2

ENERGY FLOWS AND SUPPLIES

2.1 Human Energy Consumption

Humans have harnessed diverse sources of energy to fuel our development. By examining global energy fluxes, we can propose human energy use in the context of the total energy supplied by the sun to earth. Table 2.1 shows these global energy fluxes, demonstrating that human usage of energy is a very minor fraction of the total energy absorbed by the earth's surface. However, energy use is rapidly rising, requiring the development of ever more energy resources. Furthermore, to address concerns about global climate change, humans must work to reduce the amount of the energy that comes from fossil sources, which emit CO_2.

TABLE 2.1 Global Energy Fluxes

Sources	Rates (10^{20} kJ yr^{-1})
Solar energy incident on earth	54.4
Solar energy affecting earth's climate and biosphere	38.1
Energy taken up in global evaporation of water	12.5
Energy in wind	0.109
Solar energy taken up in photosynthesis	0.0850
Energy conducted from the earth's interior to its surface	0.0100
Total primary energy consumed by humans, 2016	0.00612
Total energy produced in the United States, 2018	0.00129
Total energy consumed in the United States, 2018	0.00107
Fossil energy produced in the United States, 2018	0.00079

Sources: Energy Information Administration, 2008, *International Energy Outlook 2007,* available at http://www.eia.gov/oiaf/ieo/; Energy Information Administration, 2008, *Annual Energy Review 2007,* available at http://www.eia.gov/emeu/aer/contents.html; and Energy Information Agency, International Energy Statistics, *International,* available at https://www.eia.gov/beta/international/data/browser/#/?c=41000000020000600000000000000g00020000000000000000001&vs=INTL.44-1-AFRC-QBTU.A&vo=0&v=H&end=2016 and *Total Energy,* available at https://www.eia.gov/totalenergy/data/browser/index.php?tbl=T01.01#/?f=A&start=1949&end=2018&charted=4-6-7-14 [given in units of quad BTU per year; 1 quad BTU – 1.05×10^{15} kJ].

QUESTION 1

To put these energy flows in context, calculate what fraction of incoming solar radiation is taken up in plant photosynthesis.

Q1 ANSWER The annual amount of energy taken up by photosynthesis is 0.0850 kJ, and the total solar energy incident on earth is 54.4×10^{20} kJ. Taking the ratio of these two numbers:

$$\frac{0.0850 \times 10^{20}\ \text{kj}}{54.4 \times 10^{20}\ \text{kj}} \times 100\% = 0.00156 \times 100\% = 0.156$$

***QUESTION 2**

What fraction of total primary energy on earth is consumed by humans?

***QUESTION 3**

What fraction of energy consumed in the United States is produced from fossil energy?

QUESTION 4

In what direction would you expect the fraction of fossil fuel use to energy consumed in the United States to be trending?

Q4 ANSWER Coal has been decreasing in the United States and renewables have been increasing. But oil and gas have been increasing even faster, as shown in Figure 2.1. If these trends continue, the fossil energy fraction will increase further. Reversing this trend would require stronger regulations and/or a price on carbon release.

Our present civilization is dependent on the efficient extraction and distribution of energy supply among end-users. One convenient depiction of this energy system (for the case of the United States) is shown in Figure 2.2, showing estimated 2018 energy use, split out by both sources and end-uses. The figure shows, among other things, that U.S. energy supply substantially exceeds consumption, showing that we are a net energy exporter.

QUESTION 5

What fraction of domestic energy production in the United States is nuclear?

Q5 ANSWER Using the numbers on the left-hand side of Figure 2.2 which describes the sources of energy:

$$\frac{8.44\ \text{quad BTUs}}{95.70\ \text{quad BTUs}} \times 100\% = 0.0882 \times 100\% = 8.82$$

* Answers to starred questions can be found at the end of the book.

