CHAPTER 6

THE RISING TIDE OF HUMAN ENERGY CONSUMPTION

6.1 A new turn in the history of energy use

To prepare for this chapter, let us recall the definition of thermal equilibrium given in section 3.1. The earth's surface is in thermal equilibrium when the high-grade energy reaching it from the sun is evenly matched by the low-grade heat leaving it as black-body radiation (section 1.5). Recall also the supposition that a state of thermal equilibrium must have been present for life to make an initial appearance.

As life proliferated, the earth's surface became part of what we now call the biosphere (section 3.9). So we can speak about the biosphere itself being in thermal equilibrium. In all likelihood, the growing presence of life had little effect initially upon the balance between energy entering and energy leaving the planet's surface.

Homo sapiens joined the biosphere about 200,000 years ago.[1] For most of its time on earth, our species had no more effect than other organisms upon the thermal balance of the biosphere. Apart from occasional fluctuations due to volcanoes and colliding asteroids, heat energy going out continued to balance solar radiation coming in.

One condition of continued thermal equilibrium is that the biosphere operate mainly on what we call "renewable" energy. This assures that low-grade energy to be eliminated by black-body radiation is confined to heat resulting from the expenditure of sunlight entering the biosphere a short time previously. Under this condition there is no buildup of entropy from nonrenewable sources that might exceed the natural capacity of the biosphere to discharge its waste heat.

Another condition of thermal equilibrium is that all material structure (see section 4.3) produced by organisms within the biosphere be biodegradable. This applies both to by-products of organisms (e.g., excreta) and to their material parts. When organic matter decomposes, a portion of its residual energy is given off as low-grade heat and leaves the biosphere as black-body radiation. The remainder is retained in chemical compounds ready to serve as nutrients for subsequent organisms. And so the cycle continues. In one manner or another, all energy committed to biological activity eventually leaves the biosphere as low-grade heat.

The first condition makes sure that the low-grade energy leaving the biosphere does not far exceed the high-grade energy coming in during a given period of time. The second condition makes sure that the balance of energy-flows in and out is not disturbed by a reduction of low-grade energy flowing out. With these conditions in place, equilibrium is maintained as long as there is no impairment to the biosphere's ability to get rid of its waste heat.

Effects of nonbiological events like asteroid impacts aside, these conditions presumably held steady until the onset of industrialization. Around the middle of the 18th century, human affairs took a radical turn destined to jar the biosphere out of thermal equilibrium. An indication that something radical ws happening at this point is that human energy consumption began to rise precipitiously. Steadily increasing amounts of energy came from fossil sources (coal, oil, gas), which means that the energy involved was not renewable in the sense explained above. As a consequence, the biosphere was called upon to emit increasing quantities of low-grade heat in excess of that stemming from concurrent solar radiation.

Another aspect of human industry's increasing reliance of fossil energy was that it soon led to the development of products that are not biodegradable. The first plastic compounds appeared in the 1860s.[2] and the quantity of plastic artifacts has been growing ever since. Human activity thus became responsible for increasing quantities of material stuff that will remain within the biosphere indefinitely.

As industrialization spread around the globe, however, its most ominous aspect came to be the plethora of polluting by-products that spread in its wake. Among these are the several gases discussed in Chapter 5 (carbon dioxide, methane, nitrous oxide) that impede the discharge of heat through the earth's atmosphere. A consequence is the build-up of heat within the biosphere currently known as global warming.

On one hand, industrialization has radically increased the amount of heat awaiting discharge by black-body radiation. On the other, it has made the atmosphere increasingly opaque to the passage of this low-grade heat. Our current predicament is that the more fossil energy we bring to bear in fueling human industry, the less able the biosphere becomes to discharge the resulting waste heat.

The predicament is aggravated by other forms of structural breakdown within the biosphere also due to energy-intensive human industry. Among those examined in the previous chapter are the progressive destruction of the stratospheric ozone layer, the poisoning of crop land by industrialized agriculture, and the accelerating extinction of other species within the biosphere upon which humanity depends for its existence. There is hear unanimity among scientists currently studying such developments that human life as we know it is increasingly in jeopardy.

In one way or another, these developments are contingent upon the massive swell in human energy consumption beginning with the Industrial Revolution. The task of the present chapter is to gain a comprehensive perspective on how this predicament came about.

6.2 Energy consumption in pre-agricultural society

Our approach in this and subsequent sections will be to characterize each era to be considered with respect to (a) its typical energy sources, (b) its approximate per capita energy use, and (c) the population served by this energy consumption. We begin in this section with the era of hunter-gatherers.

Human beings most likely have not always been the biosphere's chief consumer of energy. As long as our ancestors fended for themselves individually (or in family groups), they probably lagged several species in per capita consumption—polar bears, elephants, walruses, whales, and perhaps various smaller animals that hunted in packs.

