CHAPTER 2

POPULATION GROWTH AND ENERGY CONSUMPTION¹

Note to the reader: This chapter is very number intensive; if you are intimidated by numbers and decide to skip it, at least read its conclusion.

Industrial Revolution

As we move toward addressing the complex problem of climate change, its causes and the prospects for mitigating it, we should first understand the pressures imposed on the environment by growing global population, increasing per capita energy consumption, and the sources of that energy. With this in mind, we now embark on a survey of energy sources, both conventional, that is, fossil, and renewable (or at least non carbon-emitting). The former are finite, and inevitably exhaustible, even though it may take a century or more for that to happen. As we will see later, it is likely that some of these resources will be left in the ground or be converted to uses other than energy generation.

The problems associated with population growth have a certain inexorability to them, and barring some unexpected catastrophe (including uncontrolled climate change), the global population will increase, albeit more slowly, eventually

¹The point is made below that energy is never consumed; but rather is transformed, converted from one form to another. Much is wasted, of course—the second law of thermodynamics guarantees that—and even the energy used to heat a house is eventually dissipated as thermal motion of air molecules.
becoming stable. We all understand that mankind’s numbers must plateau if the race is to survive. In the end, the problem of growing energy consumption and carbon emissions are all driven by population. This is obviously humanity’s greatest problem, and the fact that we simply believe (or hope) that the population will magically plateau at some livable level is frightening in itself. Despite the growing concern over climate change, little attention is being given to this issue.

The Industrial Revolution began around 1750 with the invention of steam power and the gradual replacement of individual human effort by machines. Before that, the earth’s population was growing slowly, doubling about every 400 years, after a long period when it was nearly constant, with birth and death rates closely matched. Between 1500 and 1800 the global population grew at the very low rate of about ¼ % per year, reaching 1 billion sometime after 1800 (Figure 2.1). But in the early nineteenth century, with the Industrial Revolution in full swing, the rate of population growth began to accelerate, increasing steadily up to about 1980 (Figures 2.3 and 2.4). Since the start of the 20th century, the growth rate has averaged about 1-1/2% per year, the global population doubling about every 50 years, with some surprisingly wild fluctuations (Figure 2.4). Growth exceeded 2% annually during the post-war “baby boom,” but has since steadily declined to the current one percent, representing a doubling period of 70 years (assuming exponential growth, see below). As of 2019 the global population was nearing 8 billion and is certain to exceed

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2 On this subject and some divergence of opinion, see “Coal and the industrial revolution, 1700-1869,” by Gregory Clark and David Jacks (unpublished).
3 London’s population in 1600 was about one million.
4 The large dip after 1910 evidently reflect the privations of WWI and the Spanish flu epidemic, both in the 1918-19 period. The big 1950-1990 peak represents the post WWII “baby boom.”
9 billion by the end of the century. Beyond that, we can only hope.

Exponential Growth

A constant doubling period represents what is called “exponential growth,” a precise technical term that is frequently misused. In exponential growth, the incremental growth during any (short) time period is proportional to the current population. Assuming exponential growth, the rule of thumb is

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\Delta P = \text{constant} \times P\]

Thus, in a certain time interval, \( \Delta P = \text{constant} \times P \). The exponential growth of a population during a time \( t \) can be represented by the formula \( P = P_0 e^{\lambda t} \) (if your inclination is to ignore this, please do so). The quantity “\( e \)” is 2.71828, the base of natural logarithms, where \( \lambda = \frac{.693}{\tau} \), \( \tau \) being the doubling period. Alternatively, \( \lambda \) times 100 is the yearly percentage increase, that is, if the population is increasing at 2% per year, \( \lambda = .02 \). Any scientific calculator (as on your smart phone) can easily do the calculation.
that the doubling period in years is approximately $70/P$, where $P$ is the yearly percentage growth (technically, $69.3/P$), so that at a 2% growth rate, the population (or other quantity) would double in 35 years. Many natural processes increase in this fashion. Such growth is ultimately much faster than linear, where the population grows at a constant rate.\(^6\) In the latter case, the population would grow by the same amount per year, while in exponential growth, the percentage growth (PG) per year is constant. To avoid the mathematics, which we leave for the footnotes and the appendix, we simply note that in the case of exponential growth, a plot of the doubling period of the population against time should be a flat straight line. Figure 2.2 shows that this has not been the case any time since at least 1700.\(^7\) Indeed, we can see that the growth of the global population has been faster than exponential during most of this period because the doubling period has been steadily dropping (from over 500 years to barely 35). Happily, the growth rate has declined since the 1970s (Figures 2.3 and 2.4) and is expected to continue to do so under the pressure of resource exhaustion and cultural changes. In any case, total population will continue to increase (at a slowing rate one assumes; see Figure 2.3) during the 21\textsuperscript{st} century, and we can feel comfortable (if that is the proper word) using a final figure of at least 9 billion when looking at man’s effects on the environment (note that Figure 2.3 forecasts a population of 11 billion in 2100).

\(^6\) If a city has a population of 100,000 and is growing at 1,000 per year, this growth is linear, and after 70 years, the population will be 170,000. If the population is growing exponentially at 1% per year, in 70 years the population would grow to 200,000. Or after 280 years, the numbers would be 380,000 and 1.6 million!

\(^7\) If, for example, the doubling period had been a constant 150 years between 1700 and the present, about a ½% annual growth rate, the population would have increased by a factor of 4.5. In fact, it increased by a factor of closer to 10. Note that Figures 2.2 and 2.3 are only in approximate agreement due to uncertainties in historic world populations.
Figure 2.2 Global population doubling period since the end of the 17th century. It decreased almost linearly until the 1970s. Alternatively, the growth rate (in per cent per year, P) increased almost linearly in that period. For example, the earth’s population reached 1 billion in about 1800. It had doubled since about 1500 (304 years). It then doubled in only 123 years, and doubled again in 47 years. See the text. Wikimedia Commons.
Figure 2.3. Estimated global population (blue) and growth rate (red) since 1750, with projections to 2050. From Our World of Data.
Figure 2.4. Global population (blue) and population growth rate (red) since 1900, showing additional detail. The “baby boom” between about 1946 and the early 1960’s is very clear.

It should be obvious that unless rescued by technology, specifically widespread use of renewable energy resources such as solar and wind, the earth’s exploitable fossil fuel resources will eventually be exhausted, simply because they are finite. This is the message of exponential growth of consumption against a finite resource: it must always lead eventually to its exhaustion or at least depletion and irrelevance. This argument, by the way, applies to other natural resources, so that is another global problem to be faced.\(^8\)

Figure 2.5  A schematic representation of how declining death and birth rates, at different times, can generate a stable population. Historically, declining death rates have been mostly due to a large reduction in infant mortality.

Population and Energy Consumption

Although it is generally true that energy consumption tends to be proportional to population, we can see from the figure below (Figure 2.6) that global energy use per capita (“energy intensity”) varies greatly over the globe, with the U.S. using over 10 times the per capita energy of some developing
countries. The current global average is about 3 kW per capita (power), or a yearly energy consumption of about 25,000 kWh, or, as in Figure 2.6, about 2 “tonnes of oil equivalent (toe).” But Figure 2.6 can be seen as an evolutionary diagram, with countries moving from lower left to upper right as they develop; increasing wealth (GDP/capita) leads to increasing energy intensity (energy per capita).

Figure 2.6. GDP/cap in 2011 US Dollars vs Energy Use Per Capita (in toe; see below). There is something like a linear relationship between energy use and GDP (per capita; lower

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9We discuss energy and power units below, but the kilowatt is a unit of power and the kilowatt-hour (kWh) is an energy unit. To get yearly energy consumption in kWh, multiply the power in kW by number of hours in the year, 8760. We will discuss these units and the difference between power and energy, below. While there is also a correlation between national energy consumption and GDP: the energy consumed per unit of GDP (E/GDP), is fairly constant (at about 1/3 watt per $ of GDP, or conveniently, in energy units (per year) rather than power, about 2 kWh per dollar of GDP (see below for the definition of kWh).
left to upper right), with a lot of scatter. Notice that the most energy-efficient countries are those with large GDP per capita but relatively low energy consumption per capita (Japan and most of the EU countries). This amounts to low energy use per unit of GDP. The disparity between the western industrialized nations and the less developed world is dramatic. The “toe” is about 11,600 kW-h. Current (2018) U.S. GDP per capita is about $60,000. (European Environment Agency)

Globally-averaged per capita power consumption has remained around 3 kW since 1980, but we can reasonably expect that as developing countries become more advanced, their per capita energy use will grow, and it is in these very countries that population growth will also be most rapid. Of course increasing population can work against per capita wealth, and there will be haves and have-nots. The existence of a natural resource base in these countries will be paramount, but it is inevitable that as both standard of living and population grow in these areas, a rapid increase in total energy consumption will take place. There lies the greatest threat to controlling global energy use and resultant greenhouse emissions. As countries develop, their per capita energy consumption grows, and population growth exacerbates this, and emissions grow along with both. At the very least it will be essential that most of this additional energy produced in the coming decades be generated from non-fossil sources. The reason for this will be developed in Chapter 5.
Interlude: Power and Energy Units

Because we are about to embark on a wide-ranging discussion of global energy reserves, we need to address the units in which energy resources are measured, bought, and sold, which are basically of two kinds. The first is peculiar to the particular resource, and is a measure of the quantity, in volume or weight (mass) of that resource. Often these measures are very idiosyncratic, an example being a barrel of oil. The second way of looking at a resource is to express it in universal energy units such as joules, kilowatt-hours, British thermal units (BTUs), or tons (tonnes) of oil equivalent (toe), making it easier to compare the contribution of the resource to others and to global totals. This means that we cannot avoid talking about the several common units of energy and power, and the reader is warned in advance that some very large numbers will be used, described in some very unfamiliar terms. This, sad to say, is unavoidable.  

