fig. 2].

9.1.2 LOCATION

Location of a dwelling is also an important determiner of energy consumption, not for the dwelling itself, but for energy consumed by the residents for transportation. Proximity to work, school, shops, church, and entertainment makes a significant difference to transportation energy demand. (See Chapter 8 for more information on sustainability issues related to transportation.)

9.2 HEATING AND COOLING

In most locations, daily and seasonal temperature variations are wide relative to the range of temperatures required for human comfort (approximately 20–23 °C, depending on humidity and clothing). Residential heating and cooling reduces the temperature variation inside the dwelling compared to the outside, providing thermal comfort to the occupants and enabling work, play, and entertainment. As shown in Figure 9.1, on average across the U.S., thermal comfort is provided by 36.6% of all residential energy consumption. Like all energy consumption, energy consumption for heating and cooling has sustainability implications. (See Chapter 4.) Greater efficiency can provide the same thermal comfort with less energy consumption. Increased residential heating and cooling efficiency can be obtained by improving the building envelope or by improving the efficiency of furnaces and air conditioners.

9.2.1 BUILDING ENVELOPE

The building envelope consists of the roof, walls, windows, and base of a dwelling. The purpose of the envelope is to shield occupants from outisde weather and to maintain dry and comfortable conditions inside the dwelling. The ideal building envelope would eliminate both heat loss in the winter and heat gain in the summer via perfect roof and wall insulation and windows that neither conduct heat nor allow radiation to pass through. But perfect insulation is not possible, and all windows conduct heat and are transparent to thermal radiation. So furnaces and air-conditioners must make up heat lost in the winter and remove heat gained in the summer.

The effectiveness of roof and wall insulation is quantified by its R-value, a measure of the resistance to heat transfer through the insulation material, quantified by the R-value in units of hr-ft^2-°F/BTU. Higher R-values are better. Large R-values are achieved with thicker insulation constructed from low-thermal-condictivity materials. The Energy Star program recommends levels of roof, wall, and floor insulation at `https://www.energystar.gov/index.cfm?c=home_sealing.hm_improvement_insulation_table`. In Northern US climates, R-values of 49–60 hr-ft^2-°F/BTU are recommended.

Windows are an important part of any building's envelope. They provide natural illumination while shielding occupants from weather. Like walls and roofs, it is desireable that windows eliminate heat loss in the winter and heat gain the summer. However, windows are typically worse insulators than walls and roofs, owing to thin glazing.

The insulative properties of windows are quantified by the U-Factor. The U-Factor is the inverse of an R-value. Typical U-Factors for windows are 0.2–1.2 BTU/hr-ft^2-°F. (Corresponding window R-values are 5–0.83 hr-ft^2-°F/BTU.) Lower U values are more insulative. Heat gain from solar radiation is quantified by the solar heat-gain coefficient (SHGC), the ratio of solar energy that enters the room to solar energy incident upon the window. SHGC values range from 0 to 1, and lower SHGC values indicate better insulative properties.

9.2.2 FURNACES

Furnaces provide space heating, often from an out-of-the-way location in the dwelling (e.g., basement). Furnaces convert a fuel (typically natural gas or heating oil) into heat by combustion. The heat is delivered to the dwelling via circulating water or air.

Furnace efficiency is quantified as Annual Fuel Utilization Efficiency (AFUE), the percentage of useful heat output to fuel energy input, accounting for transient effects during operation across the year. The maximum AFUE rating is 100%. Heat that leaves with the exhaust products serves to reduce AFUE. AFUE is different from and lower than steady-state thermal efficiency. The American Society for Heating, Refrigerating, and Air-conditioning Engineers publishes Standard 103, which specifies how AFUE is to be measured.

All furnaces sold in the U.S. have an AFUE rating, and a minimum AFUE rating of 80% is required for gas-fired furnaces. (`https://www.eia.gov/analysis/studies/buildings/equipcosts/pdf/appendix-a.pdf`) High-efficiency furnaces recover heat from exhaust gases, and some reach AFUE values of 98% or higher. A tradeoff exists between efficiency and initial cost. Models with high AFUE are more expensive, initially, but save money on fuel costs over time.