One reason is that both hunting and gathering are unreliable and often inefficient procedures. Only a relatively small portion of the planet's vegetation comes in forms humans can digest (fruits, grains, nuts, tubers), and these required foraging over wide and frequently shifting areas. As far as hunting is concerned, an individual's success rate with ungulates such as deer and antelope probably averaged one or two a week.[3] Although small herbivores like monkeys might be encountered more routinely, probabilities of hitting them with spears and arrows were probably rather low.

Estimates like these suggest that individual hunters had good reason to band together in groups where chances of a shared meal were several times greater. By working together, hunters could subdue large animals like mammoth in open combat, and could herd them into traps where they were easily slaughtered. Since a small mammoth provided the energy-equivalent of about 50 reindeer (Smil, *Energy*, 19), for example, each participant could walk away from a kill with more food energy than he could acquire in several days of solitary hunting.

Beyond shared fortunes in the hunt, another advantage of group participation was efficient division of labor. Designated adults could cut up the meat and carry it back to homebase (perhaps caring for infants simultaneously), allowing others to continue the hunt. Similar advantages were available in foraging groups, where some could prepare the food at hand while others went looking for further gleanings.

Assuming bands of 3-6 hunters, and an average family size of 6 per hunter (Smil, *General Energetics*, 101), we can estimate an average community size of 20-40 individuals.[4] Given the success of this arrangement over many millennia, we can also assume that people generally could rely on energy inputs sufficient to meet their basic requirements. This amount can be estimated as roughly equivalent to one billion joules per person per year, the amount needed to sustain the poorest of the world's people today (Smil, *General Energetics*, 200).

Average worldwide human population during this era has been pegged at 4-5 million (Ponting, *Green History,* 90; Goudie, *Human Impact*, 9).

6.3 The introduction of agriculture

Agriculture began with the transition from food collection to food production. The upshot of this transition is that food (plant and animal) is no longer gathered from the wild but rather grown deliberately under human supervision. Although accounts vary in specifics, there is general agreement that the agricultural era began between 6 and 9 thousand years ago (Smil, *Energy*, 23; McNeill, *Something New*, 8; Simmons, *Changing the Face*, 89).

In term of efficiency, raising crops had many advantages over foraging in the wild. Farmers could concentrate on crops best suited to their needs, and could avoid having to travel long distances in search of food. Once suitable farmland had been located, its yield could be improved by various techniques of irrigation and fertilization. And since farming communities tended to be relatively permanent, it became feasible to store food for use during unproductive periods. Another advantage was the diversification of labor made possible within the community. Some members could specialize in heavy work like clearing forests, others in repetitive tasks like weeding and harvesting, and yet others in domestic jobs like cooking and weaving.

As farming practices became more productive and surpluses developed, small communities expanded into established towns. Surpluses were needed to feed a growing number of specialists—administrators, soldiers, craftsmen, and merchants—not engaged directly in food production. Insofar as the services provided by these specialists tended to make food production more efficient and reliable, however, greater surpluses became available and expansion continued. Whereas agricultural villages contained only a few hundred people, the earliest known cities (e.g., Ur in Mesopotamia) probably contained several thousand people (Ponting, *Green History*, 295).

Several millennia passed, however, before the growth of cities had a major impact on world population. By 5000 BC the total was still around 5 million people, having risen perhaps a million since the era dominated by hunters and gatherers (Ponting, *Green History*, 90). Annual per capita energy consumption, on the other hand, increased several fold to the neighborhood of 6 billion joules (Simmons, *Changing the Face*, 24).[5]

6.4 Muscle-driven technology

Early agriculture was powered by human labor. A major step forward in productivity came with the introduction of draft animals around 3500 BC. Oxen and water buffalo apparently were domesticated first, followed by horses about 3000 BC (Ponting, *Green History*, 271).

Domesticated animals were employed to draw conveyances before they found use in farmers' fields. Once adapted to this latter use, however, animals became increasingly indispensable in the production of food. They provided a ready supply of nutrient-rich fertilizer, deposited conveniently just where it was needed. And they provided muscle power for farming techniques that were previously impracticable.

Prior to the domestication of oxen, cultivation of farm land was done with hoes. It has been estimated that a farmer working with a hoe needed upwards of 100 hours to prepare a hectare of land for planting. Given an average-sized ox pulling a simple wooden plow, the farmer could accomplish the same task in about 30 hours (Smil, *Energy*, 48). Although an investment of labor and land is required to keep farm animals fed, efficiency gains of this magnitude made farming with animals far more productive than anything achievable with human muscle power alone.

In addition to their usefulness in fertilization and tilling, animals also made big differences in irrigation. Although small quantities of water can be elevated (from wells and lakes) by hand-powered devices like buckets and Archimedean screws, traditional agriculture tended to avoid land that could not be reliably watered either by rainfall or gravity (via ditches from rivers). As animal power became available, however, devices were invented that could lift much larger quantities of water over greater heights. One such device was an escalator-like arrangement of clay pots that filled at the bottom and discharged at the top; another was a series of metal buckets on the rim of a large wheel turned by the circular motion of animals through a right-angle gear train (Smil, *General Energetics*, 120-121). Animal-powered irrigation both increased the productivity of established cropland and opened up new areas to cultivation.