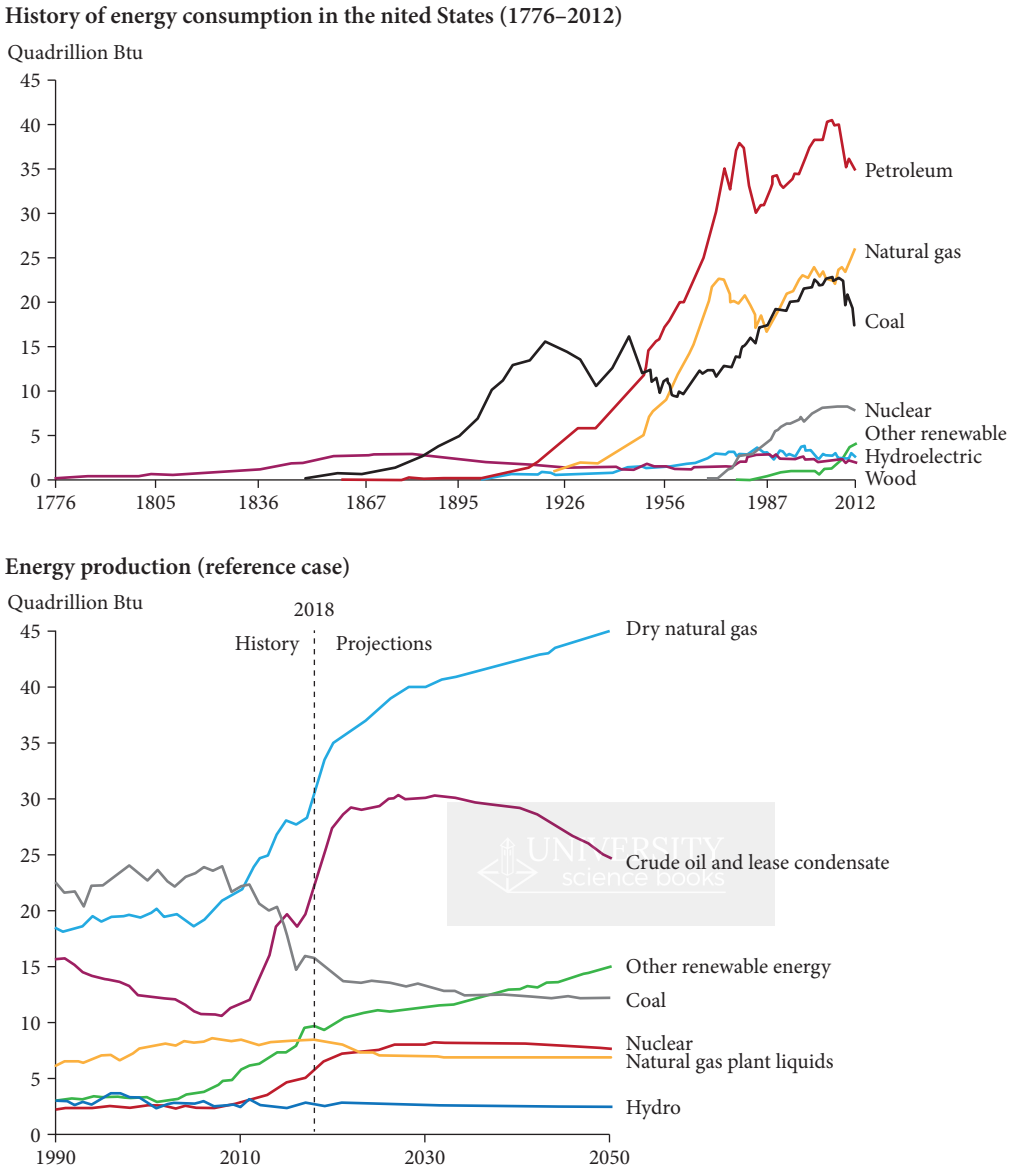
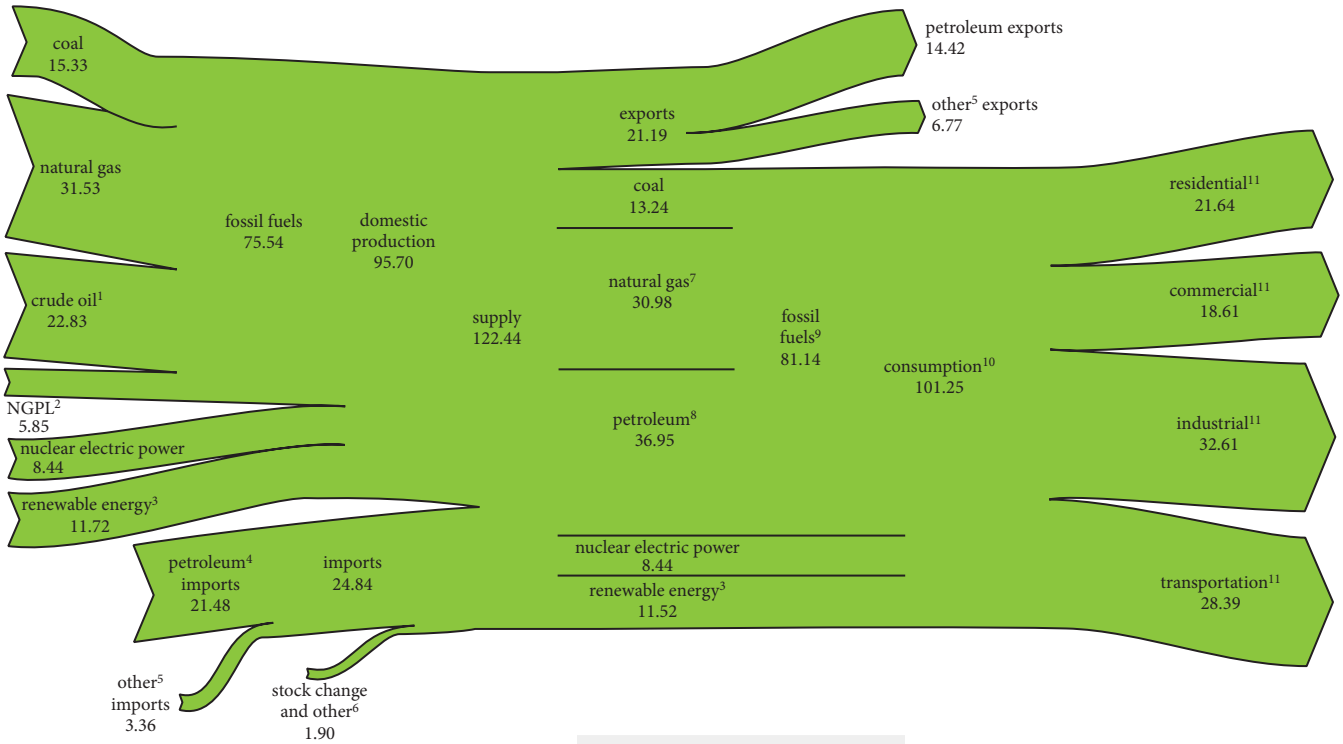