Fortunately the most common unit of power (rate of energy production or consumption), the familiar watt, named after James Watt, an inventor of the practical steam engine, is also the most useful. The rate at which energy is produced or consumed, in watts, is energy per unit time, typically per second. Thus a light-bulb will be rated by the number of watts of electric power it consumes at a certain voltage, for example, 75 watts. An electric stove may use a constant rate of a kilowatt (kW, 1000 watts) of power while cooking a ham, and in one hour the total energy used is one kilowatt-hour (kWh), a kW of power consumption for one hour. The kWh is a useful and common

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10Skip this section if numbers and units bother you. But they do matter.
11You might pick one you feel comfortable with, say the “quad,” and using the conversion factors in the appendix, convert everything to that unit.
unit of energy, especially electrical energy. While this may seem like an awkward unit (energy divided by time, multiplied by time), it is familiar to anyone who bothers to read their electric bill.\textsuperscript{12} But the basic energy unit (in the world-wide metric system) is the joule (named after James Prescott Joule, one of the discoverers of the conservation of energy in the mid-19\textsuperscript{th} century), and the watt is one joule per second (J/s).\textsuperscript{13} This means that the joule and the kWh are both energy units, and indeed, a kWh is 3.6 million joules.\textsuperscript{14} Given the scale of global energy consumption, the earth’s energy budget is often expressed in tera-watt-hours (TWh) where the prefix “tera” means one trillion, one followed by 12 zeros, or $10^{12}$, using “power of ten notation.”\textsuperscript{15} We cannot really escape this notation, so the reader might as well practice it. A typical automobile travelling at 70 mph possesses somewhat less than a million joules of kinetic energy, a “mega-joule (MJ, $10^6$ J).” There are about 1 billion ($10^9$) cars in the world so that if all were driving 70 mph at one time, that would represent nearly $10^{15}$ or one quadrillion, joules. One quadrillion joules is also called a “petajoule” (PJ).\textsuperscript{16} Refer to the table below for definition of the

\begin{itemize}
\item \textsuperscript{12} If your electric bill is $100 a month, and the rate is 6 cents per kilowatt-hour, you have used just under 1700 kWh of electrical energy during the month. Because there are 24 hours in a day, your power usage averages 2.4 kW. There are, of course, many fixed charges and fees that inflate your bill.
\item \textsuperscript{13} Another unit of power is the horsepower (hp), used, among other things, to rate automobile engines. The hp is based on the fact that a horse was thought to be capable of about 33,000 foot-pounds of work in one minute. It is about 746 watts, and surprisingly there is a slightly smaller “metric horsepower.”
\item \textsuperscript{14} Which is easy to see since a kilowatt is 1000 J/sec, and multiplied by 3600 seconds per hour gives 3.6 million joules per kw-h. See the Appendix for the conversion factors from one unit to another.
\item \textsuperscript{15} In power of ten notation, the exponent is just the number of zeros following the 1 (or some other number). Thus, $10^2$=100, $10^9$=1,000,000. And so on. So we have “kilo-“ meaning 1000, “mega-“ meaning a million, “giga-“ meaning one billion, and “tera-“ meaning a trillion. We should be familiar with these prefixes from worrying about storage in our computers or flash drives. The list goes on.
\item \textsuperscript{16} Alternatively, it takes about 100 kW to keep it moving at 70 mph, against rolling friction and air resistance. This has to be supplied by burning gasoline. For a billion cars, this represents about 100 GW of power being wasted in the form of heat due to friction.
\end{itemize}
petajoule (PJ), exajoule (EJ) and so on, which, again, we cannot easily avoid.\textsuperscript{17}

<table>
<thead>
<tr>
<th>(10^6) watts, (10^6) joules</th>
<th>megawatt (MW), megajoule (MJ),</th>
</tr>
</thead>
<tbody>
<tr>
<td>(10^9)</td>
<td>gigawatt (GW), gigajoule (GJ)</td>
</tr>
<tr>
<td>(10^{12})</td>
<td>terawatt (TW), terajoule (TJ)</td>
</tr>
<tr>
<td>(10^{15})</td>
<td>petawatt (PW), petajoule (PJ)</td>
</tr>
<tr>
<td>(10^{18})</td>
<td>exawatt (EW), exajoule (EJ)</td>
</tr>
<tr>
<td>(10^{21})</td>
<td>zettajoule (ZJ)</td>
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<tr>
<td>(10^{24})</td>
<td>Yottajoule (YJ)</td>
</tr>
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Table I.

In 2012 the earth’s total energy consumption was estimated at 150,000 TWh, or about 540 exajoules (EJ), the “exajoule” being \(10^{18}\) joules (see the table).\textsuperscript{18} This is over 500,000 times the kinetic energy of those billion cars in the example above. By 2014, the number was close to 580 EJ, or nearly 0.6 ZJ.\textsuperscript{19} Averaged over the year, this number, 580 EJ, represents a rate of energy consumption, that is, \textit{power}, of about 19 trillion watts or 19 \textit{terawatts} (TW), which is a convenient (more or less) number to remember.\textsuperscript{20} One can

\textsuperscript{17}For what it is worth, these prefixes, which describe \(1000^5\), \(1000^6\), \(1000^7\), and \(1000^8\), have their origin in the Greek “penta”, “hexa”, “hepta,” and “octa,” though the connection is somewhat obscured. The backwards z-y-x-…is supposed to be continued. A little care has to be exercised here, because, as we will see below, one quadrillion Btu is known as the “Quad.”

\textsuperscript{18}Thus the world energy consumption in joules is about 580 followed by 18 more zeros, succinctly written as 580x10\textsuperscript{18}. Today’s consumers are becoming familiar with “tera-“ because external hard drives can now store “tera-bytes” of data. Then a yottabyte would be a trillion trillion bytes or 10\textsuperscript{24}. In 2004, 86% of world energy consumption came from fossil fuels, and it is now down to about 81%. See “World Energy Consumption”.

\textsuperscript{19}Estimates from the International Energy Agency and other sources such as the International Energy Outlook vary somewhat because of the difficulty of making such an estimate. The uncertainty may be several percent. As an aside, one will often find this number quoted as about 14,000 Mtoe (14 x 10\textsuperscript{9} toe), the “toe” being “tons of oil equivalent.” A weird and wonderful thing.

\textsuperscript{20}This is about 2.6 kW/person or 80 GJ/person/year. The gigajoule is 10\textsuperscript{9} J.
perhaps see why the otherwise annoying terms, like *petajoule*, *exajoule* or *exawatt* are used. The internationally agreed upon prefixes peta-, exa-, and so on can be applied to any quantity. Note that 19 TW, divided by the earth’s population, 7 billion souls, yields about 2.6 kW per person average rate of energy consumption, comparable to the value of 3 kW we used earlier.

![World Energy Consumption](image)

**Figure 2.7.** World energy consumption over time by resource. Global energy consumption has increased by 3000% since 1820. *Our Finite World*, Gail Tverberg. Based on Vaclav Smil estimates from *Energy Transitions: History, Requirements and Prospects* together with BP Statistical Data for 1965 and subsequent.²¹

To further complicate these matters, and reflecting British dominance of coal production, steam technology, and the thermodynamics of energy conversion in the 18th and 19th centuries, the *British Thermal Unit* or Btu (sometimes BTU) is

²¹ In this diagram, coal (in red), for example, now generates about (200-50)=150 EJ of the total global energy budget.
still a commonly used unit of energy. Air conditioners or hot water heaters continue to be rated in Btu in the U.S.\textsuperscript{22} One Btu, which is the amount of energy required to raise one pound of water one degree F (\!) is about 1000 joules (1055.056), so conversion is relatively easy, and the Btu still has some intuitive value that the joule does not, though remember that our familiar watt is one joule per second (J/s).\textsuperscript{23} In some discussions, rather than the metric system units of TJ, PJ, and ZJ, the \textit{Quad} is used. One Quad is a quadrillion Btu, that is, $10^{15}$ Btu, or almost exactly 1 EJ,\textsuperscript{24} which makes things a bit simpler. Thus the global energy consumption of 600 EJ is about 600 Quad. Convenient? Hard to say, since none of these units, nor any of the quantities themselves, are very memorable or intuitive. I will try to make this as painless as possible.

