Fossil Fuels and Energy

CHAPTER 9

Where fossil fuels come from and how they are used

Energy Sources

The flow of energy drives the biosphere of the Earth, and it drives human civilization. Energy flows can be described in units of **Watts**, equal to **Joules** per second, where Joules is a unit of energy like calories. A hairdryer might use 1000 W of power, or 1 kiloWatt (kW). For global energy fluxes, it is convenient to speak in terms of **teraWatts**, equal to 10^{12} Watts, abbreviated as TW.

The sun bathes the Earth in energy at a rate of about 173,000 TW. Photosynthesis captures about 100 TW. Mankind is consuming about 14 TW of energy per year. Some of our energy use comes from the sun; wind, hydroelectric, solar, and biomass energy are all driven ultimately by sunlight. Of these, the largest source of energy is hydroelectric power, which makes up about 2% of the global energy supply (Figure 9-1). Renewable energy, defined as geothermal, solar, wind, wood, and waste electric power, supplies about 0.3% of our power.

All of our energy ultimately comes from stars, mostly our sun.

Humans are also mining one-use-only energy sources from the Earth, in fossil fuels and radioactive elements. Nuclear energy is mostly driven by decay of uranium, which was formed into its unstable high-energy nuclear state in supernova explosions of stars. I guess you could say that nuclear energy is fossil starlight. It accounts for another 2% of global energy production.

Fossil fuels derive their energy from ancient sunlight, harvested by photosynthesis that took place millions of years ago. Over Earth's history, photosynthesis has preserved a sizable amount of reduced carbon, and the energy in this carbon can be harvested by reacting it back with O_2 to regenerate CO_2 and H_2O. In other words, the carbon can be burned, releasing its energy as heat; or it can be respired, as when you digest your lunch, capturing the energy to drive biological processes.

Most of the reduced carbon on Earth is so diluted in rocks and sediments that for practical purposes it is useless as a fuel. It takes very special circumstances to preserve the carbon in a pure enough form to be a convenient energy source. Fossil fuel carbon comes in all three phases: solids, liquids, and gases.

Only a small fraction of the buried organic carbon is in a convenient form for fuel.

The largest traditional fossil fuel reservoir is **coal**. The carbon in coal comes from land plants, that were deposited in swamps. The organic carbon is preserved in swamps because the standing water protects it from degradation by oxygen in the atmosphere.

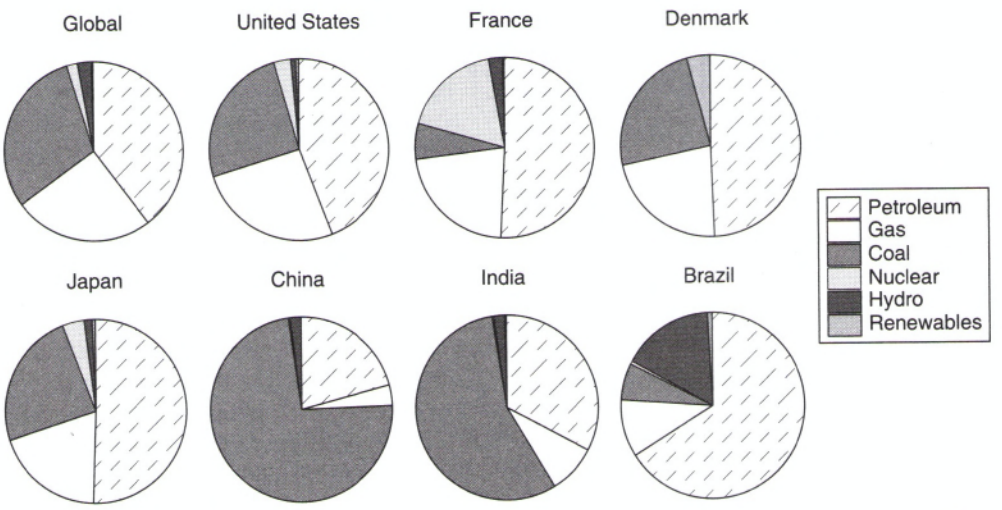

Figure 9-1 The sources of energy used globally and in various countries. From the U.S. Energy Information Administration, data from 2006 and 2007.

Coal from freshwater swamps contains less sulfur than coal from saltwater swamps, because of the sulfate, SO_4^{2-}, dissolved in seawater that winds up as sulfur in the coal. Upon combustion, the sulfur forms droplets in the air called *aerosols* that scatter sunlight, then it deposits as acid rain. High-sulfur coal also has mercury in it, making coal power a leading source of mercury release to the environment.

Coal is the most abundant fossil fuel, and the future of Earth's climate depends mostly on what happens to that coal.

Over time, the carbon accumulates into thick layers of what is called **peat**. If the peat is buried and cooked for millions of years, it turns into coal. There are different grades of coal depending on how well cooked it is. The highest grade of coal has been cooked the longest, and it is composed almost entirely of carbon, the original hydrogen and oxygen driven off as water, CO_2, oil, and gas.

The British Petroleum Company (BP), in their annual report on global energy (see Further Reading) estimates that there are 1,000 gigatons (Gtons) of carbon in coal reserves. Another source, an academic article by Rogner (also listed in Further Reading), estimates that the total amount of coal ultimately available might be 10 times that. David Rutledge at CalTech argues that there is much less coal available than this. However, it is commonly assumed that there is enough coal to supply our needs for several centuries, if we choose to use it.

In the United States, coal is mostly used for generating electricity (Figure 9-2). Coal itself is cheap and abundant in many parts of the world, and if a coal-fired power plant is already built, it can produce electricity more cheaply than pretty much any other source.

The energy stored in **oil** was originally harvested from sunlight by photosynthesis that took place in the ocean. Plants in water are generically called **algae**. Microscopic algae suspended in the ocean are called **phytoplankton**. Phytoplankton in the ocean produces about as much organic carbon by photosynthesis every year as the terrestrial biosphere on land does. A tiny fraction of the dead phytoplankton ends up in sediments; the rest gets eaten by something, animal or bacteria, in the water column or in the top layer of sediments.