9.2.3 AIR-CONDITIONERS

Air-conditioners cool and dehumidify indoor air to provide thermal comfort to building occupants. Air-conditioners use electricity to achieve their objectives. The energy efficiency of air-conditioners is quantified by the Seasonal Energy Efficiency Ratio (SEER), the ratio of cooling provided (in BTU) to electricity consumed (in W-hr) throughout the season. Larger SEER values indicate higher efficiency.

As of 2015, U.S. air-conditioners must adhere to regionally-dependent efficiency standards. In the southwest, a minimum SEER value of 14 BTU/W-hr is required. In other parts of the U.S., a minimum SEER value of 13 BTU/W-hr is mandated.

9.3 HYGIENE

Hygiene is a significant consumer of household energy and water for showers, dish washers, toilets, and clothes washers and dryers.

To minimize environmental impacts of showering and dish washing, low-flow showerheads can be installed. Low-flow showerheads provide the obvious cost benefit of reducing water bills. But if less water is consumed, low-flow showerheads also reduce energy consumption for water heating. Furthermore, sewerage costs are reduced, because low-flow showerheads decrease the amount of gray water released into the sewer system.

Saving water and energy in dish washing can be accomplished by purchasing an automatic dishwasher. At https://www.energystar.gov/products/appliances/dishwashers, the Energy Star program shows that automatic dishwashers save water and energy costs relative to hand washing ~~of d~~ishes.

To save water consumed by toilets, displacement and dual-flush systems are recommended. A displacement system occupies volume in the tank, reducing the amount of water used for each flush. Dual-flush systems provide half- and full-flush for disposal of liquids and solids, respectively.

Clothes washers and dryers consume both water and energy. Purchasing washers and dryers with Energy Star ratings can reduce energy and water consumption by 25% and 33%, respectively (https://www.energystar.gov/products/appliances/clothes_dryers).

9.4 LIGHTING

Indoor lighting provides illumination for rooms, typically by consuming electricity. Since Edison's invention of the electric light, filament-based incandescent lighting technology dominated household lighting. However, in recent years, Compact Fluorescent Lights (CFLs) and Light Emitting Diode (LED) lights have revolutioninzed the lighting industry and improved lighting efficiency significantly. LED bulbs are 6–10 times more efficient than incandescent lighting. In addition, LED bulbs promise much longer lifetimes, with more than 10 times longer service per bulb than incandescents. Both higher efficiency and longer life reduce total cost of ownership of LED bulbs compared to incandescent bulbs by nearly two orders of magnitude.

Of course, the least expensive light is the one you don't have to use at all. Building design techniques such as light harvesting utilize natural light to the greatest extent possible, eliminating the need to consume electricty for artificial indoor lighting.

QUESTIONS

9.1. This chapter covered four important aspects of household sustainability (purchasing, heating and cooling, hygeine, and lighting). What additional areas of household living are important from a sustinability point of view?

9.2. What tradeoffs do you observe in daily household living? I.e., in what areas of household living does sustainability become worse as a result of improved sustainabiltiy elsewhere?

9.3. Locate the furnace in your dwelling, and find its AFUE rating. If you were to replace your existing furnace with a furnace with a 98% AFUE rating, how much energy would you save annually? What is the price of that saved energy? What is the annual cost savings from this energy efficiency intervention? Assuming that the 98% AFUE furnace lasts 20 years and that you want to break even financially, what is the maximum price you should pay for a 98% AFUE furnace?

9.4. Locate the air-conditioner in you dwelling, and find its SEER. If you were to replace your existing air-conditioner with an air-conditioner with a SEER of 40 (near the maximum SEER rating as of this writing), how much energy would you save annually? What is the price of that saved energy? What is the annual cost savings from this energy efficiency intervention? Assuming that the 40 SEER air-conditioner lasts 15 years and that you want to break even financially, what is the maximum price you should pay for a 40 SEER air-conditioner?

9.5. Rank the U-Factor and solar heat gain coefficient (SHGC) for single-, double-, and triple-paned windows. Does the ranking make sense? Rank the costs of the windows.

9.6. If you are a college or university student, write a letter to yourself that describes the future household in which you want to live. What is the size of the dwelling? What are its sustainability features?