As another example of a somewhat idiosyncratic unit is the \textit{toe} or “ton of oil equivalent,” which is the energy content of an ideal ton of oil, about 42 GJ. Sometimes the GGE (gasoline gallon equivalent; 33 kWh, 120 MJ) is also used! To make things worse, if that is possible, the 42-gallon barrel of oil (bbl) is also a standard and familiar energy unit, in this case, in terms of volume. As unpleasant as all this may be, it is just a reflection of history, geography, and differences among scientific and engineering practice. Annoying to be sure, but in this business, every argument turns on the numbers.

\textsuperscript{22}They are actually rated in Btu/hour, which is, of course, a unit of power. Thus a rating of “1000 Btu” represents 293W. As homeowners will know, the “ton” (or RT, refrigeration ton) is also used, and one ton is 12,000 Btu/hr. As the amount of energy required to raise one pound of water one degree F, the Btu is definitely archaic to any devotee of the metric system.

\textsuperscript{23}It is a bit odd that no convenient unit of energy has taken hold in the British system, which is mostly used now in the U.S. since the UK has gone metric. The standard unit is the foot-pound, but is has little currency in ordinary conversation. The joule is rarely heard in the U.S. despite the fact that the unit of power, the joule per second or watt, is almost universal. The Btu is widely use in heating and air conditioning, but not much of anywhere else. To get an idea of the size of the joule, a 1.5v AAA battery can store a little over 5000 J of energy.

\textsuperscript{24}To be precise, 1 Quad equals 1.055 EJ. Or a Quad is $2.9 \times 10^{11}$ kWh or 0.29 TWh.
In 2014, U.S. total energy consumption was 2.3 Gigatons (2.3 x 10^9 metric tons, or tonnes) of oil-equivalent, about 96 EJ (or Quad). This works out to about 300 GJ or 7 mtoe per capita, or a constant power usage of about 10 kW (Figure 2.6). To the extent that we can, we will generally use the metric system unit, the joule, and its multiples, megajoule (MJ), gigajoule (GJ), petajoule (PJ), etc. See the appendix for further guidance.

Global Energy Resources

Estimating the earth’s recoverable energy resources (or “ultimate recoverable resource,” URR) is almost as much art as science, and it is not free of politics. Much of the earth has been explored, and global geology is fairly well understood, the major exception being the deepest oceans, meaning that something like one third of the planet is still unexplored. It is also true that the notion of what is “recoverable” can change with time, and this especially applies to resources such as tar sands and oil shale, which can yield to new technologies. Some resources may be too expensive to extract, or may take more energy to produce than they can yield, in which case they are not really energy sources, but that too can change with new technological developments. The world’s “proven reserves” are much better known than the ultimate or “total recoverable reserves” at any given time, but they also will change over time, as can be seen from Figures 2.7 and 2.17.

It should be obvious that while knowledge of an entire recoverable resource is critical, it is also important to understand

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25 The metric ton is variously abbreviated as MT, Mt, and mt. It seems advisable not to use “MT” because it might be taken to be “mega-ton.” The metric ton is 1000 kg, hence actually a unit of mass.

26 Nations often overstate their resources for reasons of internal politics.
the rate at which that resource can be, or is being, exploited, since this will determine its lifetime. Over the long term, one would expect this rate of production or consumption to follow something like a “bell-curve,” perhaps with an extended tail as the resource approaches depletion (see Figures 2.10 and 2.11). Nonetheless, a useful rule of thumb, which has to be employed very carefully, allows us to estimate the life of a resource by dividing the total recoverable resource by the rate at which it is produced or consumed, the so-called “reserve to production ratio” or R/P. This tells us how long the resource will last if used at the current rate and if no new resource is found in the meantime. We can think of that as a kind of minimum time a resource might last, and eventually both the resource and the rate of consumption will have to decline toward zero as depletion of the resource approaches. As will be seen from some concrete examples, the R/P ratio can be quite time dependent, as new reserves are discovered. Indeed, estimated oil reserves have more than doubled over the past three decades (Figure 2.7), and the reserve to production ratio, rather than declining, has grown by nearly 70% (Figure 2.8). Does that mean that a given resource, say oil, will never be exhausted? Of course not. Obviously the R/P cannot be taken too seriously as a measure of how long a resource may last, but used carefully, it can be helpful in talking about exploitable resources.
Figure 2.7. Growing Proved Reserves of Oil Since 1980. They have more than doubled since 1980.
Figure 2.8. Oil Reserve to Production Ratio (R/P) Over Time Since 1980. (Plazak)

Alternative Figures 2.7 and 2.8. Phil.Trans. A. Jan. 13, 2014 (not used)

Some energy sources, especially petroleum, are used in pharmaceuticals, plastics, asphalt, and other applications where energy is not the end-use, and eventually—and that time may not be too far off—oil will become too valuable to burn in internal combustion engines or furnaces. It is worth remembering that energy is never “consumed,” it is just transformed, and also that
the second law of thermodynamics guarantees that however it is produced or utilized, energy will be wasted in the form of heat.  

Global energy reserves can be divided into three natural categories: fossil, nuclear, and renewable. Total proven fossil reserves are estimated, in energy units, at something over 60 zettajoules (ZJ) or $60 \times 10^{21}$ joules. Used at the current rate of 19 TW or nearly 600 EJ per year, these fossil-fuel reserves would last on the order of 100 years, the R/P ratio, neglecting the inevitable growth in energy consumption and the likely growth in proved reserves. At a 1% growth rate of consumption, which is not unreasonable, the reserves would be exhausted in half that time. While the reserve-to-production ratio may be a kind of useful fiction, it can also be very misleading. If the rate of production grows while the reserve remains constant, the life of the resource will be overestimated. On the other hand both may grow, as is often the case, and at unpredictable rates, in which case not much is learned.

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27 The first law of thermodynamics says that energy is conserved. The second law can be expressed in various ways, one being that entropy always increases in real processes. This means that useful energy is always decreasing in such processes, typically being lost in the form of heat.

28 Or, 40 ZJ, which is 40,000 EJ, and if current consumption is about 580 EJ, then the R/P (really R/C) is about 70 years.

29 One often hears that in 1980, say, we were told that we only had 25 years of oil left. But that was only the R/P ratio, which is not the same thing. At best R/P is a very crude measure of the longevity of a resource.
We will discuss each of the fossil fuel resources as we move along, but before we do so, we need to emphasize that no resource will be exploited at a constant rate. Typically, production will drop as the resource is depleted, and, as noted above, production will follow something like a bell curve, or what has come to be known as a “Hubbert curve”\(^{30}\) (Figures 2.9, 2.10). Thus growth in exploitation of a resource will eventually peak or plateau and then inexorably (or almost inexorably) decrease. As noted, the tail of the curve may be extended as the value of the resource obeys the law of supply and demand (see Figure 2.10). The Hubbert curve, with all its

\(^{30}\)Approximately a Gaussian or normal distribution with a longer tail. See the mathematical appendix.
imperfections, is a better approximation to the exploitation of a typical finite resource than the R/P ratio and was first popularized as a way of estimating the future of fossil-fuel resources by M. King Hubbert in the 1960s, although Malthus would have understood it at the end of the 18th century. We can see from Figure 2.10 that U.S. oil production followed the Hubbert curve very well until the last two decades, as new technologies (including “fracking”) have reversed the decline in production.

Figure 2.10. Hubbert’s curve for U.S. production, with actual production (in green) to 2014.

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Figure 2.11. World Energy Consumption as a Function of the Type of Resource Over the Past Half-Century (top), and
projections beyond 2020. The annual growth rate in consumption of fossil fuels since 1970 is 2\%.

The area under the Hubbert curve amounts to the ultimate production of the resource, and at the peak, one-half the total resource will, in theory, have been produced. This should only be thought of as a model of how a resource is exploited, not the gospel truth, and is really not much more than curve-fitting.\(^{32}\) Although Hubbert accurately predicted that U.S. oil production would peak in 1970, as noted, recent developments, including hydraulic fracturing ("fracking") and horizontal drilling have reversed the decline.\(^{33}\) In the end it would be folly to say of any resource extracted from deep underground, that all or even most reserves are known, and new technology may make oil drilling practical in ocean depths below 5km—even to 10km. In general, technology and scarcity may make it possible to extract reserves that were previously not exploitable. Nonetheless, all fossil fuels, at different rates, will eventually be exhausted, or decline to the point that they are more valuable for their chemical properties than as energy sources. The same will happen with stocks of fissionable material if the exploitation of nuclear power is not prevented by politics (or, if you prefer, public skepticism). In short, unless controlled fusion someday becomes feasible, future energy will have to come from renewable sources.\(^{34}\) This is inescapable.