Further improvements in productivity followed with more effective plow designs (Smil, *Energy*, 30-32), more efficient yokes and harnesses (Smil, *Energy*, 42-47), and the development of animal breeds better suited for regimented labor. It will be noted that improvements of this sort by and large are results of human ingenuity. While improvements in the use of animal power were still being made into the modern era, the basic technology was largely in place by 1000 BC (roughly the beginning of the Roman Republic).

By this stage in history world population had doubled several times over, approaching the neighborhood of 50 million (Ponting, *Green History*, 90). Per capita energy consumption also had increased significantly, to an estimated 13 billion joules per year (Simmons, *Changing the Face*, 24).

6.5 Technology, animal power, and additional forms of energy

Using animal labor in the production of human foodstuff was a major step in humankind's growing control of energy used for its own advantage. The fact that cattle can be used to plough fields, to haul loads, to turn water wheels, and then eventually be killed for meat, was enough to establish animal power as a mainstay of civilization up to the modern period. In many parts of the world today, including Amish farms in North America, agriculture still relies on draft animals as a major source of energy.

There nonetheless are obvious limits to the number of animals that can be made to cooperate in a given human venture. Further increases in per capita energy consumption in the centuries leading up to the Industrial Revolution were due largely to improvements in technology. On one hand, there were improvements in the equipment by which animal power was brought to bear. On the other, technological advances opened the way to harnessing new sources of energy.

An illustrative case of the former was the evolution of instruments pulled by animals for breaking up ground. Ards (hoe-like devices rigged for pulling), which were in use worldwide by 1000BC, gradually gave way to moldboard plows that could dig deep furrows in heavy soil. Cast-iron moldboards were common in China by the third century AD (Smil, *Energy*, 61). And cast-iron plows with wheels came into general practice after the technology was introduced in Europe during the early modern period (Smil, *Energy*, 70).

Parallel improvements were made in techniques for harnessing draft animals to their implements. Head yokes for oxen gave way to more efficient neck yokes, while throat-and-girth harnesses were replaced by breastbands as the preferred means of equipping draft horses. Given that a single properly equipped draft animal can produce the work-equivalent of three or more human laborers (Smil*,* *Energy*, 49), when large teams of animals are enabled to work together the gain in foodstuffs produced can be substantial. Developing technologies like these not only increased the amounts of food energy available per capita within farming communities, but generated surpluses for trade and for the expansion of urban centers as well.

Although animal labor continued to be important into the modern era,[6] technological improvements in the use of wind and water power were more influential in preparing for the arrival of the Industrial Revolution. Wind had been used to drive sea-going vessels since antiquity. During the early Roman era, sails were basically square in shape and were fixed perpendicular to the ship's main axis, which made sailing upwind difficult. By the end of the medieval period, however, major seapowers worldwide had ships with triangular sails and stern-post rudders (Smil, *Energy*, 137) which, in combination with deeper hulls, made them efficient converters of wind energy into humanly controlled motion.

On land, wind had been harnessed for human purposes as early as the eighth century AD. Early windmills were capable of roughly the same amount of power as a term of horses (Smil, *General Energetics*, 301). Steady improvements in design and construction increased their efficiency several times over, until they became the most powerful sources of energy available in areas without water power (Smil, *Energy*, 108). Wind power was still used extensively in Northern Europe and the United States during the early stages of the Industrial Revolution (Smil, *General Energetics*, 142).

The history of water power, in turn, goes back at least to the first century BC, when horizontal water wheels were used to mill grain in Egypt (Ponting, *Green History*, 274). According to the Domesday Book of 1086, thousands of stream-driven grist mills were then operating in parts of England (Smil, *Energy*, 103). Improvements in technology of water wheels led from the early horizontal version (wheel level with stream), through vertical arrangements (water running under or over an upright wheel), to radical water turbines of the early 19th century (water swirling under pressure toward directly-facing blades). Water wheels were instrumental in the engineering of deep underground mines, which required continuous power at a high level of reliability.

Another form of water power to be noted is that provided by fluctuating water levels in ocean tidal basins. The first tidal mill was built near Venice in 1044 (Ponting, *Green History*, 275), and more sophisticated versions were still being used in England some 800 years later. Because of siting limitations, the contribution of tidal mills to early industry was relatively minor.

Although these are the chief forms of energy associated with the developing technology of this era, there are several others that deserve brief mention. One such is gunpowder, knowledge of which traces back at least to the ninth century AD (Smil, *Energy*, 114). Apart from its use in fireworks, the role of gunpowder in human history has to do primarily with violence and warfare. This, however, does not justify our overlooking the relatively peaceful role of blasting powder in the excavation of mines and quarries (http://www.cumbria-industries.org.uk/gunpowder.htm).