Figure 2.1 The fuel mix of energy consumption in the United States has changed dramatically over the past centuries, including a recent dramatic increase in renewable feedstocks. *Sources:* The data in the plots are from the U.S. Energy Information Agency, *Energy Sources Have Changed Throughout the History of the United States,* 2013, available at https://www.eia.gov/todayinenergy/detail.php?id=11951 and *Annual Energy Outlook 2019,* 2019, available at https://www.eia.gov/pressroom/presentations/capuano_01242019.pdf

U.S. energy flow, 2018

quadrillion Btu



[1] Includes lease condensate.
[2] Natural gas plant liquids.
[3] Conventional hydroelectric power, biomass, geothermal, solar, and wind.
[4] Crude oil and petroleum products. Includes imports into the Strategic Petroleum Reserve.
[5] Natural gas, coal, coal coke, biomass, and electricity.
[6] Adjustments, losses, and unaccounted for.
[7] Natural gas only; excludes supplemental gaseous fuels.
[8] Petroleum products supplied.
[9] Includes –0.03 quadrillion Btu of coal coke net imports.
[10] Includes 0.15 quadrillion Btu of electricity net imports.
[11] Total energy consumption, which is the sum of primary energy consumption, electricity retail sales, and electrical system energy losses. Losses are allocated to the end-use sectors in proportion to each sector's share of total electricity retail sales. See Note 1, "Electrical System Energy Losses," at the end of U.S. Energy Information Administration (EIA), *Monthly Energy Review* (April 2019), Section 2.
Notes: • Data are preliminary. • Values are derived from source data prior to rounding for publication. • Totals may not equal sum of components due to independent rounding.
Sources: EIA, *Monthly Energy Review* (April 2019), Tables 1.1, 1.2, 1.3, 1.4a, 1.4b, and 2.1.

Figure 2.2 The U.S. Energy Information Association (EIA) produces this Sankey diagram annually to show the relative contributions of various energy sources and sectors of energy consumption. The units here (quadrillion BTU) are the preferred energy unit used by the U.S. EIA; see conversion factor in the notes to Table 2.1. *Source:* U.S. Energy Information Association, available at https://www.eia.gov/totalenergy/data/monthly/pdf/flow/total_energy.pdf.

This snapshot in time obscures a key element of the energy challenge: with exponentially growing population, global energy demands are increasing apace. Figure 2.1 shows U.S. energy consumption over time.

***QUESTION 6**

What fraction of energy consumed in the United States goes to transportation?

QUESTION 7

Which source of energy was dominant in 1900? Which is dominant today? Which has grown the fastest in the last 20 yr?

Q7 ANSWER Looking at Figure 2.1, we can see that coal was dominant in 1900, but petroleum is dominant today. Natural gas has recently been the fastest-growing energy source in the United States.

***QUESTION 8**

What decade saw the fastest growth in consumption of energy from coal? From petroleum? Natural gas? Nuclear?

2.2 Exponential Growth

In Chapter 1, you encountered the concept of exponential growth as it pertains to human populations and consequently to human activities such as energy consumption. Here we will grapple with exponential growth quantitatively. Exponential growth arises from a quantity that grows as a constant *percentage* rate, so that a quantity Q grows in proportion to how much is present at a given time, shown by differential equation (2.1), or integrated equation (2.2), where k is the fractional growth rate:

$$\frac{dQ}{dt} = kQ \tag{2.1}$$

$$Q = Q_0 e^{kt} \tag{2.2}$$

For exponential growth, the doubling time (time elapsed for $Q/Q_0 = 2$) is constant and equal to 0.693 k^{-1}.