For a variety of reasons, including the immediacy of the threat of global warming and the current, if temporary, oil glut, focus has shifted substantially from the energy crisis and

\(^{32}\)Two good papers on modelling future oil supply appeared in 2010: Brandt (2010) and Sorrell and Speirs (2010).

\(^{33}\)The term “tight oil” is often used to describe resources that can only be exploited by heating or fracturing the sedimentary rock in which they are found.

\(^{34}\)Controlled nuclear fusion is not technically renewable, but would be virtually inexhaustible.
conservation, to eliminating the deleterious effects of burning fossil fuels. These two issues are obviously closely intertwined since going to greater use of wind and solar as well as nuclear, would address the problem of exhaustion of fossil fuel sources at the same time it addressed climate change. Our new understanding, and the focus of our narrative, is that we cannot afford to exploit the planet’s fossil fuel resources until exhaustion, because of global warming, something we turn our attention to in Chapter 3.

Between 1980 and 2012, U.S. energy consumption increased by 29%, a growth rate of less than 1% and a doubling time of 87 years, assuming exponential growth, while in the same period, global energy use increased by a much faster 85%, a 1.9% annual growth rate. During those 32 years, the earth’s population increased by only about 56%. Thus the world’s population continues to grow, but as expected, energy intensity (energy units per capita) is also growing. The growth in per capita energy consumption over those three decades was 15-20%. Global population is projected to grow to perhaps 10 billion (plus or minus a billion) before it saturates or plateaus, and it is reasonable to assume that developing countries, in which most of the population growth will occur, will eventually reach levels of energy consumption comparable to at least the most efficient European countries such as France and Germany (about 5-6 kW per capita--Figure 2.6). This projects to perhaps 16 ZJ of additional global energy needs by the end of the century just due to the growing population, and it could

35 If interested, see the appendix for how this calculation is made.
36 As we saw earlier, global per capita energy consumption is now 80 GJ/yr or a rate of about 2.5-3 kW per person continuously.
easily be much greater. Cumulative global energy consumption might total 70 ZJ or more during that period. The problem is: how do we reach that level of global energy consumption and do it while reducing net greenhouse emissions? That, needless to say, is a very tall order. It will require determination and discipline, and above all, a rapid move away from fossil fuels. But while global energy consumption will certainly increase, greenhouse emissions do not have to. More later.

Fossil Fuels

We could simply say that no matter what the planet’s fossil fuel reserves are, we should stop burning them as quickly as possible, and move on. But they differ in their actual or potential impact on the environment, which is important to understand. Currently over 80% of the world’s energy is generated from fossil fuels, dramatically showing their importance to mankind, as if that were needed. The dominant fossil fuel resources are coal, oil, and natural gas, which currently contribute almost equally to the global energy budget (29%, 31%, 21%, respectively).

The energy content of coal has been exploited since the first millennium BC, by the ancient Chinese, the Greeks, and the Romans among others. Coal was used as a fuel in medieval times, but really came into its own in Britain in the 18th century, powering the Industrial Revolution. Coal is a biomass resource,

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37 Another way to look at it is that sometime after 2100 the average global rate of energy consumption may reach 40-60 TW, 2-3 times current values.
38 50 ZJ without any growth! For future reference, this would emit 1000-1500 Gt carbon, with about half going into the atmosphere.
39 I use net because of carbon capture and sequestration; perhaps even removal. It is easy to see that we must reduce our average CO$_2$-eq greenhouse emissions per unit of energy by a factor of at least two, from about 70 kg per million Btu to under 30 (or from about 200g/kWh to 1000), just to maintain current emissions.
a sedimentary rock containing a high percentage of carbon, and at present generates about 40% of the world’s electricity, but no longer plays much of a role in transportation. Coal can be thought of as captured sunlight which through photosynthesis grew freshwater plant material that was eventually heated, compressed and solidified over geological time scales. It can be over 90% carbon, as in the case of anthracite, but also contains hydrogen, sulfur, and even trace amounts of mercury and arsenic.

In the case of natural gas, solar energy is stored in the chemical bonds that make up methane, CH₄, the principal component of natural gas. That chemical energy is released in combustion, while in coal it is the elemental carbon itself, which burned with oxygen, generates energy. Crude oil, which also has a biological and hence solar origin, is a very complex mixture of hydrocarbons which can be refined to yield a variety of combustible compounds and a whole host of other petrochemicals which have wide application.

A convenient way to compare diverse energy sources is in terms of energy densities (energy per unit of mass or weight), which are similar for the fossil fuels, with natural gas and LNG being highest at almost 15 kWh/kg, gasoline at 13, and coal ranging from about 7 to 10. Hydrogen has a much higher energy density of 39 kWh/kg, and fissioning ²³⁵U can generate 20 GWh/kg, over a million times that of fossil fuels. The prices per Btu of the fossil-fuel resources we are considering are comparable, which explains in part why one has not become

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⁴⁰At an average of about 10 kWh/kg for fossil fuels, we find the pure metric value of 36 MJ/kg. Another way to look at it is to consider the energy density per unit volume in MJ/L (megajoules per liter). In this case, natural gas has a very low value of 0.04 MJ/L compared to the others at 22-50. Liquified natural gas (LNG), on the other hand, is relatively high, at about 22 MJ/L and LP gases are also high.
dominant, and short-term price fluctuations can change the cost ranking.\textsuperscript{41} For comparison, the price is typically expressed in U.S. dollars per million Btu (MMBtu or MBTU). Crude oil, the most versatile resource, is currently the most expensive (at $60/bbl) at about $10/MMBtu (3¢/KWh), natural gas ($3/1000 ft$^3$) follows at about $3/MMBtu (1¢/KWh), and coal (at $45/ton) is the cheapest at about $2/MMBtu (0.75¢/KWh).\textsuperscript{42} This is, however, far from the whole story. If used in generating electricity, a better way to evaluate the cost is to consider what is known as the “levelized cost of electricity” (LCOE), which, in some sense, is the net cost of generating a kWh of electricity taking into account all costs, including transportation, plant construction, etc. Typical values of LCOE are shown in Figure 2.21, in which coal is the most expensive. Since it is also the dirtiest, its role in the global energy mix can be expected to shrink. Oil is used primarily for heating and transportation, and rarely to generate electricity. Natural gas is largely used to generate electricity, but could become more important in the transportation sector.

**Coal; “It May Be Dirty But It’s Cheap”**

The most important features of coal are its abundance and its energy content. Coal has fueled the huge Chinese economic expansion and aided in lifting millions of Chinese out of poverty. China consumes about half the world’s coal and recently the U.S., with its own huge coal reserves, slipped to third place, behind India. Currently world coal consumption is nearing 10 billion tons (10Gt) annually, and until recently it was

\textsuperscript{41}In recent years, the price of oil has been as high as $140/bbl and as low as $35, and Figure 2.18 shows the fluctuation in natural gas prices by about the same factor.

\textsuperscript{42}These numbers obviously fluctuate with the price of the resource.
the most important global fossil fuel source. Coal yields between about 5000 and 15000 Btu of energy per pound,\(^{43}\) and generates a global total of about 160 quadrillion Btu per year (160 Quad, 160 EJ). This represents an average rate (power) of about 5 TW, 28-29% of the global energy budget, but down from over 50% in the 1930s.

![Global Coal Consumption, 1965 to 2015](image)

**Figure 2.12.** Global coal consumption since 1965, showing contributions from China, U.S. and India.

Coal *reserves* (proved, recoverable) are estimated at somewhat over one trillion tons (1000 Gt)\(^{44}\) representing a total energy content of a bit over 20 ZJ. At the current rate of consumption of 10 Gt tons per year, this reserve could last about a century (R/P > 100 yrs), with the caveats given above, and current efforts to reduce coal consumption may prolong that further. Indeed, some, or much, may actually be left in the ground. There is some evidence that stated coal reserves have

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\(^{43}\)Which is 3-9 kWh/kg.

\(^{44}\)In the U.S., “ton” refers to the “short ton,” 2000 lbs. The “long ton” used in Britain among other places, is 2240 lbs. The “metric ton”, usually spelled “tonne,” on the other hand, is 1000 kg or about 2205 lbs.
been inflated by several countries for political reasons, and yet the total global resource, independent of whether it is practical or economic to exploit it, may be as high as 400 ZJ in energy terms! At the current rate of coal consumption that would last centuries, but if asked to meet the entire global energy needs it would have a life of not much over 100 years. Burning this entire resource base could put 4000 Gt of carbon into the atmosphere. More on that later.