Also worth mentioning is the fact that fossil fuels did not have to wait for the 18th century to play a part in human industry. As early as 200 BC, the Chinese burned natural gas to evaporate brines (Smil, *Energy*, 167). Oil wells were being hand-drilled in Burma in the 10th century AD (Simmons, *Changing the Face*, 199). Most of the coal fields in England were being worked by the early 1600s (Smil, *Energy*, 159); and by 1700 England and Wales had an output of about three million tons of coal a year (Simmons, ibid.). These uses presaged the massive shift to fossil fuel that marked the Industrial Revolution itself.

As mankind moved into the industrial age, it had devised techniques to harness not only the muscle-power of other animals, but also the kinetic energy of wind and water, the gravitational energy of the tides, the solar energy stored in fossil fuels, and the chemical energy of gunpowder.

Over the course of this pre-industrial period, in summary, improvements in technology had doubled the average energy consumption per person to approximately 38 x 10^9 joules (Simmons, op. cit., 24). World population, in turn, had doubled several times to something in the neighborhood of 600-700 million people (Ponting, op. cit., 92; Goudie, op. cit., 10; Simmons, op. cit., 104).

6.6 Industry and the ascendancy of fossil fuel

Between 1750 and 1900, technologically advanced countries in Europe (led by England) moved gradually from agrarian economies to economies dominated by machine-driven industry. This transition, commonly known as the Industrial Revolution, was epitomized by the development of efficient steam engines in the 1760s and by the invention of the internal combustion engine roughly 100 years later. By the beginning of the 20th century, use of these new power sources had spread worldwide (making possible WWI), and the period of transition had given way to the industrial age in which all countries to some extent participate today.

Although steam engines can also operate on biomass fuels (wood or charcoal), the efficient versions that got the Industrial Revolution underway depended primarily on coal. And while the first internal combustion engines ran on coal gas (Smil, *Energy*, 168), commercially successfully designs relied on fuels refined from oil (diesel or gasoline). Demand for fossil fuels increased with the harnessing of electricity as a commercial power source, inasmuch as most generators in operation by 1900 were run by steam turbines powered by coal (Smil, *Energy*, 170).[7] The result of these combined influences was a massive increase in use of fossil fuels, accompanied by a proportionate decrease in reliance on renewable energy sources.

Independently of amounts consumed, the shift to fossil fuels resulted in dramatic changes in the methods by which consumer goods are produced. Prior to this period most goods were either handicrafted locally (the so-called "cottage industry" system) or produced in small mills usually driven by water wheels. Given the superior power outputs of fossil-fuel driven steam engines, however, methods of production became organized in the form of centrally powered mills and factories. Many of the technological innovations made during this period had to do with machinery that could be driven by centralized power units (e.g., Cartwright's power loom and Crompton's spinning mule).

Among the social consequences (many quite disruptive) of the resulting factory system was the amassing of large numbers of workers in workplaces where they could be assigned specific tasks that could be effectively supervised. Combined with standard economies of scale (fixed costs covering increasing amounts of goods produced), more efficient use of labor enabled goods to reach the market at prices considerably lower than had been commanded previously. Inasmuch as goods mass-produced in this fashion tended at fist to be staple items, consumers of these products generally found less of their incomes being taken up by basic necessities.

As a result of this tendency, increasing numbers of people with ordinary incomes had money left over for what previously had been considered luxuries. More people were able to afford tea and spice imported from the Orient, more people were enabled to acquire fine clothing and dinnerware, and more had both leisure and means to spend vacations abroad. As the luxury market expanded, moreover, new ways were made available to dispose of extra income. The first passenger railway opened in England in 1825, an iron ship for passenger travel was launched in 1843 (Simmons, *Changing the Face*, 201-202), and privileged New Yorkers had the choice of electric lighting by 1882 (Smil, *Energy*, 170). A defining moment of the Industrial Revolution was the Great Exhibition of 1851 in London's Hyde Park (Hughes, *Environmental History*, 120), in which many items displayed were intended for luxury consumption.

In sum, whereas technological innovations during previous eras tended to provide better ways of doing things that people were doing already, technology during the Industrial Revolution was directed increasingly toward providing goods and services that were not previously available. Not only did the technology producing these benefits use up increasing amounts of fossil energy in its own right, but the machinery involved in delivering them (railways, ocean liners, electricity systems) became increasingly energy intensive. The benefits in question also became available to increasing numbers of people. The upshot of these tendencies in combination was a massive increase in energy consumption during the early stages of the Industrial Revolution.

By the end of this period (1900), per capita energy consumption worldwide stood at about 56 billion joules a year (Smil, *Energy*, 187).[8] World population at this time was in the neighborhood of 1.6 billion (Goudie, op. cit., 10; Ponting, op. cit., 241; et. al.).

6.7 Energy use and population

Annual per capita energy consumption estimates for the periods treated thus far are repeated below in the form of a simple graph.