While energy use is increasing everywhere, the annual rate of increase (and thus the doubling time) varies by country. This is shown in Figure 2.3, which outlines the projected energy growth in the fastest-growing countries of the Organization for Economic Co-operation and Development (OECD), contrasted with the faster-growing non-OECD countries.

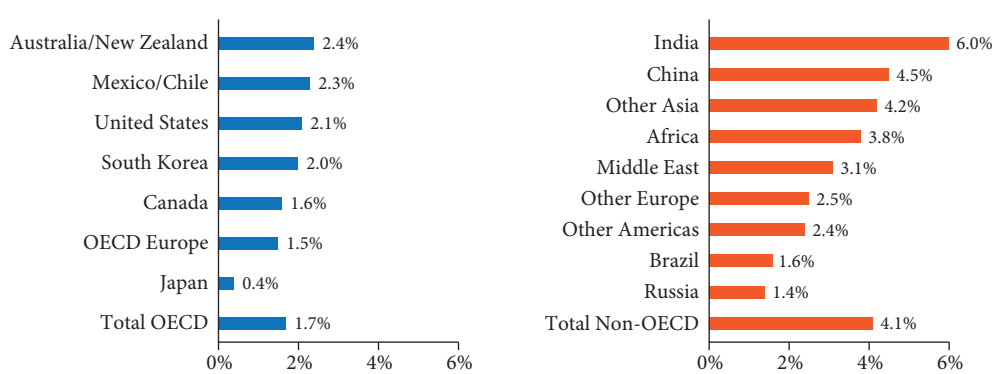


Figure 2.3 Projected energy trends (2015–2040) in selected OECD (left) and non-OECD (right) countries. *Source.* The Energy Information Administration, *International Energy Outlook 2018,* available at https://www.iea.org/reports/world-energy-outlook-2018.

QUESTION 9

In 2017, global energy demand grew 2.3%, according to the International Energy Agency. For this growth rate, what would be the doubling time of energy demand?

Q9 ANSWER Using the relationship where doubling time equals 0.693 k^{-1} we find:

$$t_{\text{double}} = \frac{0.693}{0.023\ \text{yr}^{-1}} = 30\ \text{yr}$$

***QUESTION 10**

If the world energy consumption were to increase at 2.8% per year, how long would it take to double?

QUESTION 11

If this rate of growth (2.8%) continued for the next 100 yr, how would human energy consumption compare with all the solar energy incident on earth?

Q11 ANSWER According to Table 2.1, human consumption of energy is currently 0.00612×10^{20} kJ yr^{-1}. We calculated the doubling time for a rate of growth of 2.8% to be 25 yr in Q10. If this rate of growth continues for 100 yr, this will have doubled four times, and thus would be 16 times larger:

$$16 \times 0.00612 \times 10^{20}\ \text{kJ yr}^{-1} = 0.0979 \times 10^{20}\ \text{kJ yr}^{-1}$$

Comparing this to total solar energy incident on earth (54.4×10^{20} kJ yr^{-1}):

$$\frac{0.0979 \times 10^{20}\ \text{kj yr}^{-1}}{54.4 \times 10^{20}\ \text{kj yr}^{-1}} \times 100\% = 0.00180 \times 100\% = 0.180\%$$

This is still a very small fraction!

QUESTION 12

If this rate of growth (2.8%) continued longer, starting at today's value, how long would it take to equal the solar energy incident on earth?

Q12 ANSWER For this question, we need to use the equation for exponential growth:

$$Q = Q_0 e^{kt}$$

Taking the natural logarithm, we get:

$$\left(\frac{Q}{Q_0}\right) = kt$$

where $k = 0.028\ \text{yr}^{-1}$, $Q = 54.4 \times 10^{20}$ kJ yr^{-1}, and $Q_0 = 0.00612 \times 10^{20}$ kJ yr^{-1}

Solving for t:

$$t = \frac{\ln\left(\frac{Q}{Q_0}\right)}{k} = \frac{\ln\left(\frac{54.4 \times 10^{20}\ \text{kj yr}^{-1}}{0.00612 \times 10^{20}\ \text{kj yr}^{-1}}\right)}{0.028\ \text{yr}^{-1}} = 325\ \text{yr}$$

This takes a while!

TABLE 2.2 Selected Country Energy Use and Projected Increase

Country	Population (million)	Energy Use (kWh per capita)	Projected Annual Increase (%)
India	1,366	805	6.0
China	1,433	3,927	4.5
Australia	25.2	10,071	2.4
United States	329	12,994	2.1
South Korea	51.2	10,417	2.0
Brazil	211	2,620	1.6
Canada	37.4	15,588	1.6
Russia	146	6,603	1.4

Source. Energy Information Administration, *International Energy Outlook 2018* (https://www.iea.org/reports/world-energy-outlook-2018)

QUESTION 13

Table 2.2 lists 2019 per capita energy use for selected countries and the current growth rate. What are the top three countries in total energy use?