The major drawback to the widespread burning of coal is found in its CO$_2$ emissions, which amount to over 200 lbs per million Btu, or about 300 grams per kWh. This is 70% more than the CO$_2$ emitted in burning natural gas, and 50% more than gasoline, motivating attempts to gasify coal or to eliminate its use altogether. Gasifying coal yields syngas (SNG), a natural gas substitute consisting mainly of H$_2$ and CO, and allows easier capture of CO$_2$ produced in the process. On the other hand, SNG has a much lower energy density than natural gas. Germany has recently embraced coal gasification on a large scale while deciding to move away from nuclear power completely.

Coal’s difficulty, as we have pointed out, is that it is “dirty,” in terms of both CO$_2$ and other emissions, motivating major efforts to end its burning, despite the relatively large reserves. Currently over 40% of GHG emissions result from burning coal, and no reasonable goal of reducing CO$_2$ emissions can be achieved without drastically reducing its use. In the end this depends on national and global politics. The U.S. has the

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46 As we will see in Chapters 4 and 5, this could raise CO$_2$ levels to over 2000 ppm with a temperature increase approaching $10^6$ C ($18^0$ F).
world’s largest coal reserves, amounting to about 240 Gt, about a quarter of the earth’s estimate reserves. At current prices, this reserve is worth about $10 trillion. Will it actually be left in the ground? If the move away from coal seems inevitable, it must be remembered that nearly 1/3 of the world’s energy is generated from this fossil resource, and that amount will have to be replaced, ultimately, by nuclear or renewable sources, but in the short run by increased production of oil and natural gas.

Currently, despite its abundance, coal is not really competitive with cheap natural gas for generating electricity (Figure 2.21), and the gap would be even wider if the costs of mitigating coal’s CO$_2$ emissions were assessed to its price. But coal is the simplest fossil resource, requiring little in the way of complex extraction or processing, which makes it attractive in developing economies.

Oil

The first commercial oil well is usually considered to be Edwin Drake’s near Titusville, Pennsylvania in 1859. Production grew quickly thereafter, in the U.S. and around the world, and within a decade, U.S. production was over 4 million barrels (bbl) per year, steadily growing. Petroleum soon became the engine of military and industrial expansion, and by 1950 it surpassed coal as the number one source of world energy. World proven oil reserves are thought to be about 2 trillion barrels, with some estimates reaching twice that value, and at the upper extreme is a 7 trillion bbl estimate by the International Energy Agency (IEA), but in any discussion of reserves, we have to distinguish between proven reserves, prospective reserves, and so on. As with coal, it has not been

\footnote{Which BP (British Petroleum) itself says is “sufficient to meet 52.5 years of global production.”}
uncommon for countries to inflate their reserves for political purposes. The designation P90 (or 1P) has been used to label reserves with a 90% probability of being produced, and P50 (2P) resources with only a 50% probability.\textsuperscript{48} Many factors will determine whether unproven reserves become proven, or whether a reserve is technically or economically producible.\textsuperscript{49} Currently about 31% of global energy needs are met by oil, only slightly more than coal, but its versatility gives it a critical role, especially in the transportation sector, where it provides about 95% of the energy. The standard measure of oil resources, the 42-gallon barrel (159 liters), is clearly archaic, but still widely used. In energy markets, world oil may be sold by mass, weight, volume, or even in energy units; in Europe it is usually sold in metric tons (tonnes).

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{world_oil_production.png}
\caption{World Oil Production Since 1930, by Region. Source? Find better.}
\end{figure}

\textsuperscript{48}Or “provable and probable.” P10 or 3P is used for proved plus unproved. The latter are broken down into probable and possible.
\textsuperscript{49}See http://www.netl.doe.gov/publications/others/pdf/Oil_Peaking_NETL.pdf. Also technically recoverable resource (TRR) or ultimately recoverable resource (URR). The 7 trillion estimate is from the International Energy Agency (IEA) in 2012: World Energy Outlook.
The figures above, especially Figures 2.7 and 2.8, show that global “proved” petroleum reserves have grown substantially at the same time that oil consumption has also increased rapidly. The estimated global reserves of crude oil of at least 2 trillion bbls (2000 Gb) are more than twice the 680 billion bbls assumed in 1980, despite the consumption of over 500 billion bbls in that period (Figures 2.7 and 2.8). This has resulted from further exploration and the discovery of new crude oil reserves, increased efficiency of extraction, including fracturing and directional drilling, and may grow further with the opening up of known reserves which previously could not be technically or economically exploited, such as shale oil. Some have taken this to mean that oil will never be exhausted, which is a very dangerous belief, belied by Figures 2.14 and 2.15. 50

Figure 2.11 shows that we have not yet reached “peak oil,” beyond which global production will inexorably decrease, but few analysts expect that production will continue to increase beyond 2030. And while some of the growth has come in restatement of reserves by OPEC countries, improved extraction techniques and rising prices have played a major role. Looking forward, however, the situation is not so rosy. As can be seen in Figures 2.14 and 2.15, new crude oil discoveries have been in a steep decline since the 1960s and consumption has exceeded production since the early 1980s. In 2015 replacement amounted to only about 10% of production, and new discoveries were at their lowest level since 1952, though part of that has to do with the relatively low price of oil, something that will certainly not persist. Given that globally we now consume 5-10

50The Peak Oil site shows that “peak oil” has already been reached in many countries, including, of course, the U.S.
barrels of oil for every new one we find, the production and discovery curves had eventually to cross, as indeed they have (Figure 2.14). The figure is slightly misleading, however, since growth in reserves is not counted, but only new discoveries. So total reserves have actually increased even as new discoveries have failed to match production. But a 2014 projection is that “a sustained decline in global conventional [oil] production appears probable before 2030 and there is significant risk of this beginning before 2020.” Another estimate is that by 2025, 80% of all the world’s oil will have been extracted, mostly in the previous 60 years. Figure 2.16 shows how U.S. proved reserves have declined since 1980, as well as the way the decline has plateaued in the last two decades. It is important to note here, by the way, that while U.S. crude oil production has spiked since about 2007, making the U.S. the world’s largest producer by a significant margin, the global growth over that period has only been at about a 1.3% rate, not changing Figure 2.14 by very much.

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51 An excellent online resource is http://www.theglobaleducationproject.org/earth/energy-supply.php, run by the Association for the Study of Peak Oil. In recent years, discoveries have ranged from 5-17 x 10^9 bbls per year, while in 2017 consumption was a little under 100 million bbls/day or about 3.5 x 10^10 bbls/year. In other words production has outpaced discovery by a factor of 2.5.

52 Miller and Sorrell (2014).

53 Ibid, Miller and Sorrell.

54 Despite these facts, production can exceed demand in any given year, since production is driven by price, and an imbalance can easily occur. In the long run, however, the prospects are poor.
Figure 2.15  Oil discoveries vs. consumption since 1950. The yellow curve is the excess of discoveries over production, which turned negative after 1990. 
http://www.theglobaleducationproject.org/earth/energy-supply.php
The present global rate of oil consumption, about 100 million bbl per day (bpd) is likely to increase absent major efforts to reduce use of fossil fuels, as the developing world expands its use of energy. This rate of consumption of over 30 billion barrels per year yields a reserve to production ratio of not much over 50 years, having slowly increased for the last 35 years, and averaging about 40 years during that entire period (Figure 2.8). It is quite clear that the world will be burning petroleum at current levels or higher through the middle of the century and perhaps beyond unless political action is taken. The

Figure 2.16. U.S. Proved Oil Reserves. Energy Trends Insider
reserves are there,\textsuperscript{55} despite the fact, already noted, that the rate and size of new discoveries continues to decline, even including shale and tar sands oil, which while currently important in the U.S., is making a small contribution to global production.

To make the situation clearer, we should examine these reserves in terms of energy content. The accepted value is 5.8 million Btu per barrel of oil (Boe), or about 6 GJ/bbl. This means that the current reserve of about 2 trillion bbls has an energy content of around $10^{19}$ Btu or about 12 ZJ (zettajoules). If the IEA’s high estimate of 7 trillion bbls is realistic, however, this figure swells to 40 ZJ.\textsuperscript{56} We have seen that global energy consumption to 2100 will total something like 70 ZJ.

It has long been pointed out that fossil fuels are too precious to waste generating heat. Petroleum, which is a complex mixture of many organic molecules, provides the raw material for all kinds of pharmaceuticals, plastics, and a host of carbon-based exotic materials such as carbon fiber and carbon nanotubes. Who can say what future material scientists and chemists will do with these molecules? It could be argued that this alone is sufficient reason to stop burning petroleum. Fortunately, either because of atmospheric pollution ($\text{CO}_2$ and equivalents) or the escalating cost of these fossil fuel resources as they become scarce and expensive to extract, the earth may retain enough of them to meet these more sophisticated needs.