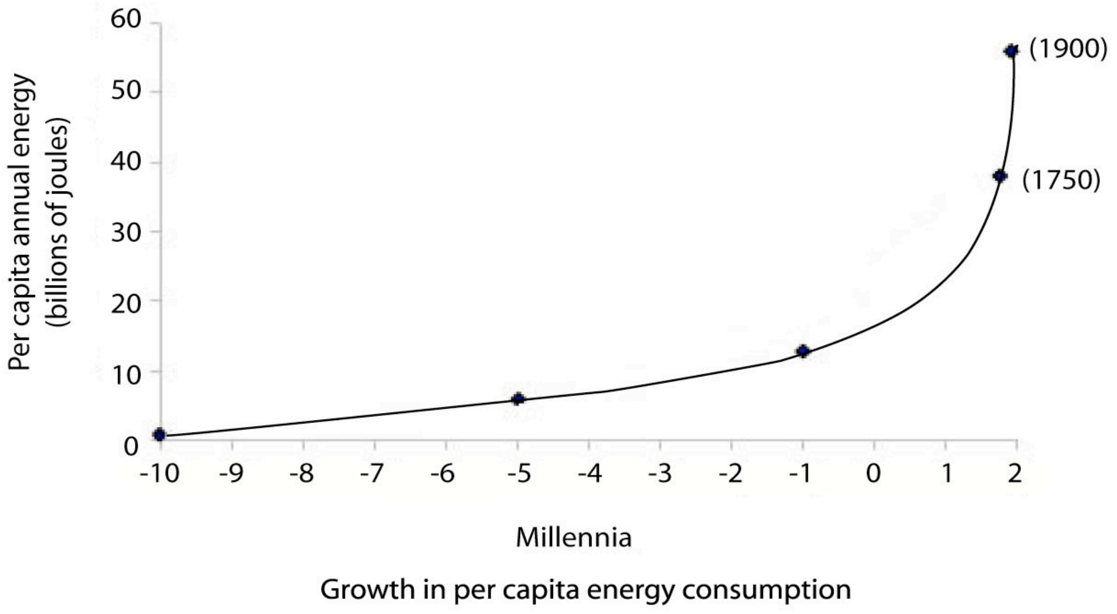

Figure 6.1

Points determining the shape of this curve are taken from estimates documented in sections 6.2 through 6.6 above. Despite the necessarily tentative character of these estimates, the graph clearly exhibits the form of an exponential progression.

Growth in world population for the same stretch of time may be shown on a separate graph, as follows:[9]

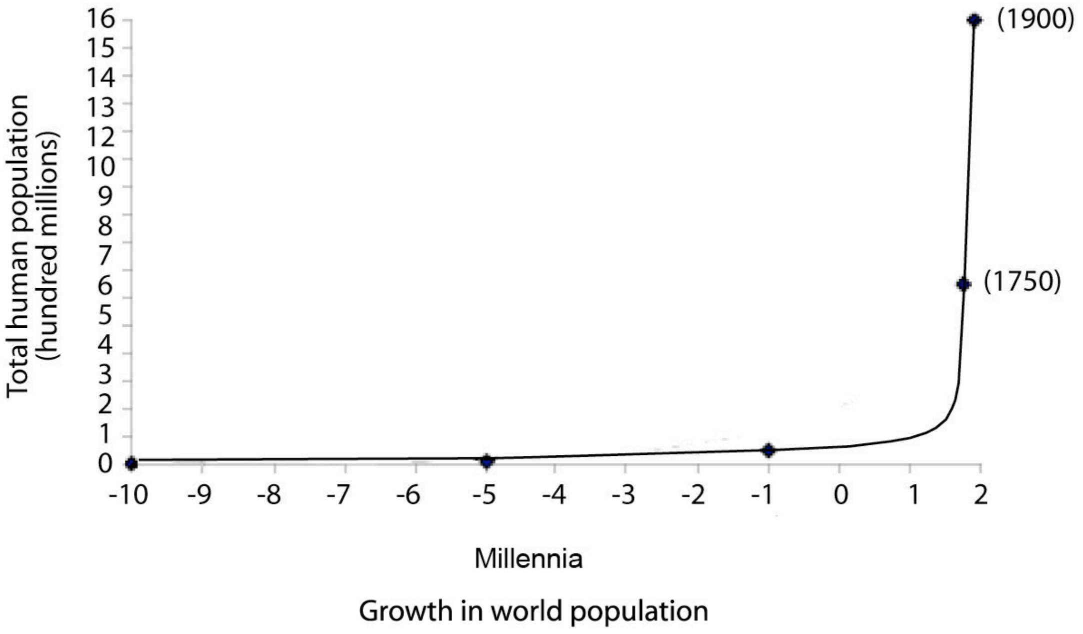

Figure 6.2

The curve here is notably similar to that above, although steeper from 1000 BC to 1750 AD (due in part to recurrences of bubonic plague) and correspondingly straighter on either end.

Multiplying population times per capita energy use at any given point, of course, would give total energy consumption for the time in question. There are several reasons, however, for keeping the two sets of data separate, rather than presenting them in combination.