CHAPTER 10

Land Use and Urban Planning (JVA 4)

Figure 10.1 shows the relation between urban denisty and transport-related energy consumption [36, Fig 2].

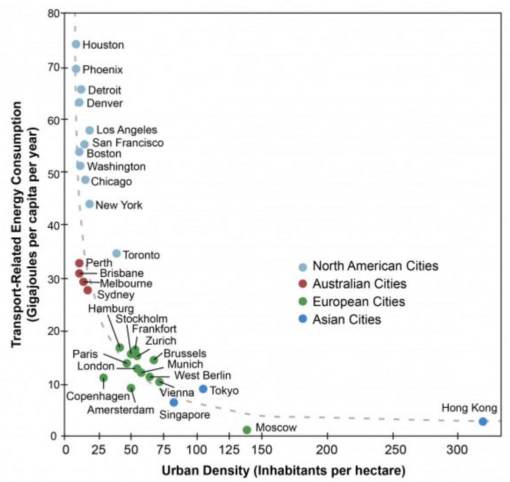

Figure 10.1: Relation between urban denisty and transport-related energy consumption [36, Fig. 2].

CHAPTER 11

Government and Regulations (MKH 7)

CHAPTER 12

Systems Thinking and Complexity Theory (MKH 4)

Sustainability challenges are characterized by sometimes-mysterious interactions among seemingly-unrealated entities, such as air, water, plants, animals, food, agriculture, transportation, cities, energy, economy, and government. Many of those interactions are highlighted in previous chapters. Systems thinking is a way to conceptualize and make sense of these interactions and the behaviors that emerge from them. The purposes of this chapter are to introduce systems thinking and a related philosophical field, complexity theory, and to encourage readers to adopt a systems view of the world.

12.1 SYSTEM DEFINITION

Donella Meadows defines a *system* as “an interconnected set of elements that is coherently organized in a way that achieves something” [37, p. 11]. Example systems include a volleyball team, the solar system, the Earth, an ant, a bacterium. Meadows’ definition has three pieces: elements, interconnections, and a telos.

Systems have elements, distinct entities with their own characteristics, behaviors, and qualities. Elements are sometimes known as *holons* [38, p. 216]. The elements or holons of a volleyball team include passers, setters, hitters, and a coach. A volleyball match is another system that *contains* two teams (and their holons) plus a net, a court, and a referee. The holons of the solar system include the sun, planets, asteroids, and meteors. The Milky Way galaxy is another system whose holons include many solar systems and comets. The universe is yet another system that includes the Milky Way and innumerable other galaxies.

The elements are interconnected in ways that allow them to interact. The interconnections, themselves, may have spatial, electrical, mechanical, temporal, or other characteristics. I.e., elements can be arranged in space and connected electrically and/or mechanically, and those arrangements and connections can change over time. Material and information can *flow* along the interconnections between the elements

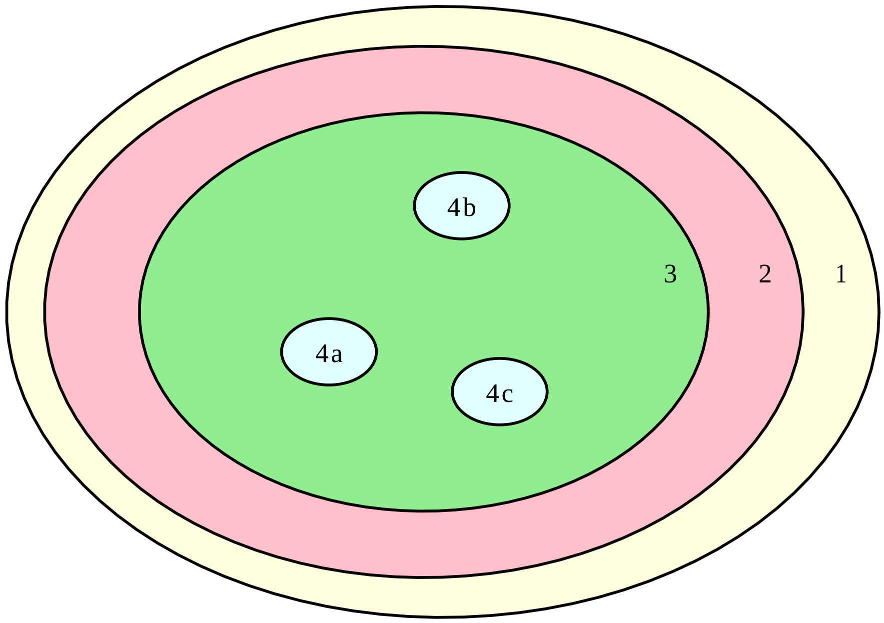

Figure 12.1: An example holarchy.