Q13 ANSWER Multiplying the per capita energy use by the population shows that China was the top energy user in 2019 with 5.63×10^{12} kWh. The United States (1/4 of China's population) was second, with 4.28×10^{12} kWh, while India (almost as populous as China) was third, with 1.10×10^{12} kWh. However, India's energy use is growing fastest, followed by China.

India: $$1366 \times 10^6 \text{ people} \times \frac{805 \text{ kWh}}{\text{person}} = 1.10 \times 10^{12} \text{ kWh}$$

China: $$1433 \times 10^6 \text{ people} \times \frac{3{,}927 \text{ kWh}}{\text{person}} = 5.63 \times 10^{12} \text{ kWh}$$

Australia: $$25.2 \times 10^6 \text{ people} \times \frac{10{,}071 \text{ kWh}}{\text{person}} = 0.254 \times 10^{12} \text{ kWh}$$

United States: $$329 \times 10^6 \text{ people} \times \frac{12{,}994 \text{ kWh}}{\text{person}} = 4.28 \times 10^{12} \text{ kWh}$$

South Korea: $$51.2 \times 10^6 \text{ people} \times \frac{10{,}417 \text{ kWh}}{\text{person}} = 0.533 \times 10^{12} \text{ kWh}$$

Brazil: $$211 \times 10^6 \text{ people} \times \frac{2{,}620 \text{ kWh}}{\text{person}} = 0.553 \times 10^{12} \text{ kWh}$$

Canada: $$37.4 \times 10^6 \text{ people} \times \frac{15{,}558 \text{ kWh}}{\text{person}} = 0.582 \times 10^{12} \text{ kWh}$$

Russia: $$146 \times 10^6 \text{ people} \times \frac{6{,}603 \text{ kWh}}{\text{person}} = 0.924 \times 10^{12} \text{ kWh}$$

QUESTION 14

If the current growth rates were to continue, how long would it take for China's per capita energy use to equal that of the United States?

Q14 ANSWER Continued constant percentage rate leads to exponential growth:

$$Q = Q_0 e^{kt}$$

If Q_1 and Q_2 are per capita energy use for the United States and China, respectively, then when they are equal:

$$Q_1 e^{k_1 t} = Q_2 e^{k_2 t}$$

$$\frac{Q_1}{Q_2} = \frac{e^{k_1 t}}{e^{k_1 t}} = e^{(k_2 - k_1)t}$$

$$Q_1 = \ln Q_2 = (k_2 - k_1)t$$

$$t = \frac{\ln Q_1 - \ln Q_2}{k_2 - k_1} = \frac{\ln 12994 - \ln 3927}{0.045 - 0.021} = 49.9 \text{ yr}$$

China would catch up to the United States in per capita energy use in 2069.

***QUESTION 15**

How long would it take India to catch up to the United States?

QUESTION 16

The growth in energy consumption has diminished in the west, partly due to the shift of manufacturing overseas, where it contributes to other countries' energy consumption. If you were working for the Energy Information Agency and tasked with producing a ranking of energy use by country, but attributing the energy consumption to the end-user of all goods, what additional data would you seek to use? How would you define the ranking?

Q16 ANSWER Each country's *effective gross* energy consumption would be adjusted downward according to the energy embedded in exported goods, and upward according to the energy embedded in imported goods. Estimating these "embedded energy" values would be difficult, but both could possibly be estimated by determining the average energy intensity of traded goods and using this as a multiplicative factor on the trade volumes in dollars.

Exponential growth applies to areas other than energy. For example, during an early age of rapid agricultural expansion (1810–1850), the farmed area of the planet increased from 1.43 billion hectares (ha) to 1.78 billion ha, or on average, 0.6% per year.