One reason is that total human energy consumption from the 18th Century onward has been increasing at rates too steep to illustrate on a simple linear (nonexponential) scale. In point of fact, when the curve of Figure 6.1 is imposed on that of Figure 6.2, the result exhibits a rate of increase approximating that of a chemical explosion. Gunpowder, for instance, oxidizes (i.e., burns, producing heat) at a rate increasing exponentially with temperature. The positive feedback process involved progresses so rapidly that the resulting explosion appears instantaneous. What we see depicted in Figures 6.1 and 6.2 together is an "explosion" in humane use of energy. The severity of this exponential progression is more evident if its two major components are presented separately, thereby showing that each component is subject to exponential increase itself.

Another reason for separate presentations is to counter the assumption that increase in overall energy use during recent centuries is due primarily to increase in population. As the preceding discussion has shown, there are factors of both sociological and technological nature that have had major effects on the increasing amount of energy consumed by individual humans. While it undoubtedly is the case that human energy consumption would not have increased so dramatically over the past several centuries without accompanying increases in total population, an important condition for understanding our present dependence on fossil energy is to realize that it does not stem from population growth alone.

A third reason is that separate treatment of the growth processes depicted in Figures 6.1 and 6.2 invites reflection on the manner in which these two processes in fact interact. It seems clear, on the one hand, that population growth in localized social groups often is accompanied by growth in social complexity. And growth in social complexity can provide resources, like administrative oversight and division of labor, that enable a group to make more energy available to its individual members. On the other hand, several authors have suggested ways in which increasing amounts of energy use per capita might lead to increasing numbers of people taking advantage of energy surpluses (e.g., Ponting, op. cit., 38, 42; Smil, *Energy*, 22; Hughes, *Environmental History*, 48). We will look more carefully at these suggestions later, in connection with the relation between population and economic growth.

6.8 Energy use in the 20th century

The worldwide output of fossil fuels surpassed the total amount of biomass fuel consumption just before 1900 (Smil, *Energy*, 187). While use of biomass energy continued to increase gradually during the 20th century (by a factor roughly of 1.75), consumption of fossil fuel during that period increased many times over. The upshot of these trends is that over 90% of fuel consumed by human activity today has fossil origins.

Since coal already was in extensive use before 1900, its continued use in the 20th century expanded at a slower rate than that of either oil or natural gas. Annual worldwide use of coal grew from about 800 million metric tons in 1900 to about 4,000 million in the 1990s.[10] This amounts to a five-fold increase over a period of 100 years. World consumption of oil, on the other hand, increased from about 20 million metric tons in 1900 to about 4,000 million in the 1990s, an increase of almost 200 fold. And total annual consumption of natural gas during that period went from about 7 billion cubic meters to about 2,000 billion, amounting to more than a 280-fold increase.

When these three categories of fossil-fuel use are taken together, a remarkable pattern of growth emerges. From 1900 to the end of the century, human use of fossil energy increased almost 21 fold, from about 480 to about 10,000 million tons of oil equivalent.[11] This compares with the 1.75 fold increase noted above for biomass energy. Superimposing the steeply climbing curve for fossil fuel upon the gradually rising curve for biomass energy, we see an increase from roughly 960 million metric tons annual oil-equivalent consumed in 1900 to roughly 10,600 million in the late 1990s. This constitutes approximately an eleven-fold increase in overall human energy use during the 20th century.

This pattern seems all the more remarkable in contrast with the growth in overall energy use during the Industrial Revolution itself. In 1750, humankind consumed roughly 260 million oil-equivalent tons of energy. By 1900, the annual total had grown to about 900 million. This amounts to something less than a 4 fold increase in 150 years. The corresponding increase for the 100 years between 1900 and 2000 was three times greater. If we were to graph this increase on the millennium scale employed in Figure 6.1, the line of increase would show an almost vertical rise.

Rather than attempt to represent the pattern graphically, we may express it in terms of doubling times. The 4 fold increase between 1750 and 1900 constitutes a doubling every 75 years. This doubling rate generates the tail of the curve in Figure 6.1 that takes on the appearance of an "explosion" in energy use (section 6.7). By contrast, energy consumption during the 20th century grew at a doubling rate of 25 years. When one thinks of the astounding acceleration in energy use that occurred within the span of only a few decades, it is hard to avoid the image of an explosion that has reached its final stages.

Let us view this from the standpoint of per capita consumption. From 1900 to 2000, human population worldwide grew from about 1.6 to 6 billion. Total human energy use by 2000, given the estimate quoted above, stood at about 10,600 metric tons oil-equivalent per annum—the equivalent of 424 x 10^{18} joules. This latter figure divided by 6 billion comes to about 71 billion joules per person per year.