(holons). The spatial characteristics of interconnections can be visualized as container (parent-child) relationships or as sibling relationships. A word that describes the arrangement of holons is *holarchy* [38, p. 216]. Figure 12.1 shows a holarchy of 6 holons. Elements 1, 2, and 3 exhibit parent-child (container) relationships, with 3 being contained by 2 and 2 being contained by 1. Items 4a, 4b, and 4c are contained by element 3, with sibling relationships among themselves. Two systems with identical holons will behave differently if their elements are arranged differently.

A volleyball team is arranged spatially on the court. Its players move spatially through time during the play for each point but also from point to point as they rotate between points. Planets are arranged spatially in the solar system, and their spatial relationships to each other change in (mostly) predictable ways through time.

Systems have a telos or a purpose, an ultimate aim. Some sytems have multiple purposes. The teloi of a volleyball team include player development, winning, and fun. The telos for the solar system may be interpreted as providing a home for Earth and, ultimately, humans.

12.2 SYSTEM CHARACTERISTICS

Humans understand system characteristics so deeply that some characteristics are reflected in the proverbs and aphorisms of language.

The behavior of a system is always different from the behavior of its elements or holons, for interactions play a central role in the functioning of a system. Put in the language of Section 12.1, the higher (enclosing) levels of a holarchy behave in ways that are different from (often very different from) lower (enclosed) levels of the holarchy. As a whole, a volleyball team behaves differently from its coach. The universe exhibits different characteristics from the Earth. Systems are said to have *emergent behavior*, because system behavior is radically different from its holons. Indeed, for a system, "the whole is greater than (or at least different from) the sum of its parts!"

Because behaviors differ from one level to another in a system and because interactions play a large role in the behavior of a system, systems often appear to be unpredictable. To use a mathematical term colloquially, systems are "nonlinear." A volleyball team goes into a funk, despite handily winning the first set of a match, and lose the first 8 points of the next set. Weather in the Earth system cannot be forecasted, even with the best meteorology, more than a few days in advance. A colloquial word to describe unpredictability is *chaotic*.

> A related branch of mathematics called *chaos theory* studies dynamic systems whose changes in behavior are disproportionate to changes in initial conditions. However, in chaos theory, systems are entirely predictable if initial conditions are specified identically (mathematically) from one experiment to another. The difference between the seeming unpredictability (but actual predictability) of chaos theory and the chaotic behavior of real-life systems described here is that real-life systems can behave differently *even if* initial conditions are specified identically.
>
> The distinction is blurred when measurement uncertainty is considered. In chaos theory, an infinitesimally small perturbation of initial conditions can produce wildly different outcomes. But in the real world, an infinitesimally small perturbation is indistinguishable from zero due to finite measurement precision. Thus, a real-world system with apparently the same initial conditions (to within measurement uncertainty) can exhibit wildly different behavior, as a systems view of the world would predict.

The presence of connections among holons in a system means that perturbing one part of a system will have effects beyond the initial perturbation site in both space and time. A volleyball coach can position her players to thwart a opposing hitter whose spikes go “down the line,” but her team’s defense will now be vulnerable to the opposing setter’s “dinks” to the middle. In the Earth system, installing a hydropower station will provide electricity, but it will also create an upstream lake, expose downstream riverbanks, and change fish and other wildlife migration patterns. Vernon Ehlers, former U.S. congressman for Michigan’s 3rd district, often said, “You can never do only one thing.”

The apparent unpredictability of systems extends to human actions intended to influence the behavior of systems. A volleyball coach can *think* she is motivating a player with a stinging critique but produce the opposite effect, demoralization. Human efforts to “manage” forests decimate old growth stands. Colloquially, we name this unpredictability “unintended consequences.”