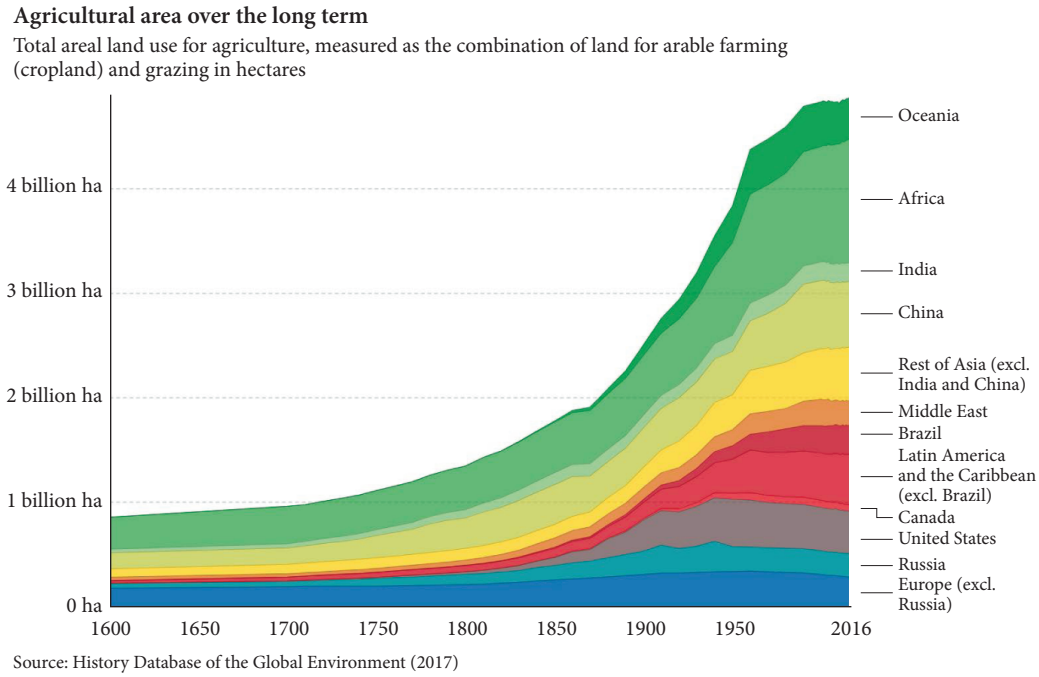


Figure 2.4 The farmed area of the planet increased rapidly beginning in about 1800.
Source: Adapted from *Our World in Data: Crop Yields,* available at https://ourworldindata.org/yields-and-land-use-in-agriculture.

***QUESTION 17**

At this expansion rate, how long would it take to double from the area farmed in 1810, 1.43 billion ha? Is your answer consistent with Figure 2.4 in the years after 1850?

QUESTION 18

If the rate of agricultural expansion referenced in Q17 were to continue to exponentially grow, how long would it take for all of the habitable land areas of the earth to be covered by crops? The earth's total land area is 150 million km^2, of which about 70% is designated as habitable; 1 km^2 is equal to 100 ha.

Q18 ANSWER Use $Q = Q_0 e^{kt}$ to solve for t.
70% of 150 million km^2 gives 105 million km^2 habitable land:

$$0.70 \times 150 \times 10^6 \text{ km}^2 \times \frac{100 \text{ ha}}{\text{km}^2} = 1.05 \times 10^{10} \text{ ha}$$

$$Q = Q_0 e^{kt}$$

$$1.05 \times 10^{10} \text{ ha} = 1.43 \times 10^9 \text{ ha } e^{(0.006)t}$$

$$\frac{1.05 \times 10^{10}\ \text{ha}}{1.43 \times 10^{9}\ \text{ha}} = 7.34 = e^{(0.006)t}$$

$$\ln(7.34) = 0.006t$$

$$t = \frac{\ln(7.34)}{0.006} = 332\ \text{yr}$$

Starting from 1810, this would mean in 2142 we would have all habitable land occupied by agriculture.

QUESTION 19

Crop productivity has greatly increased since 1850, thanks to the "Green Revolution" of the early twentieth century, when agricultural output was dramatically increased thanks to the development of crop breeding and the use of fertilizer. If the graph in Figure 2.5 were representative of crops worldwide, how much could the acreage be decreased to achieve the 2014 food production? Is there any evidence of this effect in Figure 2.4?

Q19 ANSWER Crop productivity was 3–4 times higher in 2014 than in 1850, according to Figure 2.5, suggesting that the 2014 acreage requirement was 3–4 times lower than it would otherwise have been. In fact, the acreage growth curve does bend over (Fig. 2.4) starting around 1980, and acreage was substantially lower in 2016 than would be predicted from the earlier exponential growth.