The sediments covering most of the sea floor do not contain enough organic carbon to ever make oil. Typical deep-ocean sediments have less than 1% organic carbon by weight, but typical **oil source rocks** contain something like 3% to 10% organic carbon. Most oil comes from very

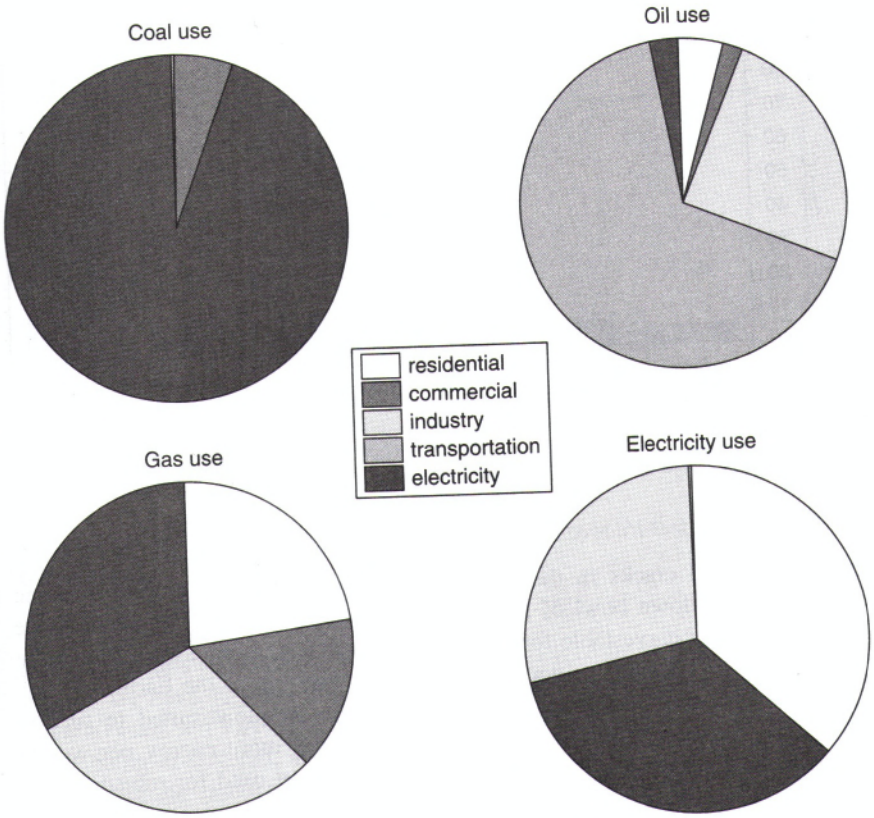

Figure 9-2 How different forms of fossil energy are used in the United States. From the U.S. Energy Information Administration.

specific oil-source rock layers just a few feet thick. These source rocks formed near continents and under water that has no oxygen dissolved in it, which is called **anaerobic** conditions.

If organic-rich sediments are buried to a depth in the Earth between 2 and 5 km, they will be heated to temperatures of 50° to 150°C. This has the effect of converting some of the dead plankton into oil, consisting of chains of carbons with hydrogens attached (Figure 9-3). If the temperature goes higher, the carbon winds up as methane in natural gas.

> Oil is probably the most convenient but the least abundant of the fossil fuels, so it is the most expensive.

If the mud is too impermeable, any oil or gas produced could just stay there in small droplets or bubbles, out of drilling reach. Alternatively, it could flow through the pores of

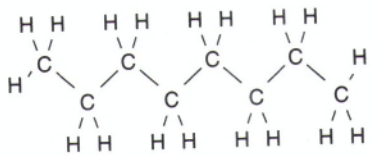

Figure 9-3 The structure of normal octane, a hydrocarbon chain such as found in petroleum.

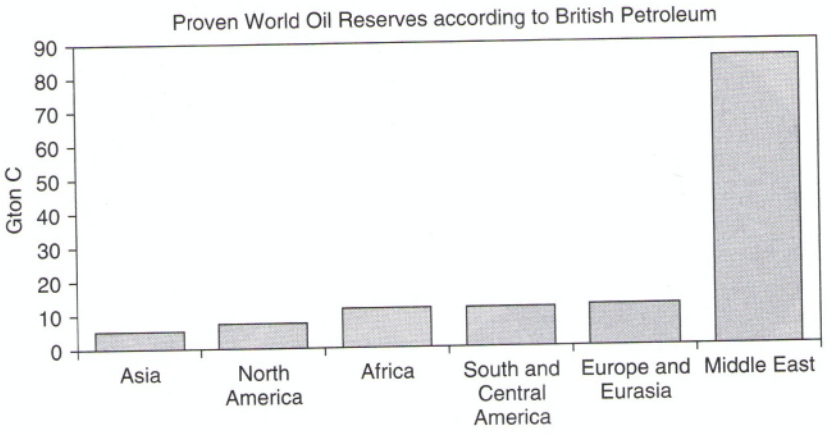

Figure 9-4 The amount of proven petroleum reserves, by region, from British Petroleum.

sandstone or through faults and cracks in the sediment column, perhaps to collect in some upside-down pool in an upside-down bowl of impermeable rocks. Only a tiny fraction of the oil and gas ever produced is in a harvestable form today, that is to say, mobile enough to have collected together but not mobile enough to get squeezed all the way out of the Earth.

Oil is the most expensive of the fossil fuels because it is uniquely suited to fueling transportation (Figure 9-2). As a combustible liquid, it easily carries more energy per weight than any batteries that have been developed so far. Coal has not been used for transportation since the days of the steam locomotive, and gas must be carried in a pressurized container, as opposed to petroleum, which sits happily in an unpressurized fuel tank.