Often, systems appear to act to preserve their structure. A volleyball team that goes “out of system” when returning a serve reverts to their “base” positions after their scramble. Droughts on Earth are usually followed by a return to normal rainfall. The phrase “reversion to the mean” describes the self-correcting nature of systems.

Sometimes it seems that systems have a “mind of their own.” People say “larger forces are at play” to indicate their lack of agency in the face of a self-correcting system. The phrase “rearranging the deck chairs on the Titanic” describes how some human activities appear, at times, to be meaningless.

12.3 IMPLICTIONS OF SYSTEMS

Given the above characteristics of systems, opportunities and challenges can be identified.

12.3.1 SYSTEM OPPORTUNITIES

To begin identifying system opportunities, consider system structure. Lower levels of a holarchy provide materials and information to upper levels. Higher levels of a holarchy often serve to organize and utilize the outputs from elements in lower levels. Thus, the connections between enclosed (lower-level) and enclosing (higher-level) holons in a holarchy enable one of the most important system opportunities: specialization. Specialization enables metabolisms, organisms, and manufacturing supply chains, for example. Large, technical projects, such as managing airlines; building, launching, and flying interplanetary spacecraft; and designing, building, and operating chemical plants; are made possible by what Graedel and Allenby call “directed technological holarchies” [38, p. 217].

Systems thinking is natural for many engineers. Those involved in large projects are themselves individual holons in a holarchy of supervisor/engineer relationships. Engineered components (e.g., spacecraft) are delivered for integration into systems (e.g., launch vehicles). Indeed, analysis techniques for machine dynamics, chemical plants, thermodynamic systems, etc. are all predicated upon holarchies. "Control volumes" and "free body diagrams" serve to break down systems to analyze their elements piece-by-piece, per holon. Positional and electrical constraints expressed as equations put the systems "back together" and describe the connections among components/elements/holons.

Engineers confront the complexities of engineered systems as they endeavor to produce engineered obejects that meet performance "requirements" and fulfill their intended purposes, their teloi. To do so, "safety factors" and mass, power, volume, and cost margins are applied. Progress updates are delivered during "design reviews" to master engineers who find problems with and suggest solutions for designs and plans.

What if one desires to change system behavior? Meadows [37, Ch. 6] gives an extensive list of "leverage points" to change system behavior. A shorter list includes two important ways to intervene in a system to overcome its predilection to maintain structure and, ultimately, change its behavior: change the elements and change the connections.

Change the elements One way to achieve changes in higher-level function of a system is to make small changes to lower-level elements. Substituting one volleyball player for another can have dramatic effect on the behavior and performance of the team.

Change the connections Another way to change the functioning of a system is to change either the rates or routes of information and material flows among elements. In previous centuries, the development of railroads allowed material (goods) to move more quickly through the Earth system (economies). By stringing telegraph (and later telephone) lines, humans were able to move information more quickly through economies and across the Earth. Today, the internet enables the highest information transfer speeds in history, resulting in massive societal changes that were unimaginable a century ago. Undoubtedly, increasing the material and information velocity through economies has increased human well-being in many ways. But the velocity increases have also enabled unprecedented rates of economic growth, fossil fuel energy consumption, and CO_2 emissions. *You can never do only one thing.*

Other ways to change system behavior In addition to changing the elements and changing the connections, system behavior can be fundamentally altered by (a) adjusting the spatial arrangement of elements, (b) introducing delays to the interactions between elements, (c) adding or removing storage for materials and energy, (d) changing the rules of interactions among elements, and (e) changing the telos of a system.

12.3.2 SYSTEM CHALLENGES

Although systems present many opportunities, they provide many challanges as well, especially for those who would intervene to change their behavior. (1) Systems are difficult to understand, because many systems contain large numbers of holons, making thorough analysis impossible. Systems are *complicated*. (2) Even if it were possible to analyze the behavior of *all* holons, system emergent behaviors mean that higher level characteristics cannot be predicted from complete knowledge of the behavior of all lower-level elements. (Systems are *complex*.) (3) Even worse, the unpredictability of high-level system behavior means that unintended consequences arise from emergent behaviors. Thus, systems are perceived as being uncontrollable. (4) All of the above can make systems, including collaborative technological holarchies, difficult to manage. (5) The self-preservation characteristic of systems means that systems have a "mind of their own" and can seemingly resist attempts to change them. Maddeningly, for the volleyball coach, substitutions sometimes have little effect, even making team performance worse due to some unexpected interactions among the players.