During the period between 1,000 BC and the beginning of the Industrial Revolution, per capita annual energy consumption grew from 13 to 38 billion joules, which amounts to a growth of roughly one billion joules per century. During the 150 years of the Industrial Revolution, per capita annual consumption grew from 38 to 52 billion joules, on increase of about 9.3 billion joules per century. During the 20th century alone the figure increased another 19 billion joules. This pattern of growth by itself has the appearance of an exponential increase. The massive human expenditure of energy that the biosphere has to cope with today is due to more than a rapidly growing population. It has to do as well with the enormous amounts of energy we are consuming as individuals.

6.9 Entropic consequences of our accelerating use of energy

Increasing energy use by humans is not necessarily a bad thing. It may be viewed merely as part of the general tendency for biological processes through the ages to take up ever larger portions of incoming solar energy. When life first appeared on earth, the proportion of solar energy going into metabolic processes was negligible. During recent times, that proportion has increased to about one percent of incoming energy (section 4.2). Given that humankind is only one among millions of species, the increases in human energy consumption documented in the previous section contribute only a small portion of that one percent.

The entropy resulting from this recent surge in human energy consumption, however, cannot be so easily dismissed. As stated in the Second Law of thermodynamics, every unit of energy expended within an operating system gives rise to a corresponding unit of useless entropy (Chapter 1). In the case of the biosphere, this means that all energy consumed within it is degraded into forms no longer capable of doing work. Whatever form this entropy takes, it must be expelled for the biosphere to provide continued support for its top consumers (section 4.8).

Several forms of entropy resulting from human activity have been examined earlier in this chapter. One is low-grade heat, which humans produce in common with all living organisms. Low-grade heat is discharged from the biosphere by black-body radiation. Because of interference from other forms of entropy resulting from human activity, however, the mechanisms of black-body radiation have ceased to function normally. As we have seen, this has resulted is the current crisis of global warming.

Another form of entropy mentioned previously is material waste. Biological waste material is usually decomposed into compounds capable of providing nutrition to producer organisms (plants and algae), while the low-grade heat resulting from decomposition leaves the biosphere as black-body radiation. Increasingly prominent among waste products of human industry, however, are toxins that poison the decomposers and plastics that are not subject to decomposition. Once again we find circumstances in which humanly produced wastes impede the processes by which other wastes are removed from the biosphere.

The third form of entropy considered previously is degraded functional structure. Functional degradation is occurring on a massive scale today as a result of species extinction brought about by human activity. Inasmuch as functional structure is immaterial (in the sense of section 4.4), its degraded form, unlike plastics and low-grade heat, is not a substance in its own right. Accordingly, it is not something that ideally might be eliminated from the biosphere. The humanly-imposed impediment in this case thus is not an *interference* with the processes by which entropy is removed, but rather a proliferation of *circumstances* in which its removal is essential for ecological stability. Removing entropy (disorder) in such circumstances boils down to regaining the structure (order) lost by the ecosystems in questions.

This is a process requiring both time and energy. The time at issue is the time taken to regenerate the ecosystems affected, or more likely to replace them with other ecosystems. And construction of ecosystems proceeds at an evolutionary pace, spanning decades or even centuries.[12] As far as energy is concerned, augmenting the functional interactions within a given ecosystem generally calls for increasing its number of participating species, which in turn involves increasing the amount of energy expended within the system.[13] The energy required may not be readily available, inasmuch as the species to be replaced may have vanished for causes affecting species on lower trophic levels as well (consider the massive destruction of tropical rainforests).

Reflections along these lines show that the entropy stemming from human activity is not merely a negligible component of the large quantities of entropy generated within the biosphere overall. To the contrary, humanly-generated entropy tends to take particular forms that actually disrupt the discharge of entropy produced by other biological processes. One lesson we learned in Chapter 3 is that living organisms need to rid themselves of the entropy they inevitably produce in order to continue living. By impeding the processes by which other organisms discharge their entropy, human activity is undermining the structure of the biosphere itself.

6.10 Possible solutions anticipated

Before the Industrial Revolution, entropy produced by human activity by and large remained confined to where it originated. Even when local populations abused their habitats in ways that made them uninhabitable (think of the Easter Islanders), the rest of the biosphere remained relatively unaffected. By the end of the 19th century, however, the disruptive by-products of industrialization had begun to spread far beyond their points of origin (Ponting, op. cit., ch. 16). And by the late 20th century, the entropy stemming from human activity—global warming, plastic junk, decreasing biodiversity—was adversely affecting biota in all parts of the globe.

It is largely because of human intrusions like these that the biosphere has been degraded to the point of seriously threatening the well-being of its top consumers. Among people who have thought about the situation long and carefully (and without political partisanship), there is general agreement that human life as we know it is increasingly in jeopardy. The urgent question at this juncture is what can be done about it.

One response that springs to mind immediately is that we should cut back on use of fossil fuels, or even stop using them entirely. After all, fossil fuels contributed the lion's share of energy consumed the last century; and most of the noxious by-product now clogging up the biosphere are petrochemical in origin. To give up fossil fuels entirely, however, would result in misery and poverty for billions of people, which removes it from the realm of acceptable solutions.