Perhaps because such special conditions are required to produce harvestable oil, the distribution of oil deposits on Earth is very "spotty" (Figure 9-4). Most of the oil is in the Middle East, although there is a smattering scattered throughout the rest of the world. We do not know precisely how much oil there is available to harvest. The BP report tallies the proven reserves of oil, stuff that has been discovered and documented already. They say 1150 thousand million barrels of oil, which translates to 135 Gton C. The amount of oil ultimately extractable will almost certainly be higher than this. Technological advances in oil extraction can double the amount of oil you can get from an oil field. More oil fields will certainly be discovered, although there are limits to how much more oil we can expect to find. Half of the world's oil reserves today are in the 100 biggest oil fields, and most of the largest ones were discovered decades ago.

There is a class of carbon deposits for which the geological conditions were never quite right to produce oil, but from which oil can be extracted if the rocks are mined and cooked, or cooked in place by injecting steam into the well. These nontraditional oil sources are called **oil shales** and **tar sands**. The Canadians are mining and processing tar sands now. If future discoveries, technological progress, and nontraditional sources are counted together, the estimates disagree wildly, but some of them begin to reach 500 Gton C for how much "oil" there might ultimately be.

How long will the oil last? One way to calculate a number with units of time would be

$$\text{Lifetime[yr]} = \text{reserves [kg]} \cdot \frac{1}{\text{production rate}} \left[\frac{\text{yr}}{\text{kg}}\right]$$

British Petroleum calls this the **reserves to production** or **R/P** ratio. Notice that the units on both sides of the equation balance, years on both sides. The R/P ratio tells how long it would take to use up a resource if we continued using it at the rate we are using it now. The funny

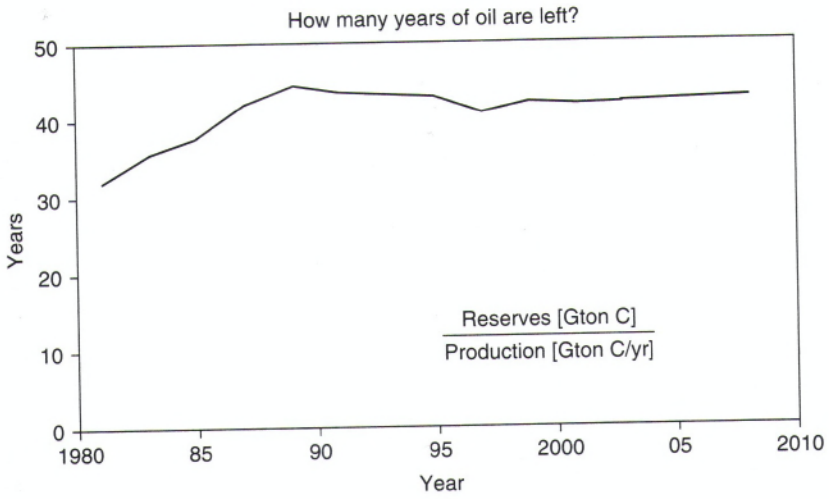

Figure 9-5 The value of the production/reserves ratio over the last 25 years. From British Petroleum.

thing about this ratio is that its value has not changed in 15 years (Figure 9-5). According to BP figures, we have 40 years of oil left, and it looks like we always had 40 years left, and we could have 40 years left forever. The clock seems to have stopped. Actually, what is happening is that oil is being discovered, and extraction efficiency is increasing, about as quickly as oil is being used. Also, the amount of oil that is classified as reserves depends on the price of oil because it only counts if it is currently profitable. The rate of consumption is growing with time, but we have been adding new oil to the reserves quickly enough to more or less keep pace with that growing demand.

There is enough oil to keep pumping for decades, but the peak rate of oil extraction could be happening right now.

Another way to estimate the lifetime of the age of oil is called **peak oil**, developed by geologist M. King Hubbert (see the Deffeyes books listed in Further Reading). Hubbert pointed out that the rate of extraction of a limited natural resource such as oil tends to follow a bell-shaped curve (Figure 9-6). The industry has a spin-up time at the beginning, gets going faster and faster, and then slows down as the resource starts becoming depleted. The crucial point is that the maximum rate of extraction comes when the resource is about half used up. Our oil is about half used up, so peak oil theory predicts that the peak is soon upon us.

This is an example of an **empirical** observation; there is no theoretical underpinning to the curve, although it sure does fit nice. But one could imagine an "extract-the-juice-from-a-popsicle-on-a-hot-day curve." The popsicle consumption rate starts off slowly at the beginning because the popsicle is too cold to eat; then, at the very end, you have to swallow the last half of the popsicle in one gulp to keep it from hitting the sidewalk (Figure 9-7). Oil analysts like Daniel Yergin (see Supplemental Reading section) argue that political and economic factors could modify the oil extraction trajectory to look more like my popsicle curve or some other.

This could be, but a bell curve seems to have worked in the past for individual oil fields. Hubbert used his idea, in 1956, to forecast the peak extraction of oil in the United States. He

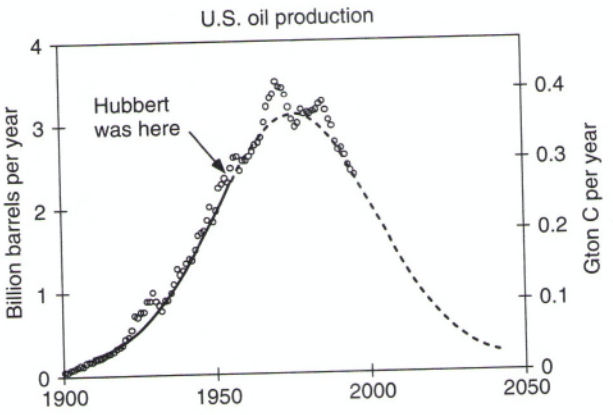

Figure 9-6 Oil production in the United States follows a bell curve. M. King Hubbert predicted in 1956 that the peak would come at around 1970, and he turned out to be correct.