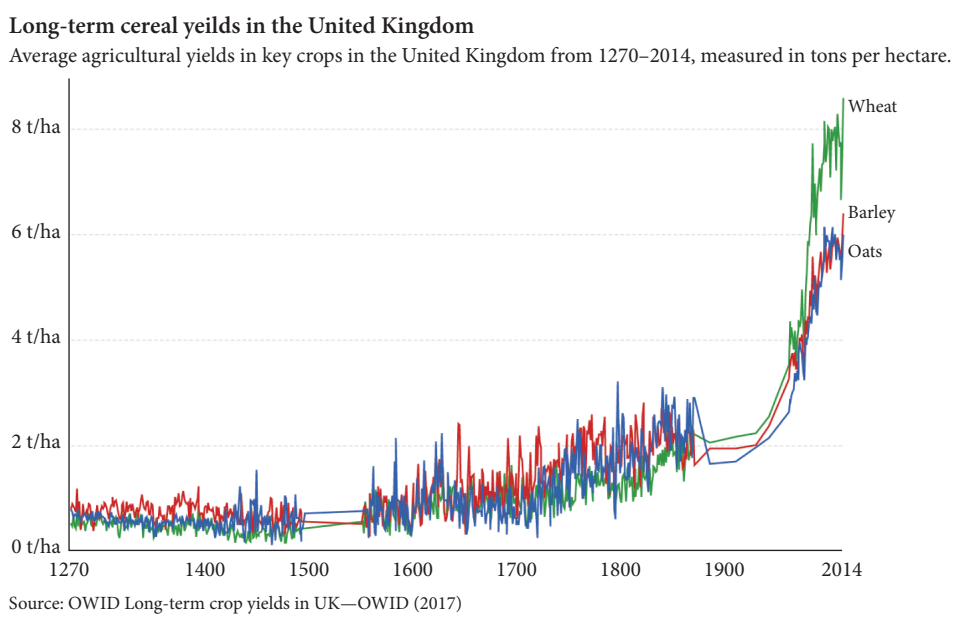


Figure 2.5 These data for the United Kingdom are representative of crops worldwide, where yields dramatically increased with the advent of fertilized usage in the "Green Revolution" of the early twentieth century. *Source:* Adapted from Our World in Data, available at https://ourworldindata.org/grapher/long-term-cereal-yields-in-the-united-kingdom.

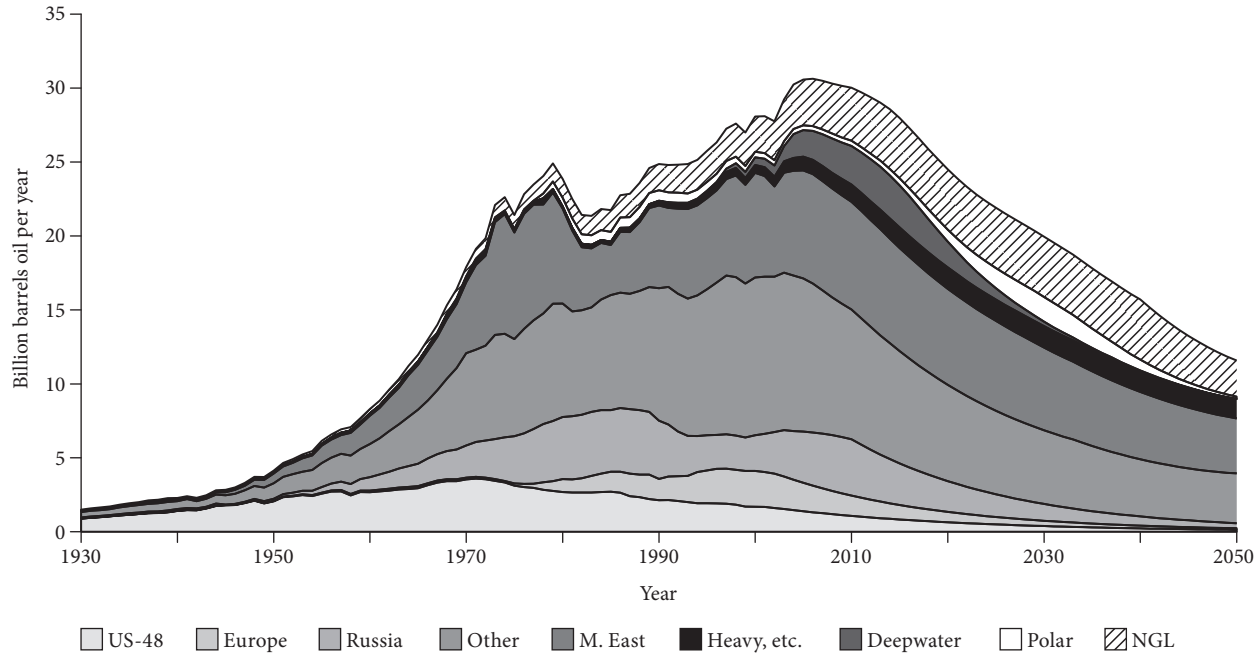


Figure 2.6 A prediction of global peak oil production in billion barrels of oil per year. "Other" denotes oil shales and coal sources; "heavy" includes bitumen and heavy oil; "deepwater" denotes oil in the water of a depth of more than 500m; "NGL" represents liquids from natural gas plants and gas fields. *Source:* Adapted from Association for the Study of Peak Oil (ASPO) Newsletter, 2004. Adapted from *Chemistry of the Environment, 3rd Ed.,* Spiro et al., University Science Books, © 2012, all rights reserved.

The exponential rise cannot go on forever; it is constrained by some sort of limit (e.g., arable land for agricultural acreage). This is just as true for fossil energy resources as for agriculture. As we will see in Chapter 5, several fossil sources of energy have been shown to "peak," meaning their extraction rate decreased after reaching a maximum, as described by the differential equation below:

$$\frac{dQ}{dt} = (2\pi)^{-\frac{1}{2}} Q_{\text{lim}} e^{-\frac{(t-t_1)^2}{2}} \tag{2.3}$$

where Q_{lim} is the limiting (maximum) rate of use and t_1 is the time it takes to reach the maximum extraction rate for an exhaustible resource. After t_1, the rate declines, forming a bell-shaped curve that has been observed in resource extraction rates.