\textsuperscript{55}If, however, the reserve is at the low end, 2 trillion bbls, oil could supply not much more than 10% of energy needs to 2100. Looked at another way, if used to meet all the world’s energy needs, conventional oil would only last 20 years.

\textsuperscript{56}It is estimated that there are 75 ZJ of oil trapped in sedimentary rocks in one form or another. See the Global Energy Assessment (GEA, 2012). The likely oil reserves alone, if burned, generating 250-800 GtC, will add 50-200 ppm of $\text{CO}_2$ to the atmosphere. Or at the present rate of consumption, about 160 GtC would be emitted by century’s end. We will find later that a current goal is to emit less than 400 GtC from all sources. “Business as usual” is not sustainable.
applications. Burning oil in furnaces and automobiles may have made sense in 1900 or 1950, but it no longer does.

**Natural Gas**

Natural gas is a combustible biogenic hydrocarbon gas, generally over 90% methane (CH$_4$). The composition does vary, however, and typically natural gas contains several other useful compounds, including propane, butane, and ethane.$^{57}$ It is usually found with other fossil fuel resources as in coal beds and often with petroleum. Because of its very simple composition, burning it in air only generates CO$_2$, CO, H$_2$O, and nitrogen oxides. The energy content of natural gas depends on its precise composition, but on average it is about 1000 Btu per cubic foot (Btu/ft$^3$).$^{58}$ One of its most attractive features is that it only emits about 117 lbs of CO$_2$ per million Btu (180 g/kWh) when burned, compared to coal’s 200+ and about 160 for gasoline. If natural gas were to completely replace coal, there would be an immediate reduction in global CO$_2$ emissions by almost 20%. Recently shale gas has become an important source of natural gas in the U.S., its exploitation made possible by hydraulic fracturing (“fracking”).

Global proven reserves of natural gas are estimated at about 200 trillion cubic meters, of which about a quarter are in Russia. At the rate of about 1000 Btu per cubic foot when burned (or in mixed metric units 30,000 Btu/m$^3$), and a little over 1000 J/Btu, the energy content of the natural gas reserves is 7-9 ZJ. Unconventional reserves, which might be eventually exploited, greatly exceed that, making the reserves comparable to those of

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$^{57}$ Much of these “alkanes” come from processing petroleum.
$^{58}$ Often the “therm” is used, representing 100,000 Btu, because it is approximately the energy emitted in burning 100 cubic feet of natural gas.
coal. Global consumption is currently about 120 trillion cubic feet (120 Tcf) annually or about 4 trillion cubic meters. The R/P ratio is then about 50 years. Until recently natural gas was too expensive to transport between continents, but now liquefied natural gas (LNG) is becoming widely shipped, and the U.S. has been moving rapidly to expand the export of LNG.

![Graph showing world proved natural gas reserves since 1960. The increase has been a factor of 8 and shows no signs of plateauing.](image)

**Figure 2.17.** World proved natural gas reserves since 1960. The increase has been a factor of 8 and shows no signs of plateauing.

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59GEA, 2012. Including gas hydrate resources, the earth may hold 1000 ZJ of unconventional natural gas.
60There are about 35 cubic feet in a cubic meter. Thus a unit like Bcfd is used in the U.S., standing for billion cubic feet per day.
Figure 2.18. Natural gas prices per million Btu (MMBtu) over the past two decades. Note the price volatility. The average has been about $5-6 per million Btu. USEIA

As with oil, there has been a huge increase in proved natural gas resources in recent times (Figure 2.17), which suggests that our knowledge of the magnitude of the resource is only approximate. Methane clathrates in permafrost and in ocean floors represent an immense reserve of methane, for good or ill. As we will see later, methane is a very strong greenhouse gas, and its release from permafrost could be very serious.

Summary of Fossil Fuel Resources

Combined, the conventional fossil fuel resources we have considered, coal, oil, and natural gas, represent a global energy reserve of at least 50 ZJ (possibly as high as 80 ZJ), with the possibility that it could be nearly 10 times that. On the basis

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61 Estimates go as high as 250 ZJ, or 5000 Gt carbon; see Previdi, et al (2013). Burning all of it would raise atmospheric CO₂ levels by over 1000 ppm. The global average temperature might rise 13° F.
of an annual use of 0.6 ZJ, the reserve to production ratio is on the order of 100 years, a number which, again, should be greeted with caution, for reasons we have described. But if all of the earth’s known fossil fuel resources are counted, without regard to whether they are in any way recoverable, the total reserve would reach over 1000 ZJ, more than ten times global energy needs in this century, a fact that is worth remembering. If burned, this resource would emit over 20,000 Gt of carbon, the consequences of which we will explore later. Conventional coal, oil, and natural gas could be essentially exhausted by the end of the century (see Chapter 7), but that does not include this remaining “exotic” resource base. But even if enough reserves are found to supply the planet’s needs well into the 22nd century (or longer), the imperative to stop burning fossil fuels, as we shall see, is inescapable.

It is, however, a remarkable, and surely sad, fact, that the “fossil fuel era,” in which mankind has exploited the planet’s vast but finite resources of coal, petroleum, and natural gas to support a burgeoning population making ever more intensive use of energy, will have had a lifetime of a mere four centuries or so, a period dwarfed by the planet’s age or even by humankind’s existence. On the time scale of human history, the fossil fuel era is but a blip (Figure 2.19). How could that have come about?

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62 Again, see the 2012 GEA report, available online (GEA, 2012).
Figure 2.19. **The fossil-fuel era on the time-line of history. Less than a millennium. In modern terms, the peak would be more than twice as high, and the width perhaps narrower. From Devins (1982).**

**Fission (nuclear) Power**

We introduce nuclear power at this point because although it is indeed virtually emission-free, it is not renewable. The public has long been skeptical of nuclear power as an alternative to fossil fuels, with the result that the exploitation of this resource is currently moribund, primarily limited by public concern and lack of political will. Whether the public response to events like the Three-Mile Island release of radioactivity in 1979, the Chernobyl meltdown in 1986, or the Japanese Fukushima disaster in 2013 is rational or hysterical, these disasters have played a major role in the suppression of the nuclear power industry. Following Fukushima, Germany committed to abandoning nuclear power generation entirely. New nuclear plants are very expensive and face lengthy regulatory hurdles, so that the prospects for increased use of fission energy are fairly poor, at least in the short run. A strong
commitment to combating global warming could change those prospects, however.\textsuperscript{63}

Nuclear energy reserves depend strongly on how the fissionable material is utilized. Currently the uranium reserve is estimated to be about 6 million metric tons;\textsuperscript{64} used in contemporary light water reactors (LWR), the total energy release is in the range of 2-20 ZJ. Using breeder reactors, which can produce more fissionable material than they consume, the resource is potentially much greater, in the neighborhood of over 1 YJ \((10^{24} \text{ J})\).\textsuperscript{65} While the possibility of a nuclear disaster is uppermost in the public mind, the problem of disposal of highly radioactive nuclear waste continues to defy easy solution. The heat generated by radioactive waste can be used as an energy source, but this still does not eliminate the disposal problem.\textsuperscript{66} Although it has been pointed out that the fly ash resulting from burning coal results in there being more radioactivity around a coal-burning power plant than a nuclear one,\textsuperscript{67} that fails to address the waste disposal problem or the possibility of an unexpected nuclear disaster. Nuclear proliferation is an additional and ongoing geopolitical problem, in part because plutonium is a byproduct of nuclear reactor operation.

\textsuperscript{63}The Westinghouse division of Toshiba Corporation declared bankruptcy in 2017 because of cost overruns in developing nuclear power.

\textsuperscript{64}“reasonably assured resource plus inferred” at a price of $130/kg.

\textsuperscript{65}Although nuclear power could thus meet global energy needs for several centuries if generated from breeder reactors, this is very unlikely to happen.

\textsuperscript{66}To put things in perspective, the radioactive waste generated so far would represent a pile about the size of the great pyramid at Giza.