> Systems are challenging and difficult to manage, because we have "linear minds in a nonlinear world" [37, p. 91].

12.4 COMPLEXITY THEORY

A field of inquiry that studies and describes systems and the interactions among their elements is *complexity theory* [39]. Complexity theory takes systems thinking in a philosophical direction to assist our understanding of the world and its systems.

Complexity theory distinguishes between complicated and complex attributes of systems. Systems are complicated, because they big and contain many parts. Although large, complicated systems are still solvable (in the sense that their behavior can be predicted) and deterministic. But complex systems, especially large systems with many connections, are neither solvable nor deterministic. They *can't* be understood by taking them apart and studying their elements. For example, a spacecraft is complicated, because it has many parts. It *might* be possible to predict, within some level of confidence, *some* aspects of spacecraft behavior (total mass, maximum thrust, etc.) simply by studying its elements. But it would be impossible to predict social, psychological, political, and other effects of Sputnik by studying its exterior, its thrusters, and its attitude control system. Sputnik is complex.

Many tenets of complexity theory emerge from systems thinking and have been discussed already: (a) systems can't be fully understood by taking them apart, (b) systems are resilient to external perturbations, (c) all modeling is an attempt to understand or describe a system via simplification, by reducing complexity, (d) all modeling necessarily involves drawing boundaries (as in free-body-diagrams and control volumes), and (e) emergent behavior means that effects cannot be tracked or predicted deterministically.

But further insights emerge from the field. In a system, complexity theory notes that all elements are connected all the time, either directly or indirectly via other connected elements. Thus, attempts to isolate elements of a real system as a way to understand the behavior of the system are futile. Any modeling or analysis that isolates elements of a system should be undertaken with much care. Elements outside of the system boundary should not be expected to affect system behavior significantly.

Chaotic characteristics, emergent behavior, and unintended consequences of real-world systems imply that human knowledge has limits, always. Humans are finite! Human knowledge is not arbitrary, but it is provisional, contextual, and contingent. Consequently, human intuition can *sometimes* be as important as scientific rationality when confronted with complexity.

Complexity theory helps us to understand that all system models, being simplified descriptions of the world developed by finite humans, involve choices. One of the most important choices in system analysis is the system boundary. Placement of the system boundary defines what is "in" the analysis (endogenous) and what is "out" of the analysis (exogenous). Thus, system models necessarily amplify some aspects or behaviors (endogenous elements and their interactions) and dampen other aspects or behaviors (exogenous elements and their interactions). There is a "boundary problem," namely that boundary placement affects knowledge obtained from any system analysis.

The "boundary problem" leads to consideration of epistemological issues such as how models and boundary placement mediate our understanding of the complex systems being analyzed. In particular, complexity theory arrives at the conclusion that there are *normative* aspects to analyzing complex systems. Placement of the system boundary is a normative choice, because the correctness of boundary placement can be evaluated relative to the purpose of each analysis. I.e., the "right" boundary placement is contingent upon the questions being asked and the problems to be solved. Therefore, it is right to ask how models *ought* to be constructed and interpreted for a given purpose. The fact that knowledge and understanding of a system are contingent upon boundary placement is one of the ways that human knowledge is always limited, provisional, contextual, and contingent.

12.5 SYSTEMS THINKING FOR SUSTAINABILITY

Systems thinking and complexity theory (STCT)[1] are valuable for understanding sustainability challenges. Indeed, STCT (a) provides a language to talk about observed behaviors of real systems in the real world and (b) brings important insights to some of the most difficult, sustainability-related problems facing society today. To demonstrate the applicability of STCT to sustainability challenges, consider the task of reducing CO_2 emissions worldwide.

Many engineers focus on the efficiency of end-use machines (such as cars, lights, and furnaces) to reduce CO_2 emissions. But STCT suggests that a narrow approach will be insufficient to reduce CO_2 emissions. Everything is interconnected, always. Focusing on end-use machines would neglect, e.g., (a) the energy conversion chain that extracts energy from the biosphere and delivers it to end users and (b) economic imperatives that give rise to energy consumption in the first place. STCT suggests that benefits would be found by widening the system boundary to include worldwide energy supply chains and the worldwide economy to form the climate-energy-economy (CEE) system.