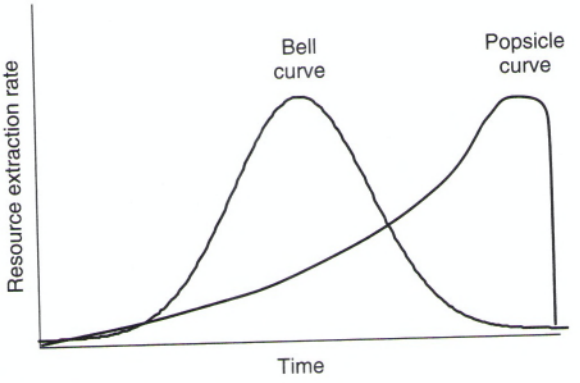

Figure 9-7 A bell curve and an "eating-a-popsicle-on-a-hot-day" curve.

predicted the peak to be sometime between 1965 and 1972, and in fact it came in 1970. The solid line in Figure 9-6 shows the time up to Hubbert's forecast, and the dashed line shows a prediction like his for the future (benefiting a bit from hindsight, I confess). Hubbert's prediction came at a time when oil production in the United States seemed endless. Figure 9-8 shows a Hubbert's Peak for sperm oil harvesting back in the whaling days.

The forecast for when the peak in world petroleum extraction will come depends a lot on what you call oil and how much is ultimately out there. Figure 9-9 shows world oil production in the past, fit to two **Gaussian** (bell) curves, one for 200 Gton C in oil that will ultimately be extractable and one for 500 Gton C. Humans have already extracted 117 Gton C. If 500 Gton C is ultimately correct, then the peak comes sometime in the 2030s. If 200 Gton C is correct, consistent with BP, the peak should be happening now. And, in fact, most oil producers are pumping oil as fast as they can now, although oil analysts argue that logistics and infrastructure are slowing things down, in Iraq for example, or in the number of refineries that are operating.

The crucial feature of the bell curve is that the maximum rate of extraction, the peak, occurs when half of the resource is still in the ground, as opposed to the peak of the popsicle-eating

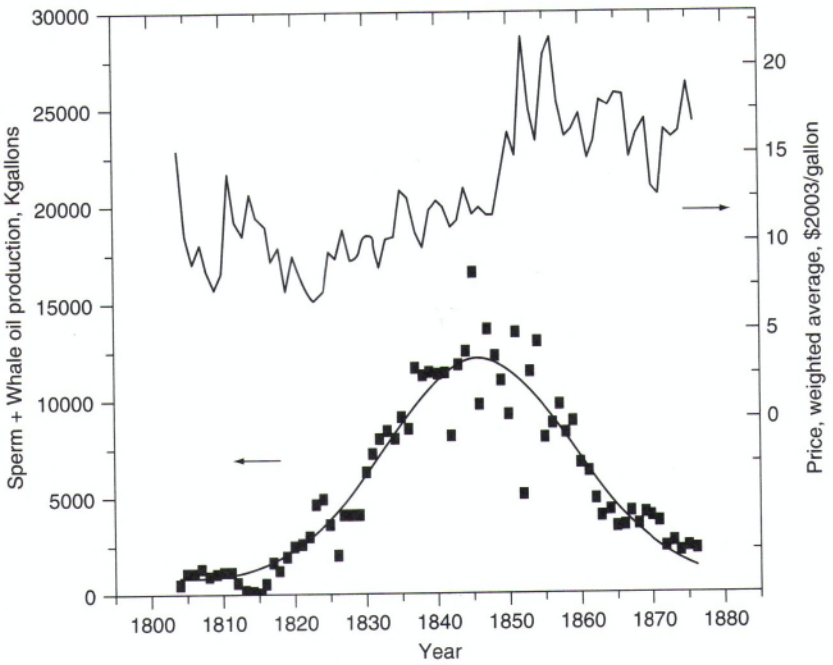

Figure 9-8 A Hubbert curve for the rate of sperm oil production. With permission from U. Bardi, Università di Firenza.

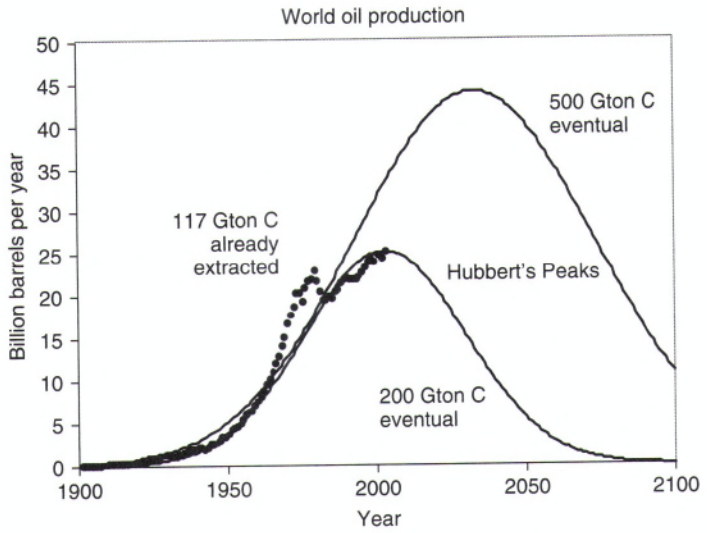

Figure 9-9 Global oil production, history so far plus two Hubbert's Peak projections.

curve, which comes at the very end. During the first part of the extraction, the growth in supply rate follows along with an exponential growth in demand, driven by increasing population and gross domestic product. If the production rate stops growing at the peak but demand continues to grow, it will appear to the market as a shortage. The lesson of peak oil theory is that the reserves to production ratio from BP gives a misleading impression, because the shortage would begin long before the oil is down to the last drop.

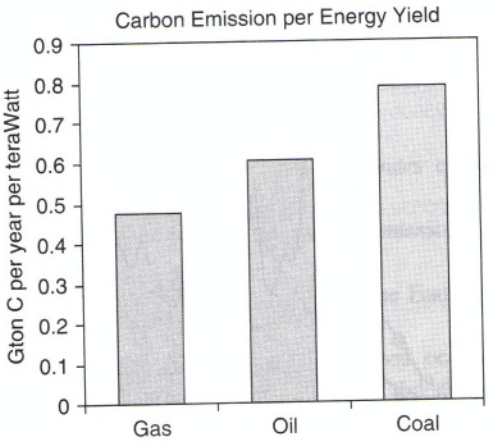

Figure 9-10 Natural gas emits less CO_2/W of energy than oil or coal.