Cutting back on the use of such fuels, on the other hand, seems both possible and socially desirable. But unless everyone cooperated in reducing their use, this approach would do little to alleviate our current predicament. Conservation of fossil energy may be part of the answer, but by itself will not solve our environmental problems.

Continuing to explore the realm of the possible, we find various other approaches that deserve consideration. One falls under the general category of technical solutions. Given that most of our environmental problems are technological in origin, it has been argued that many of them can be solved by technological means. Another approach focuses on the advantages of “clean” energy. Observing that many ecological problems stem from consumption of fossil fuel, its advocates suggest that these problems could be overcome by increased use of solar and wind power. Yet another approach views our quandary from an economic perspective. Thinking of environmental integrity as a scarce commodity, its advocates contend that our predicament can be resolved by economic incentives.

Each approach is worth examining in detail. Doing so will enable us to weigh their strengths and weaknesses, as well as to gain further insight into the causes of our environmental plight. Knowing the cause is a prerequisite for prescribing remedies. Part Two of this study is given over to an examination of alleged causes as diagnosed by the several approaches above. Part Three is reserved for consideration of possible remedies.

Notes

1. Responsible estimates vary between 150 and 500 thousand years. Counting the beginning of life (about 3.5 billion years ago) to the present as a single day, we may date the beginning of our species as occurring within the last few seconds.

2. Celluloid, the first commercially successful plastic, was introduced by its inventor, Alexander Parkes, in 1862.

3. Vaclav Smil, *General Energetics: Energy in the Biosphere and Civilization* (John Wiley & Sons, New York, 1991), p. 101. Subsequent references to this book will occur within parentheses in the test, citing short title and page number. Other books to be referenced in this manner include: Vaclav Smil, *Energy in World History* (Westview Press, Boulder, CO, 1994); Andrew Goudie, *The Human Impact on the Natural Environment* (The MIT Press, Cambridge, 1981); I.G. Simmon, *Changing the Face of the Earth* (Basil Blackwell, Oxford, 1989); Clive Ponting, *A Green History of the World* (Penguin Books, New York, 1991); J.R. McNeill, *Something New Under the Sun: An Environmental History of the Twentieth-Century World* (W.W. Norton & Company, New York, 2000); and J. Donald Hughes, *An Environmental History of the World: Humankind's Changing Role in the Community of Life* (Routledge, London, 2001).

4. Estimate varying with geographic area. Semipermanent settlements in salmon and whale territories may have included several hundred people.

5. Simmons estimate 12 million calories per diem for early agriculturists, which converts to about 19 billion joules per annum (one calorie is equivalent to about 4.2 joules). This figure has been reduced by a factor of three in the text above, under the assumption that even after farming became prevalent in certain areas the people involved constituted a relatively small proportion of the human population worldwide. Although estimates like Simmon's are based in part upon observation of presumably similar farming cultures exiting presently (op. cit., 40, 47-49), it should be understood that they are approximations at best.

6. A major use of draft animals in the 20th century was for purposes of military logistics. Ponting notes (op. cit., 272) that the British army used 1,200,000 horses during WWI, and that the Germans (despite their mechanized Panzer divisions) used 2,700,000 horses during WWII.

7. This despite the construction of the first major hydroelectric plant at Niagara Falls in 1886 (Ponting, *Green History*, 286).

8. As pointed out previously, per capita energy use estimates for earlier periods are based on extrapolations from comparable present day circumstances. Estimates from the industrial era, on the other hand, come largely from sources recorded during the period in question.

9. Population data for recent centuries are available from many sources. Entries for earlier times are taken from estimates documented in relevant sections above. A graph showing basically the same progression can be found in Goudie, op. cit., 10.

10. Unless noted otherwise, figures in this section come from Smil, *Energy*, 186-187.

11. Smil, op. cit., 187. Smil's graphs here lump fossil fuels with primary electricity (wind, hydro, tidal, and geothermal), which affect the overall pattern only marginally (Smil, op. cit., 188). Lester Brown, in *Eco-Economy* (W.W. Norton & Company, Inc., New York, 2001), 112, using more recent data, reports about 8,000 million oil-equivalent tons for the year 2000, giving an increase of 17 fold.

12. An ecosystem differs from a mere collection of organisms in that its members are related by distinct patterns of functional interaction. These patterns evolve by a process known as ecological succession. Succession generally involves a gradual replacement of fast growing by more slowly growing organisms, along with a growth in complexity of the interactions among these organisms. Ecologists often use the term 'assembly' in reference to this process, the sense being that succession amounts to "constructing" or "putting together" functioning ecosystems.

13. According to the "species-energy theory" currently debated among ecologists, increasing amounts of energy available to an ecosystem tend to reduce the breadth of its niches and thus to increase the variety of species it can accommodate. More species within an ecosystem is tantamount to more contenders in the evolutionary process of succession by which the functional structure of an ecosystem is assembled (see previous note 12). For an early exposition of this theory, see D.H. Wright, "Species-energy theory: an extension of species-area theory," *Oikos* 41, 498-506, 1983.