For the CEE system, STCT would suggest that interactions among its elements would give rise to both emergent behaviors and unintended consequences. Indeed, the rebound effect and backfire are emergent behaviors that lead to unintended consequences (less energy saved than expected) within the CEE system. As discussed in Section 4.3, the rebound effect and backfire occur when end-use machines become more energy efficient, leaving consumers with more money in their wallets. Respending that saved money in the economy leads to increasing energy demand elsewhere in the energy conversion chain. A narrow system boundary (around end-use machines only) closes off the possibility of studying an economy-wide rebound effect or backfire. In contrast, an STCT mindsent and an expanded system boundary that includes the economy (i.e., the CEE system) enable consideration of the rebound effect and backfire.

And STCT would caution against assuming that analyzing the CEE system would lead to a solution to the worldwide CO_2 emissions challenge. The CEE system boundary is *still* too narrow to encompass all factors related to CO_2 emissions. Individual and group phychology, sociological factors, political parties and other political considerations, and information and computer technology remain exogeneous to the CEE system.

[1]Systems thinking and complexity theory are so closely related that the acronym STCT will be used for the remainder of this chapter.

Furthermore, STCT indicates that the CEE system boundary will amplify some real-world behaviors and dampen others. In the case of the CEE system, it is likely that economic effects on CO_2 emissions will be overemphasized. By virture of being exogenous to the CEE system, political effects will be underemphasized by the CEE system.

Because the CO_2 emissions problem is a worldwide phenomenon that affects every human being, it seems likely that solutions will involve changes at the highest levels of human society, namely policies promulgated at the international level.[2] However, politics are exogeneous to the CEE system, and analysis of the CEE system with a view to reducing CO_2 emissions seems likely to fail.

Redrawing the system boundary to endogenize politics could unlock new possibilities for policy solutions to the CO_2 emissions challenge. A system with the expanded boundary might be called the climate-energy-economy-policy (CEEP) system.

However, even after endogenizing politics within the CEEP system, an STCT mindset would indicate that developing and implementing CO_2-reducing policies would be fraught with potential problems. Limits to human knowledge mean that no policy can ever be perfect.

Another way in which developing and implementing policies to fight CO_2 emissions is fraught arises when STCT leads us to understand that the existing CEEP system will resist perturbations. STCT predicts that entrenched interests in the fossil fuel industry will resist changes to the existing CEEP system. Reasons for resisting change include financial (maintain existing reveunes and profits) and social (maintain employment) considerations. It becomes clear that a large dose of humility is needed in policymaking. STCT leads us to believe that all policies should be considered experiments, open to continued revision as more data become available.

In the face of limits to human knowledge, emergent behavior, unintended consequences, and system resilience, how are we to develop policy? With full knowledge of unintended consequences and system resiliance, the exhortations to "change the elements" and "change the connections" can guide humble policy-making. For the CEEP system, "changing the elements" could mean improving the efficiency of energy-consuming end-use machines, such as lights, cars, and washing machines. Efficiency improvements can be legislated via efficiency *standards* or by economic incentives such as *tax breaks* or *rebates* for purchasing high-efficiency end-use machines. "Changing the elements" could also mean providing incentives for rooftop

[2] Libetarians might object to the idea that the problem of CO_2 emissions should be solved by governments at the international level, instead of at the level of economically self-interested individuals. However, the current economic system does not incentivize individuals to make choices that reduce CO_2 emissions. To move from today's economic environment to one in which individuals *are* economically incentivized to pursue behaviors that reduce CO_2 emissions, governments must surely be involved to establish the necessary economic incentives.

solar electricity generating systems. Increasing adoption of renewable energy technologies might bring the unintended consequence of reduced employment in fossil fuel sectors. Policies should include retraining or re-skilling of displaced workers to avoid disruption of the social fabric in places where job losses can be expected. And, even as policies are put in place to incentivize renewables, the fossil fuel industry would be expected to work hard to maintain its structure (i.e., its dominant position in the energy industry) by making the application processes for household rooftop solar arduous and complicated. Incentives could be provided for the fossil fuel industry to adapt to changing conditions in the energy sector.