The other main type of fossil carbon is **natural gas**, most of which is the gas **methane**. Methane carries more energy per carbon than the others because methane is the most chemically reduced form of carbon. You get energy from making CO_2 from the carbon from all fossil fuels, but you also get energy from converting hydrogen to H_2O. Methane, being more reduced, has more hydrogen than coal or oil does. Turning it around in Figure 9-10, a Watt of energy from methane releases less carbon than a Watt from coal or wood.

Methane also burns more cleanly than the other fossil fuels, producing none of the acid rain, mercury, and aerosols from coal or the smog from petroleum combustion. Methane is more difficult to transport than liquid petroleum because it is a gas and must be held under pressure. For this reason, methane associated with oil in remote locations is sometimes just burned, dramatic flares into the sky, rather than collected. Natural gas prices vary widely around the world, and they tend to fluctuate in time more than, say, coal prices do.

> Methane is the cleanest fossil fuel, and it carries the most energy per CO_2 produced.

The amount of extractable natural gas on Earth is not known as well as it is for petroleum because gas has not been explored for as intensively. Industry estimates of available gas are similar to the amount of oil, hundreds of Gton C, as proven reserves. Recently developed techniques for fracturing, or "fracking" the rock to release gas have revolutionized, perhaps doubled, the amount of gas within our reach. Like for oil, the ultimately available natural gas reservoir will certainly keep rising.

Under the right conditions, methane can freeze with water into a **methane hydrate** or **clathrate** structure, soccer-ball cages of water ice, each surrounding a single molecule of methane. Most of the methane hydrate is in mid-depth sediments of the ocean, but some can be found on land in permafrost soils. The deep sediment column is sort of a backwater in the carbon cycle, where life and chemical reactions move very slowly. But over millions of years, thousands of Gton C of methane have built up, swamping by a factor of 10 the other reservoirs of swamp gas on Earth. There is enough methane down there to totally clobber the climate

of the Earth, if it were to be released all at once, because methane is such a powerful greenhouse gas.

The methane in the hydrates seems intrinsically precarious in the carbon cycle. A model of hydrates predicts that there would not be much frozen hydrate if the ocean was about 3°C warmer, as warm it could eventually get if the climate of the surface warmed from fossil fuel CO_2. Fortunately, it takes thousands of years for the heat from the surface to reach the hydrates.

> Methane hydrates could be a slow positive feedback in the global carbon cycle, but they will probably not burp out all at once.

Melting hydrate could destabilize the sediment column to submarine landslides by producing bubbles that lift the mud grains off of each other. Hydrate ice is like regular water ice in that it would float in water if it were not buried in mud. So it is possible that submarine landslides could release methane, some of which might reach the atmosphere. Fortunately again for us, the amount of methane that could be released in a single landslide is not enough to really change the climate.

Methane hydrates are not traditionally thought of as a fossil fuel because they are difficult to extract; this is because they are frozen and do not flow unless you melt them and because they are dangerous, leading potentially to submarine landslides. But fuel companies are exploring ways of extracting methane from hydrates on land, which may end up supplying some modest fraction of our natural gas consumption.

The bottom line is that coal is the most abundant available fossil fuel, 10 to 50 times as abundant as either traditional oil or natural gas. The climate impacts of releasing various amounts of carbon are discussed in Chapter 13, but the conclusion there will be that coal is the form of fossil fuel with the capacity to take the climate of the Earth well beyond a sort of turning-point temperature change of 2°C. The future of Earth's climate will depend most on what happens to that coal.

Energy Consumption

Different parts of the world get their energy from very different portfolios of sources (Figure 9-1). India and China, the largest of the developing world, use a lot of coal, whereas Brazil uses mostly petroleum and hydroelectric power. Denmark is remarkable for windmills, which fall into the category "renewable" on this plot. France has invested heavily in nuclear energy (not renewable). The United States energy sources are similar to the global average. In part this is because the United States is a big consumer of energy, accounting for about a quarter of energy use globally (Figure 9-11).

Dividing the energy use of a country by the number of people in it gives the energy use per person or **per capita**. China has recently overtaken the United States as the country emitting the most CO_2, but there are many more Chinese people than there are Americans so that the average Chinese person emits one-tenth the amount of carbon released by the average American. The Europeans and Japanese only use half the energy per capita as the United States. Energy use in the U.S. is five times higher than the global average, so that if everyone adopted the American lifestyle it would increase the global rate of carbon emissions by about a factor of five.

Energy use is closely related to economic productivity, which is measured by the total value of everything produced for sale in a country in a year, the gross domestic productivity or

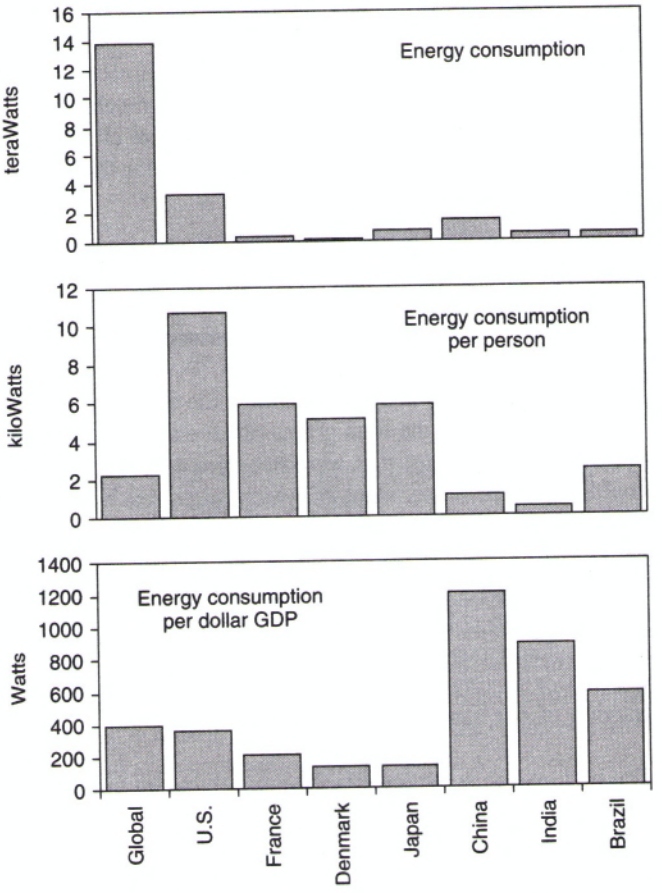

Figure 9-11 Energy consumption (*top panel*), energy consumption per person (*middle*), and energy consumption per dollar gross domestic product (GDP) (*bottom*), globally and from various countries. Data from 2008 and 2009.

