What Is Energy and How Is It Related to Wealth Production?

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14.1 Energy: The Unseen Facilitator

Energy is, at best, an abstract entity for most contemporary people. Only rarely does it enter our collective consciousness, generally in those relatively rare times when there are particular shortages or sharp price increases in electricity or gasoline. In fact, as this book will demonstrate, energy and its effects are pervasive, relentless, all-encompassing, and responsible for not only each process and entity in nature and our own economic life but also for many aspects of the basic nature of our psyches and many of the ways that world history has unfolded. Few understand or acknowledge this because the pervasive impact in energy shown in this book does not usually enter into our collective training and education, and it does not enter into our educational curricula. Why is this so? If energy is as important as we believe then why is that not more generally known and appreciated? The answers are complex. One important reason is that the energy that is used to support ourselves, our families, or our economic activity generally is used at some other location and by other people, often in order to reduce environmental impacts on people, or by quiet, automatic machines whose fuel tends to be relatively cheap. After all, coal, oil and gas, our principal sources of energy, are basically messy, smelly, dangerous, and unpleasant materials. The energy from food that we need to fuel ourselves surrounds most of us abundantly and is available readily and relatively cheaply. Society has gone to great lengths to isolate most of us physically and intellectually from the energy sources upon which our food, our comfort, our transportation, and our economy depend. It is convenient to ignore energy because many facts about it are uncomfortable to know.

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Perhaps a more important reason for our failure to understand the pervasive role of energy is that most uses of energy are indirect. Humans are conditioned, both evolutionarily and in their social education, to want and need the goods or services rendered by energy, but not energy itself. In fact energy per se, with the exception of food energy and warmth in winter, is hardly ever desirable or useful directly. This conditioning, however, does not diminish the requirement for energy for virtually everything that we do, nor compensates for the fact that our use of energy has become enormous in contemporary life. Today each average American has some 60 to 80 slaves toiling tirelessly to keep us at about 70 degrees, well fed, mobile, entertained, and so on. Where are these slaves? We can see the car engine, the furnace, or the air conditioner, but who is aware of the electric pump supplying water or running the refrigerator or the massive electrical and fossil-fueled devices digging up the Earth to bring us the energy to run these devices. Who thinks about the energy required to make the metals and plastics in our car; the timbers and concrete in our homes, offices, and schools; or the paper in this book? But they all require it, and a lot of it.

Another reason that we do not think much about energy is that energy today remains enormously cheap relative to its value. If we want water delivered to our house, we might hire a person to do the job. A very strong person can work at a rate of about 100 watts so in a 10 hour day could do 1000 watt-hours (1 kilowatt-hour) of work, say hauling water from a well to our sink or shower. If we paid that strong person at minimum wage, he or she would charge about 80 dollars for the 10 hours' work. But if we installed an electric pump, we can get the same work done for about ten cents per kilowatt-hour. Since humans work at about 20% efficiency but electric pumps perhaps 60%, the relation is tipped even more in favor of the electric pump. So, to do the same physical work with a person that a pump could do would cost about 800 times 3 or 2400 times more with the worker compared to the electric motor! So this is the main reason that an average American or European today is far richer than the richest king of old—we have cheap energy to supply us with the necessities and luxuries in life. A problem is that we have become dependent in many ways upon this cheap energy and the goods and services it supplies. The value of this energy is far more than what we pay for it, because the services energy provides is far more valuable than its monetary cost. Additionally its potential abundance is much more limited than our dependence would imply.

14.2 A History of Our Understanding of Energy

Two hundred years ago, no one understood energy as a concept, although they certainly understood many practical consequences such as plants needing sunlight for growth and the need for wood to do many economic things such as cooking and making metals or cement. Any concept of energy was tied up in confusion, often mystical, about the actual results of energy use, because energy cannot be seen or felt and only its effects can be observed. Fire was thought of as a basic substance (as in earth, air, fire, and water) rather than as the energy released from the destruction of chemical bonds generated earlier by photosynthesis and the formation of new bonds with oxygen. How could people then possibly understand energy if they did not have any concept of chemical bonds, oxygen, or chemical transformations? How could they possibly understand that the growth of plants, the work of a horse, the erosion of water, the heat generated by fire, and their own exertions had some common something that tied them all together? To them they were independent entities. The failure of educated people to understand energy comprehensively as the principles of economics were being developed was probably the principle reason that economics developed as a social, rather than more powerfully as a biophysical, science.