\textsuperscript{67}Not to mention the mercury, arsenic, and other toxins emitted.
The obvious appeal of nuclear power comes from the fact that it is essentially\(^6^8\) free of CO\(_2\) and other greenhouse gas emissions. The technology is mature and it does not suffer from the intermittency problem associated with wind and solar. New reactor technology should make power reactors much safer than the 1960s technology used at Fukushima and especially Chernobyl. Uranium is a commonly available metal, 40 times more abundant in the earth’s crust than silver, and estimates of probable reserves reach as high as 15 million metric tons. Naturally occurring uranium is over 99\%\(^{238}\)U, but contains 0.7\%\(^{235}\)U, which is the isotope used in fission reactors.\(^6^9\) When utilized in light water reactors, the uranium is enriched (LEU) to about 20\%\(^{235}\)U. Currently, LWRs are consuming about 70,000 metric tons of uranium and are generating just under 3 trillion KWh or about 10 EJ (10\(^{19}\)J) per year. The R/P is about 100 years, comparable to other energy sources, but as has been the experience with other minerals, the known reserves can be expected to grow. Australia has the largest uranium reserves, with an estimated 29\% of the world total. Finally, the uranium reserves in the oceans are truly enormous, probably sufficient to supply the earth’s current energy needs for several thousand years.\(^7^0\)

Currently about 10\% of the world’s electricity is obtained from fission, though in France, over 70\% of the nation’s energy is generated this way. The benefits of nuclear power are obvious, but so are its disadvantages. Many would argue that if the enormous global energy needs are to be met using only

\(^{6^8}\)The caveat coming from the fact that much of the energy required to mine the uranium might come from fossil fuel sources, and certainly does today.

\(^{6^9}\)Uranium reserves consist mainly of pitchblende or uraninite, containing variable concentrations of U\(_3\)O\(_8\), and coffinite.

\(^{7^0}\)But this would require perhaps 15,000 nuclear reactors, which is surely unrealistic.
renewable and other CO$_2$-free technologies, nuclear must contribute substantially to the mix, at least during a period of transition away from fossil fuels, and perhaps to provide a “base load capacity” to smooth out the fluctuations in wind and solar (see below). In many respects it comes down to coal or nuclear, and the decision ought not to be difficult. As with other non-renewable resources, the earth’s reserves of fissionable material will, if exploited, eventually be exhausted, but nuclear power could constitute the bridge between the fossil fuel era and the renewable era.

**Fusion Power**

Nuclear fusion using deuterium from seawater has been the “holy grail” of energy production for decades. Fusion would offer a virtually inexhaustible source of energy, if and when it became technologically feasible. In principle, something like 4000 YJ (4 million ZJ!) of energy could be generated by burning all the deuterium in the earth’s oceans, but because it is not now an existing energy source, we will not consider it further. Interestingly, this resource would meet the earth’s total energy needs for no more than a few million years, which may seem like a ridiculously long time, but even that assumes saturation of the earth’s population and the end of exponential growth of energy use. As a measure of what exponential growth means, at a 1% annual rate of growth of energy use, all the deuterium in the oceans could be burned in just 2000 years! Of course a growth rate of 1% per year could not be sustained for other reasons.\(^7\) In the end, it would be folly to project global energy

\(^7\)A 1% growth rate for 2300 years, this represents an increase in energy use of a factor of nearly 10 billion. For the time required to exhaust a resource at constant exponential growth, see the appendix. As an example, for a growth rate of 3%, and an R/P of 200 years, T=59 years, much less than the R/P! This is unrealistic, however, since no resource would be consumed at a constant growth rate until exhaustion.
needs or resources even a thousand years into the future, much less a million. Furthermore, the question may be asked whether the technology of fusion reactors, if and when it reaches more than the demonstration stage, could ever be scaled up to meet most of the planet’s energy needs.

**Alternative and Renewable Energy Sources**

Renewable energy sources are by definition inexhaustible. They include solar, wind, geothermal, hydroelectric, biofuel, and various ways of utilizing the energy stored in the oceans, principally ocean currents and tides (due to interaction with sun and moon). As with every energy source, cost competitiveness is an issue, as is the net energy provided by the source; i.e. whether it returns more energy than it consumes to produce it. Since carbon is released into the atmosphere mostly by burning hydrocarbons, all renewable energy sources are essentially carbon-free, except biofuels.\(^{72}\) Already, fully 1/3 of U.S. electricity is generated by other than fossil fuels, but low “capacity factors”\(^ {73}\) or intermittency is a problem with wind and solar, which means that control systems that move energy around the grid have to be very sophisticated, and new or improved ways of storing the energy must be found. These capacity factors are well below 50% for wind and solar, and can be even lower than that (see Figure 2.20), so that “base load” sources, fossil or nuclear, have to be available to handle the fluctuating inputs from wind or solar. That guarantees that they will be around for some time. The alternative is the increased ability to store energy from intermittent sources like solar and

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\(^{72}\) Confining our attention only to energy sources, and ignoring the fact that GHGs may be emitted in constructing wind farms, building solar panels, etc. Obviously deforestation puts enormous quantities of carbon into the atmosphere in the form of CO₂.

\(^{73}\) The capacity factor is the ratio of the actual output to what it would generate if operating full time.
wind that can be expected to yield to technological advances. Aside from batteries that can provide local storage, the most promising technologies involve either kinetic or potential energy storage, or storage in a thermal medium such as molten sodium. Solar or wind power could be used to pump water uphill, increasing its potential energy for release later, and energy could be stored in the form of rotating flywheels, etc.

Figure 2.20. Capacity factors for various renewable resources. Solar, of course, has a daily fluctuation as well as a seasonal one.

Solar Energy

The amount of solar energy falling on a square meter at the earth’s surface per second, averaged over daily, seasonal, and geometrical factors, is about 160 watts. This may be compared to the solar constant (total solar irradiance, TSI) of about 1360 watts/m² at the top of the earth’s atmosphere. At 160 watts/m², this represents a total power of nearly $10^{17}$ watts, or

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74Futuristic ideas include solar collectors in high earth orbit which would convert solar energy into microwaves and beam it back to earth, thus avoiding the losses discussed here!
about 2500 ZJ per year of inexhaustible energy. If only 0.02% (one part in 5000) of this could be harnessed, it would meet all the planet’s current energy needs. One can hardly cover the entire globe with solar panels, of course, and much of the sun’s energy is already committed to maintaining the climate, providing photosynthesis including agriculture, etc. Moreover solar power is intermittent, due to seasonal changes, the weather, and the earth’s rotation, putting a premium on storage. But solar technologies are rapidly evolving, so that one may anticipate solar collectors using exotic materials and technologies, with increasing efficiency. Estimates of the amount of solar energy that might practically be utilized vary by factors of 10 or more, from perhaps 1 ZJ per year at the low end, to more than 10 ZJ at the high end. Even the low number is nearly double the current (2015) global energy budget of 600 EJ per year. Currently about 12% of global electrical demands are provided by solar, without any real commitment.

To be more realistic, and taking into account cloudy days and varying sun angle, a square meter in a sunny location such as Colorado is estimated to capture about 2000 kWh per year. Today, solar photovoltaic panels have an efficiency of about 20%, which means that one square meter can generate about 400 kWh/yr of electrical energy, nearly 2% of average energy needs, though the energy capture might be less than half that

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75The required area of about 40,000 square miles of solar collectors (200 miles on a side), about the size of a medium-sized state, spread among 100 or more sites, many on the ocean surface, could be manageable. There are local environmental issues to be addressed, including the energy reflected or radiated from the collectors, and so on.
76It ought to be noted that the problem of shifting energy in the electrical grid as night or day advance is always an issue, and it may be that this will in the future be done on a global rather than continental scale. Solar energy can be stored as electrical energy in batteries, and as thermal or mechanical energy. One can expect huge technological advances in this area.
78But more than 2% of household needs.
in perennially cloudy locations. But these numbers show that a 100 square meter solar panel array on each of about one billion houses in the world could generate up to one quarter of the current global power needs, about 5 TW, without any industrial-scale projects. An optimist would argue that the earth’s entire energy needs could eventually be met entirely by solar. A realist might simply note that that will have to be the case, or, more precisely, renewables.\footnote{Since that is certainly the case, why wait?}

China, which leads the world in utilizing solar power, has doubled its installed solar capacity in just one year (2017-18) and already has large-scale pilot projects that involve oceanic floating solar panels. It is likely that such installations, miles on a side, will play a major role in the harnessing of solar energy.

The leading method of capturing solar energy today is to be found in photovoltaics, the generation of electric power from solar panels. This may very well continue to be the case but this intermittent energy has to be stored somehow, and batteries are hardly the best way to do it. There are already pilot solar plants using molten salt and other liquids to store heat generated from solar collectors. Solar energy can also be used to boil water and drive steam turbines, and passive solar heating can be used in homes, replacing natural gas. Once converted to electricity, solar power can be further converted to mechanical energy, or it can be used to generate hydrogen by dissociating water, and storing it. Technological advances in capturing and storing solar energy will no doubt play a huge role in the years to come. And if means are found to transport electrical energy directly from continent to continent, either through space or on
the ocean bottom, intermittency and storage will be less an issue and renewables could completely replace fossil sources.