GDP, units of dollars/year. Dividing energy use by GDP gives the **energy intensity**, a measure of the energy efficiency of an economy, reflecting waste or efficiency but also the difference between heavy industry such as steel production versus high-tech or service economies. Figure 9-11 shows that the Europeans and the Japanese can make money using less energy than the United States can, while the Chinese and Indians are more energy intensive (less efficient). The patterns of carbon emissions from these countries are similar to the patterns of energy use (Figure 9-12). The United States is responsible for an about a quarter of global CO_2 emissions.

Energy use and carbon emissions are related to population, economic activity, efficiency, and energy sources.

The factors that control CO_2 emission can be combined together to predict carbon emissions in the future if there were no effort to stop: a scenario known as **business as usual**. The

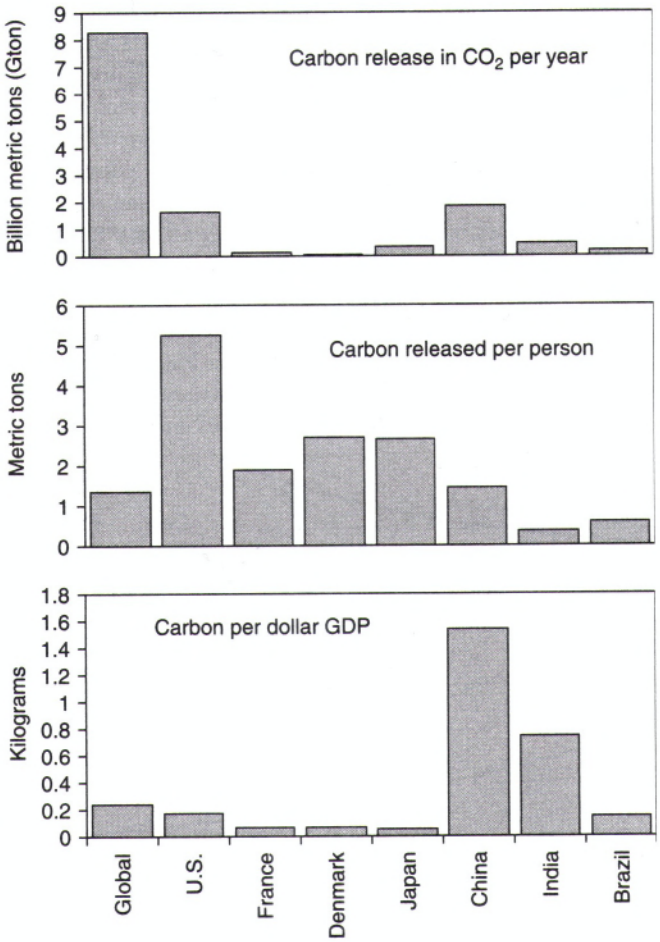

Figure 9-12 Carbon release in CO_2 per year (*top panel*), carbon release per person (*middle panel*), and carbon release per dollar gross domestic product (GDP) (*bottom*), globally and from various countries. Data from 2008 and 2009.

equation is called the **Kaya Identity**, and it is the basis for one of the online models used in the Exercises section. The results from the model are shown in Figure 9-13. The Kaya Identity is

$$\begin{aligned} CO_2 \text{ emission } \left[\frac{\text{kg C}}{\text{year}}\right] = \ & \text{Population[persons]} \\ & \times \text{GDP per capita } \left[\frac{\$}{\text{person}}\right] \\ & \times \text{energy intensity } \left[\frac{\text{Watts}}{\$}\right] \\ & \times \text{carbon efficiency } \left[\frac{\text{kg C/year}}{\text{Watts}}\right] \end{aligned}$$

Check it out for yourself that the units cancel correctly.