To "change the connections," policymakers can mandate that information about embodied CO_2 content must flow from sellers of goods to potential consumers. To incentivize rooftop solar, policymakers can mandate that grid operators buy electricity from household solar PV systems at a favorable rate.

To avoid the unintended consequences of rebound and backfire, organizations can develop policies that capture the monetary savings resulting from energy efficiency interventions. Special accounts called *green revolving funds*[40] require that monetary savings from energy efficiency be used for additional energy efficiency interventions, thereby ensureing that savings don't "leak" to the rest of the economy.

QUESTIONS

12.1. Make a list of 3 systems. What are the the elements (holons), connections (holarchy), and teloi for each system? Are they complicated or complex?

12.2. In Section 12.5, systems thinking and complexity theory (STCT) were applied to the problem of reducing CO_2 emissions worldwide. Now apply STCT to the more-specific problem of CO_2 emissions from the existing transportation system discussed 8. Begin by assessing the problems was the existing transportation system designed to solve. Continue to think about what problems we have today. Then think about the "legacy" transportation system in light of STCT. Is the legacy transportation system resilient (resistant to change)? Why or why not? If you deem the legacy transportation system resistant to change, in what ways is that true? Does our legacy transportation system exacerbate or help to solve today's sustainability challenges? If you want to change the legacy system, how would STCT suggest that interventions be made? Does the tendency to preserve structure in legacy systems mean that our existing transport system views sustainable transport as a "virus" that needs to be eliminated?

12.3. Repeat Question 12.2 for the food and agriculture system discussed in Chapter 7.

CHAPTER 13

Values and Religion (JVA 7)

CHAPTER 14

Personal Actions (MKH 5)

Student question: I know you drive a car. If fossil fuel consumption is the end of society, how do you find that justifiable? Or if you ever fly or eat anything that you don't produce or use any product that uses metals or petroleum, how do you justify that consumption?

Answer: If everyone (including me) decided today to stop using fossil fuels (FFs), a large portion of our sustainability challenges would evaporate. However, the world I was born into requires the consumption of electricity and the need for high-speed transport. (By "high speed," I mean automobile speed.) You can't live life in today's society without access to refrigeration, lighting, and transport. At present, those needs (refrigeration, lighting, and transport) are provided by FF consumption. And even worse, if I, personally, would decide to never drive a car again, I'm still not with out guilt. The food I eat is enabled by FF energy sources. So I would also need to grow, harvest, and preserve all my own food. I don't have those skills! The lights I use and the refrigerator both require coal consumption to provide the electricity they need. We live in a FF web. And it can get quite depressing.

There is plenty to lament. And there is a corporate guilt that we all face, which is why I like to think at a very broad level, at the societal level.

Even worse, many people don't know about the sustainability challenges we face. That's why I've dedicated my professional life to exploring and educating on these issues. I have come to understand that I can contribute to a way forward by doing so. And by minimizing my impact in other areas. (I think it is impossible to eliminate our environmental impacts because of the way the world is structured.) You're right that I drive a car. But I bought it used, it's tiny, and it gets over 40 mpg. You're right that I consume electricity, but I am converting all my lights to LEDs, one by one, as the incandescents reach end of life.

Table 14.1 gives four questions to consider as you make choices that affect the rest of your life. Answers that go in the direction of sustainability and make a difference without moving to an agrarian, pre-1900s lifestyle are also given in the table. If you do those things, you haven't solved any sustainability problems. But at least you'll be pointed in the right direction, relative to the rest of society.

Table 14.1: Personal Q&A

Question	Answer
How big is your house?	Small and used
What car do you drive?	Small and used
How close do you live to work, church, and stores?	Close (allowing walking and cycling)
What do you eat?	Closer to the bottom of the food chain

14.1 FOOD AND AGRICULTURE

Chapter 7 showed that the animal-based portions of the agriculture system are less efficient than the overall system. So eating fewer animal-products and more plant-based products provides improved agriculture system efficiency and a net sustainability beneift. I.e., eating closer to the bottom of the food chain brings sustainability benefits.

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