**Wind Power**

Wind power, as with solar, can be thought of as otherwise wasted energy waiting to be exploited, though while inexhaustible, it too is intermittent. Controlling factors are geographical, cost, and public tolerance of wind farms. But no one who drives across West Texas, to pick just one area, can escape the feeling that wind power is on the march. Like solar, wind energy can be generated near the site of use, although economies of scale may compromise this advantage, and wind intensity varies widely over the world. Currently installed wind capacity is about 600 GW, and wind currently supplies close to 4% of global electricity.\(^80\) In 2015 the state of Iowa generated 31% of its electricity from wind, and in Denmark wind meets about 40% of electricity needs. A global increase in wind power by a factor of 10 over 50 years does not seem impossible, and current estimates are that by 2050 25-30% of global energy needs could be met by wind power.\(^81\)

Of course the relation between the cost and value of a unit of energy is critical with any source and the intermittency of wind power creates the same problems as does solar. Most importantly, the electrical grid has to be robust and flexible enough to withstand these fluctuations in the availability of wind or solar. While it is not trivial to assess the final cost per kWh of power generated from any source, when the costs of amortizing the investment, depreciation, subsidies, environmental costs,

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\(^{80}\)Global Wind Energy Council.  
\(^{81}\)The amount of wind power generated increased by 10% in 2017. Depending on developing technologies, it may be that some continuous source of energy, nuclear or fossil, will always be needed to supply the base power.
etc., are taken into account, presently the cost of supplied wind power approaches 5¢ per KWh ($50/MWh; see Figure 2.21) which is competitive with conventional sources.$^{82}$ A measure of how fast the technologies and costs are changing is the dramatic drop in the price of offshore wind power, by 60% in 5 years. As with solar there is no current constraint on the amount of energy which could be generated from wind, onshore or offshore, other than the point at which the local wind field might be adversely affected, although environmental and aesthetic issues have been raised.

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$^{82}$ As I write this, natural gas prices are very low, which necessarily impacts the wind power industry. There are several ways to evaluate the cost of an energy source. One, called “levelized cost of electricity” or LCOE takes into account all costs of some specified period of operation, say 40 years. On the other hand, the “marginal cost of electricity” would simply be the additional cost of adding capacity. Typical values of LCOE are around 10¢ per kWh, but usually quoted in dollars or Euros per MWh, in which case the numbers are near $100. The range in LCOE is about $60 to $140/MWh (6-14¢/kWh) for all of the technologies we have discussed. See, for example, the *Lazard Levelized Cost of Energy Analysis*, version 10.0 (2016), or *World Energy Perspectives* of the World Energy Council (2013); also Figure 2.21.
Possible figure. **Growth of wind power in just the last two decades.**

**Other Renewables**

Other renewable sources of energy such as geothermal and hydroelectric may be locally important in the future, and contribute to a diverse mix of sources, but cannot really be scaled up in the way that solar and wind power can. The amount of thermal energy stored in the earth’s interior in the form of gravitational energy and heat from radioactive decay, is enormous, but little of it can be easily exploited except near tectonic plate boundaries. Large-scale utilization of this resource is not out of the question, however. Geothermal energy
is the cheapest of all sources and currently some 40 GW of power is being generated from such sources in one way or another, about 0.2% of the global energy budget.

Hydroelectricity has long been an important energy source and currently supplies about 16% of the world’s electricity and about 2% of its total energy, but conventional hydroelectricity has inevitable environmental consequences and is not easily scaled up. On the other hand, if we include energy which can be extracted from ocean currents and tides, which has to be converted into electricity to be transmitted, the numbers are potentially very much larger.  

**Biofuels**

Although biofuels have the potential to be carbon-neutral because plant-based biofuels absorb CO₂ from the atmosphere (carbon fixation) while the plant material is growing, only to release it later when they are combusted, this is rarely realized and the matter is much more complex. The production of biofuels is agriculturally intensive, and can generate as much CO₂ as is absorbed. That being the case, it is hard to see that it has any major role in meeting the earth’s energy needs, except in the short run, though some biomass may be a by-product of other agricultural processes, rather than being grown specifically as a biofuel. Ordinarily, biomass is converted to bioethanol (ethyl alcohol) through fermentation, while biodiesel is produced from oils and fats, and is commonly blended with petrodiesel. The use of bioethanol or biodiesel in gasoline or diesel fuels can reduce emissions, usually as an additive, but

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83 On the prospects of meeting the entire energy needs of the planet from WWS (wind, water, and solar), see the paper by Delucchi and Jacobson (2011).

84 Diesel refined from petroleum.
even as an alternative to burning more petroleum, biofuels have major drawbacks, which include land clearing and deforestation, use of water, the conversion of human food crops to energy resources, especially in the case of corn ethanol, and so on. And again, though renewable, as long as fossil fuel sources are used in planting, harvesting, and conversion of biomass, biofuels will not be carbon-neutral, especially since they also emit \( \text{CO}_2 \) when burned. There are some exotic options, including algae, fungi, and so on. Despite its drawbacks, in the transition to renewables, biomass cannot be ignored altogether, but it probably does not deserve current subsidies, which are mainly politically driven.

**Hydrogen**

I mention hydrogen here mainly to emphasize that it is NOT an energy source. There are no significant reserves of free molecular or atomic hydrogen on the planet; rather it is locked up in inorganic molecules like water and in all organic molecules. To obtain hydrogen for use in fuel cells, water or some other molecule has to be dissociated into its components, hydrogen and oxygen in the case of water, and the energy released in burning hydrogen in air will be somewhat less than the amount consumed in producing it. At the same time, hydrogen used in fuel cells can be a replacement for \( \text{CO}_2 \) emitting gasoline in transportation applications, so long as the energy used to produce the hydrogen does not come from burning fossil fuels. The Toyota Mirai is currently the most advanced vehicle powered by a hydrogen fuel cell.

Perhaps most importantly, hydrogen is an attractive possible storage medium for intermittent energy sources such as
wind and solar, although to be stored in liquid form, it has to be kept cold and under pressure, and energy is lost thereby.

**Conclusion**

Is there an energy crisis? The answer is clearly no if humanity is able to carry out the transition from the traditional finite resources (fossil and nuclear) to renewables, carefully. And because the transition away from fossil fuels must begin immediately (we explain why, below), some fossil resources will probably never be fully exploited. As we will emphasize many times in this story, the transition to inexhaustible renewable energy sources will take place, whether we are ready for it or not, and whether it is carried out rationally and efficiently or not. This will either happen voluntarily and in an orderly fashion, as we combat climate change, or under duress as the resources run out. Consumed at just present rates, fossil fuel reserves will—as a practical matter—be exhausted in the next century or so unless something totally unexpected happens, but we cannot afford to be that patient and above all, we cannot afford, for the sake of everyone who lives on this planet, to burn all of its fossil fuel resources. We will develop this argument in short order.

If we are to halt global warming, we cannot wait until fossil fuel stores are gone. It is clear that renewable sources can meet the earth’s energy needs if its population is kept in some kind of reasonable bounds, plateauing in the neighborhood of 10 billion. If anyone doubts that, remember that eventually, this will have to be the case. Nuclear (fission) power can aid in the

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85By the way, it is folly to be exporting energy reserves, as we now are, in the name of “energy independence.” Economically it may make sense, but doing this clearly works against energy independence in the long run. But as we say, we must transition to renewable resources well before the fossil sources run out.
transition, and controlled nuclear fusion has the potential to power the planet almost indefinitely. There could well be short term disruptions as the switch is made to renewables, since human nature seems to require a crisis before anything is done. In short, the problem is not primarily one of energy reserves, assuming some kind of rational development of alternative sources, but rather the consequences for the planet of continuing carbon emission in the coming decades. There is no doubt that global energy needs can eventually be met entirely by non-fossil sources and that this can be accomplished well before century’s end. Further, the transition to renewables will foster substantial global economic growth. This is not a “free lunch,” but nonetheless a great technological and economic opportunity.  

It is interesting and important that the spread in cost of the energy sources we have discussed in this chapter is rather small (see Figure 2.21). It is true that even a small price differential can be decisive in advancing one source over another, as we currently see happening with coal, but if the goal is to reduce CO$_2$ emissions, and certainly if the cost of mitigating CO$_2$ is included, the cost differences should not be an obstacle. Even if these differentials favor fossil fuels, governments should act to provide subsidies for new alternative sources.

We will run out of fossil fuel resources. Indeed we are running out. We may rationally manage these resources for the future, saving them as the raw material for pharmaceuticals and other essential chemical applications, and even for air transportation if we cannot solve the problem of powering aircraft with electricity provided by renewables. But we should

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86See also Chapter 11.
no longer burn them in internal combustion engines or in furnaces. This, we now know, is folly.

Figure 2.21 Levelized Cost of Energy (LCOE) for Wind and Solar Compared to Conventional Energy Sources. A Value of $40/MWh is equivalent to 4¢/KWh.