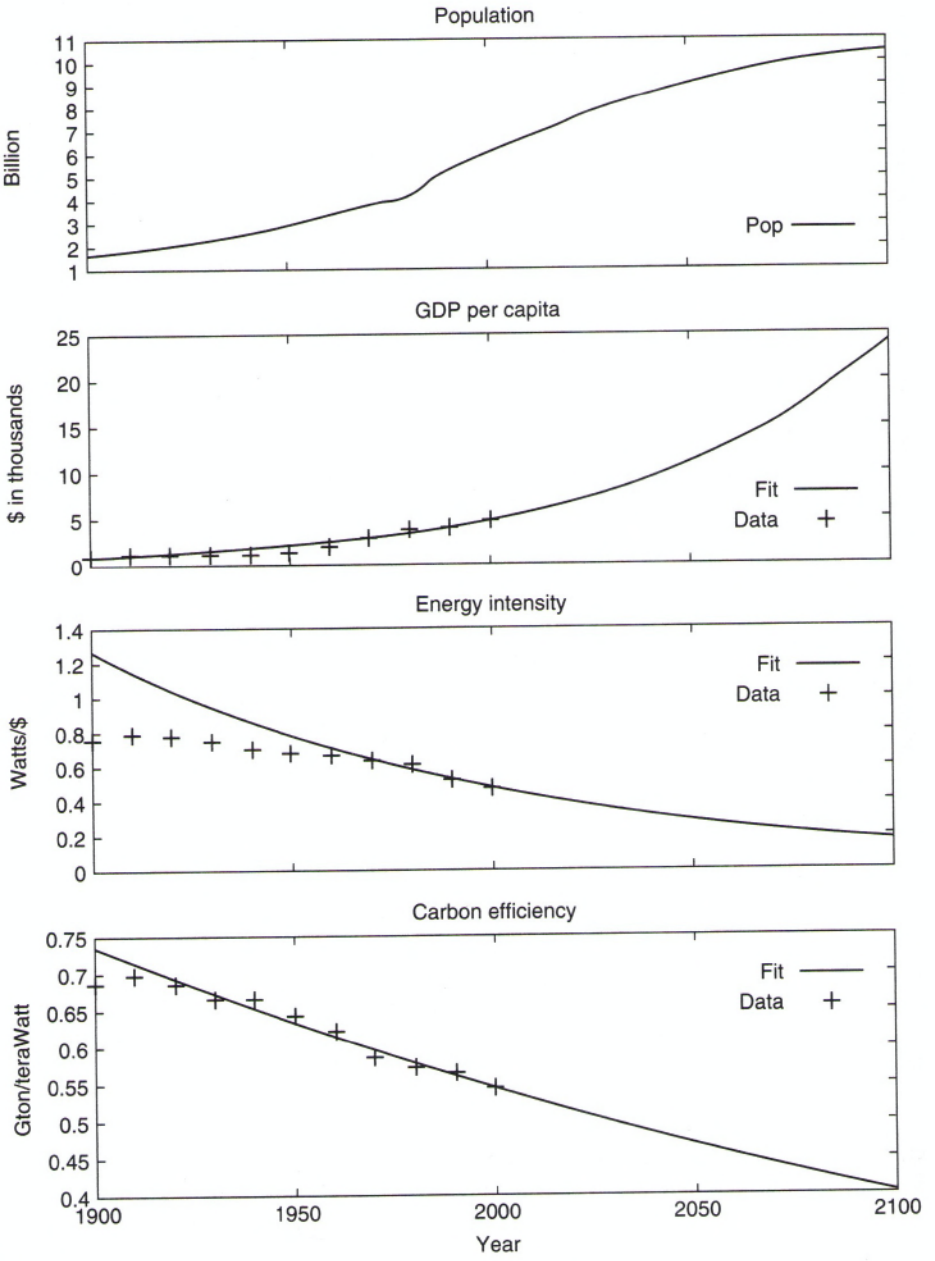

Figure 9-13 Results from the Kaya Identity model (http://understandingtheforecast.org/Projects/kaya.html).

Population has been increasing at a rate of about 1.3% per year, but this rate of growth is not expected to continue forever. Rates of population growth tend to decrease with the affluence of societies. Population is forecast to level off at some value, but that value could be 9 billion people or it could be 15 billion people. A typical "business-as-usual" forecast puts the leveling-off point at about 11 billion people.

The second factor, $GDP/person, has been rising throughout the last century at a rate of about 1.6% per year, rising from $930 in 1990 U.S. dollars in 1900, to $4,800 per person in 2000.

The third factor is the energy intensity, how many watts of energy it takes to make $1 GDP. The energy intensity reflects efficiency but also the difference between heavy and light industry (Figure 9-12, bottom). Energy intensity has been dropping by a rate of about 0.55%/year over the past century, but the last few decades have seen a drop by about 1% per year. Assuming that our energy efficiency will continue to improve at 1% per year, the Kaya identity model on the website predicts that atmospheric pCO_2 will reach 700 ppm by the year 2100 (Figure 9-14).

The final factor, the carbon released per energy yield, is the result of efficiency of the power plants but also on the characteristics of the feedstock energy source. Coal contains intrinsically less energy per carbon than does oil or gas, whereas nuclear and hydroelectric energy do not result in much carbon release, if any.

The Kaya model can be used to predict how much carbon will be released in the future, and what it would take to change those carbon emissions. You can compare your results to the CO_2 emission scenarios from the Intergovernmental Panel on Climate Change, or IPCC, which ranged from 6 to 26 Gton C emission per year in 2100.