For example, oil extraction in the contiguous 48 states of the United States peaked in about 1970 at about 4 billion barrels (bbl) of oil per year (see Fig. 2.6).

QUESTION 20

U.S. oil extraction began in earnest in ~1920. Use Figure 2.6 to estimate t_1 for US-48 (recall, this will be the *length* of time since extraction began), and then calculate what Q_{lim} this would correspond to. Can you find U.S. oil reserve data to check your estimate against?

Q20 ANSWER Estimating t_1 from the graph, ~50 yr (from the start of oil exploration in 1920 until the US-48 peak in 1970). At the peak of the curve, where $t = t_1$, dQ/dt is the amount of oil produced in US-48. Reading off the peak of the US-48 shaded area, $dQ/dt = 4$ bbl yr^{-1}, and because at this point in time (where $t = t_1$) the exponential term is $e^0 = 1$, we have:

$$\frac{dQ}{dt} = (2\pi)^{-\frac{1}{2}} Q_{lim} = 4 \text{ bbl yr}^{-1}$$

Which we can solve for Q_{lim}; $Q_{lim} = 10$ bbl of oil per year.

***QUESTION 21**

Conduct a similar analysis for Russia, where oil exploration began ~1930. (It looks more double-peaked, but use the first peak for this calculation.)

2.3 Human Energy Sources

As you calculated in question Q3, energy consumption is presently heavily dependent on fossil fuels (oil, gas, and coal). Not only do these fossil sources produce CO_2 emissions that cause anthropogenic climate change, but they are non-renewable sources that will eventually run out. By examining data on our best estimates of resource bases and usage rates, we can estimate how long each of these finite fossil energy sources will last.

The data from Figure 2.6 were taken in 2004 before hydraulic fracking technology was developed. After drilling into the earth, fracking uses high-pressure chemicals, water, and sand aimed at rock to release the natural gas inside. This technology allows access to reservoirs of natural gas that were not available previously and demonstrates how new technologies can change predictions in available resources. After 2004, natural gas was more abundant and a less expensive source of energy.

QUESTION 22

According to the EIA, as of January 2018, the demonstrated U.S. reserve base of coal was 475 billion short tons, larger than natural gas and oil resources in terms of British Thermal Units (BTUs) production potential. Annual U.S. coal production in 2017 was 775 million short tons.[1] Based on this information, will the United States have run out of coal during your lifetime?

Q22 ANSWER No, unless you are very ambitious about the length of your life! There will be no peak coal for quite some time. If we divide the reserve base by the annual production, we can estimate the time until the resource runs out at the current rate:

$$\frac{475 \times 10^9 \text{ short tons}}{775 \times 10^6 \text{ short tons per year}} = 613 \text{ yr}$$

However, the coal production rate is dropping (Fig. 2.2). Coal will likely continue to be replaced in power plants by gas and by renewables. Some of the reserves may remain in the ground.

[1] "Annual Coal Report, https://www.eia.gov/coal/annual/archive/0584_2018.pdf

***QUESTION 23**

Energy growth rates. The EIA regularly predicts future energy consumption. One recent projection estimated that world petroleum consumption will increase from 197 quadrillion BTUs in 2018 to 229 quadrillion BTUs in 2040. Assuming exponential growth this period 2005–2030, what average growth rate does this imply for total energy use?

QUESTION 24

According to the EIA, there were about 2,459 trillion cubic feet (Tcf) of technically recoverable resources (TRRs) of dry natural gas in the United States in 2018. Using the 2018 annual rate of U.S. natural gas production of 30.4 Tcf, how long with the U.S. natural gas TRR last?

Q24 ANSWER Dividing the recoverable resource by the annual production, the TRR will last:

$$\frac{2{,}459 \text{ Tcf}}{30.4 \text{ Tcf yr}^{-1}} = 81.7 \text{ yr}$$

The United States has enough dry natural gas to last about 80 yr at the current production rate. Renewables are starting to compete with gas, as the costs of wind and solar energy continue to decrease, and as restrictions on carbon emissions are strengthened.

***QUESTION 25**

If the TRR were to increase to 3,000 Tcf, and the annual rate of production were to be reduced to 20 Tcf yr^{-1}, in response to the increasing competitiveness of alternate renewable energy sources, how long would the natural gas reserve last?

2.4 Conclusions

The amount of energy that humans *consume* is a small fraction of total energy that is *supplied* to the planet in the form of solar radiation, but human energy use has constantly increased over human history. The energy resource mix used to generate electricity and fuel transportation is constantly changing, but the sum total increases with the exponential growth of the human population. Economies of scale mean that larger countries are typically more energy efficient. Fossil energy resources are by their nature finite and nonrenewable, and the production of these feedstocks will peak.