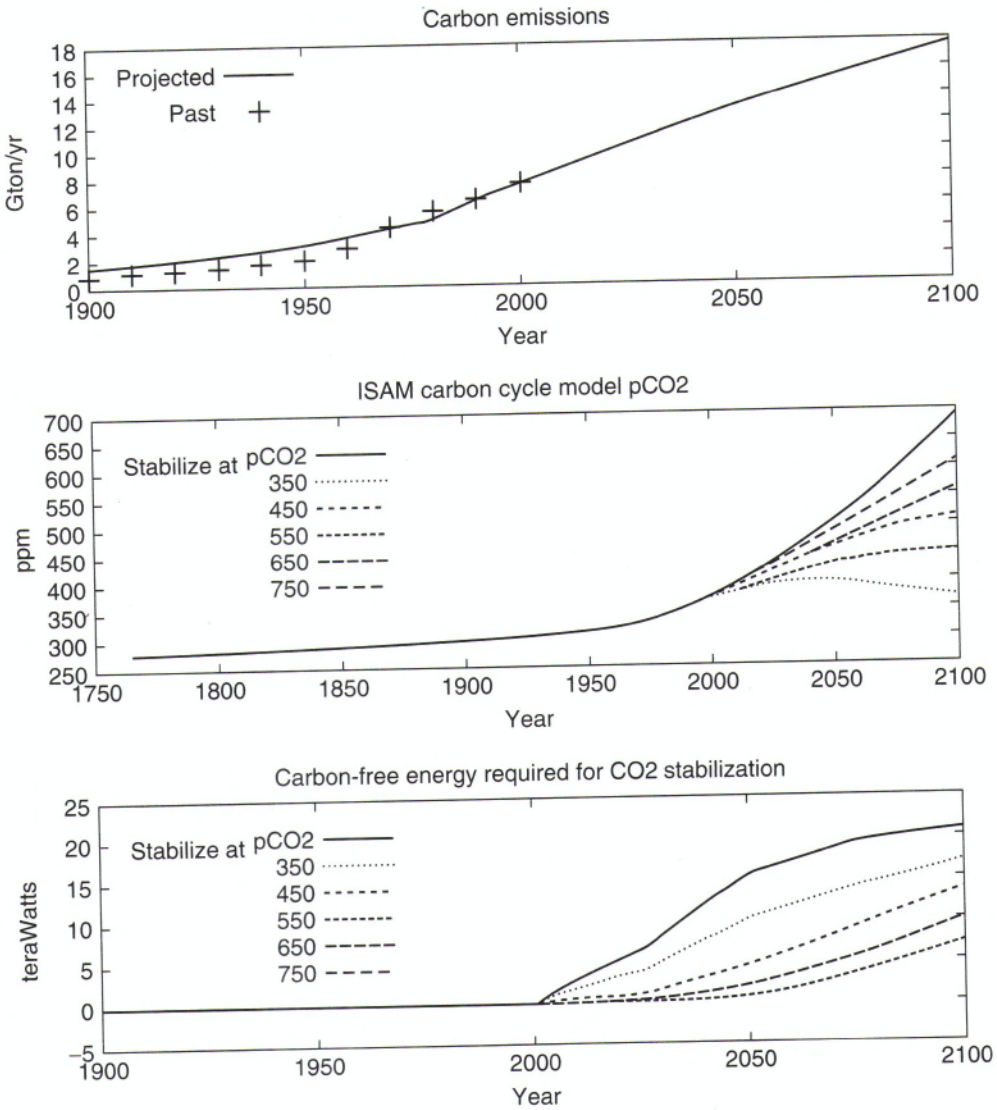

Figure 9-14 More results from the Kaya Identity model.

Chapter 10 describes what happens to that CO_2 after it is released, and Chapter 13 discusses what it means, in terms of energy, to avoid as much as possible the climate impacts of fossil energy.

TAKE-HOME POINTS

- Ultimately, the energy available to humankind includes instantaneous solar energy, which is abundant but spread out; stored solar energy in the form of fossil fuels; and stored energy from stellar explosions in the form of radioactive elements.
- Of the fossil fuels, coal is the most abundant. Oil may run out in the coming decades, and the peak rate of oil extraction may be upon us even now.
- We can project energy demand in the future as the product of population, economic growth, and energy efficiency.

STUDY QUESTIONS

1. Contrast the three forms of fossil fuel carbon, in terms of their origins, inventories, and uses.
2. Which are the least and most reduced forms of carbon fuel? Which form carries the most energy per carbon?
3. Compare peak oil theory to last-drop R/P calculations. What are the strengths and weaknesses of each? How does each relate to economic shortage of oil?

FURTHER READING

BritishPetroleum. Energy in Focus. *BP Statistical Review of World Energy*, 2009.

Deffeyes, K. S. *Hubbert's Peak: The Impending World Oil Shortage*. Princeton, NJ: Princeton University Press, 2003.

Rogner, H. H. An assessment of world hydrocarbon resources. *Annual Review of Energy and the Environment.* 22:217–262, 1997.

U.S. Department of Energy, Energy Information Administration. International Energy Outlook 2003. Available at: www.eia.doe.gov.

Exercises

1. **Hubbert's Peak.** Point your web browser to http://understandingtheforecast.org/Projects/hubbert.html.
   a) You will see two different data sets to plot against, along with the three parameters (knobs) that control the shape of the Hubbert curve. Nothing fancy here: We are just matching the curve to the data by eye. First start out with the U.S. oil production. The page comes up with some values for the curve that look pretty good to me, but you should try varying the numbers in the box to see how tightly those values are constrained. In particular, there may be combinations of values that could be changed together to fit the data nearly as well but with different values. How much wiggle room is there for U.S. oil production?
   b) Now switch to global oil production with the pull-down menu. When do you forecast the peak of oil extraction? How does it depend on your assumption of how much oil will eventually be extractable. How much wiggle-room is there for the year of the peak in global oil extraction?
2. **The Kaya Identity.** Point your web browser to http://understandingtheforecast.org/Projects/kaya.html.
   a) Find the plots for gross domestic product per capita, energy intensity, and carbon efficiency, and compare the model hind-cast (*solid line*) with the data (*plus signs*). How well constrained are the growth rates by the past data? Make a table showing the high and low values that

you find plausible for each parameter. Of course, the future might not follow the dictates of the past; this is not a mechanistic prediction but just a blind extrapolation. Using the past as a fallible guide, however, take a guess at what the range of possibilities is for each of the input values. Remember that these assume business as usual, with no decrease in carbon emissions to avoid climate change.

b) How much carbon is humankind predicted to emit by the end of the century? For each of the input parameters that you estimated the uncertainty of in part a, which end of the uncertainty range gives the highest and lowest carbon emissions? Add columns to your table showing the CO_2 emission rates for the high and low parameter estimates. Combining the uncertainties in all of the parameters, run the model with all the high-CO_2 emission values of the parameters and then the low-emission values, to find the highest and lowest plausible carbon emission for 2100. The emissions are used to drive a carbon cycle model, called ISAM (**Integrated Science Assessment Model**), the results of which are shown in the second output plot. According to the ISAM model, what could the range in atmospheric pCO_2 be like then?

c) What rate of improvement in carbon efficiency would be required to limit atmospheric CO_2 to at most 450 ppm?

d) Politicians often talk about CO_2 cuts as a fraction cut by the year 2050. The rate of carbon emission as a function of time would decrease with time following an exponential function according to

$$\text{fraction cuts} = \text{emission rate(time)}/\text{emission rate(0)} = e^{kt}$$

where

$$k = x\%/yr/100\%$$

if x is the rate of change of carbon efficiency, like the -0.3% per year that comes up in the model interface by default. Using the carbon efficiency improvement rate from part c, calculate the fraction cut from 2000 to 2050 required to stabilize CO_2 at 450.

3. IPCC CO_2 Emission Scenarios. Open a new browser window for the ISAM carbon cycle model, at http://understandingtheforecast.org/Projects/isam.html. This page shows the results of IPCC carbon emission scenarios made by more sophisticated crystal balls than our simple Kaya identity (and then offers to run the results of the scenarios through a carbon cycle model). On the Kaya page, try to reproduce the year-2100 carbon emissions from scenarios A (business as usual, or BAU), B (BAU with carbon stabilization), C (slow growth), and F (gonzo emissions). What input parameters are required?