As in most other things in their life that they did not understand, ancient people attributed energy, or at least some aspects of it, to a god or gods: the sun, of course, was worshiped by many cultures who understood clearly its importance for their food and warmth, but there were many other energy gods or special energy-related entities: Prometheus, Hephaestus, Pele, Vesta, Hestia, Brigid, Agni, and Vulcan to name a few. These people had no possible way to see that there were common concepts linking the sun and the fire resulting from burning wood, nor could they understand that so many other processes that they also attributed to different gods (wind, rain, agriculture, the existence of wild creatures, and so on) were also connected to the sun. The knowledge that a sharp sixth grader today has about energy and science in general would be far beyond what the most learned person would understand 400 or even 200 years ago. We have learned an astonishing amount about how the world really works through science. Even today, however, we cannot measure energy directly but only its effects! But we have become much better at that and in understanding how all of this is related.

During 200 years, from roughly 1650 to 1850, a series of remarkable discoveries and experiments, mostly from French, Scottish and English scientists, allowed us to understand in a comprehensive way the essentials of energy. First and foremost among these were the remarkable discoveries of Isaac Newton. Newton discovered the three laws of motion, and in the more than 350 years since then no fourth law has been discovered! He also derived the law of universal gravitation and wrote critically important books on optics. Nevertheless by his own admission, he did not understand economics, and he lost most of his money on an ill-advised investment scheme. He said "I can calculate the motion of the heavenly bodies, but not the madness of the crowd."

14.3 Newton's Laws of Motion

The first law says that a body in motion (and this includes no motion, i.e., rest) tends to stay in that state unless acted upon by an outside force. This is completely counterintuitive, as most moving things come to a stop! But Newton realized that it was an outside force, friction, that caused them to stop, and if there were no friction they would continue in their path indefinitely. The first law explains many things we experience—the momentum of an automobile when we put in the clutch, the path of a baseball (although we need to include gravity), and even centrifugal force.

The second law says that the acceleration of an object, say a baseball being hit, equals the force applied to the object divided by the mass of the object. It is familiarly written as:

$$F = MA$$

which can be rewritten as:

$$A = F/M$$

Thus a powerful baseball hitter, such as the legendary Babe Ruth, was capable of applying great force (F) to a baseball with his bat, accelerating it greatly (A), and giving it enough velocity (sometimes) to travel out of the ball park. The force that he applied could be measured by measuring the mass (M) of the baseball and the amount that the ball was accelerated. If one could make a baseball twice as heavy with a lead core, it would, other things being equal, be accelerated only half as much.

Newton's third law of motion says that for every force, there is an equal and opposite force. This is evident when you are in a small boat and move your body one way and the boat moves in the opposite direction. It is obvious to anyone who has fired a rifle that the gun moves back against your shoulder when the bullet is accelerated forward. It was also obvious to early designers of ship-borne cannon that if proper arrangements were not made the recoil of the cannon could do more damage to the ship shooting it than to the target!

Newton also determined the "universal law of gravitation" that two bodies would attract each other as the product of their masses and the inverse of their distance squared. This law is so powerful that it can be used to explain essentially perfectly the orbits of planets around the sun, the movement of a hit baseball, or the relation of electrons to the nucleus of molecules.

Probably the most important results of Newton's work are that it showed that the physical world followed definite laws that appeared (and still appear) to never be broken no matter where or when applied and that many of these laws could be expressed by simple mathematical equations. Although the concept of energy was not yet known to Newton, we now understand that energy was related to matter by the relation of force to mass. In the hundreds of years of science that has followed, many have tried to find simple, elegant mathematical laws that were as powerful as Newton's, but with the exception of Albert Einstein and James Clerk Maxwell, few succeeded.

The essence of what "force" (as in Newton's second law) was, where it came from, and how it changed over time remained elusive. The next important step in our understanding was the understanding of the relation of physical energy to heat. It was obvious that over time a lot of fuel wood was needed to run any major production process. Also, it was certainly apparent to observers that many physical actions were associated with heat, as was obvious by the heating of turning wagon wheels or a hard working horse or person, or the drilling of the hole in a cannon. But why this should be or what it meant remained elusive.

14.4 The Mechanical Equivalent of Heat

Many early scientists and engineers, seeing and understanding the tremendous force made possible when water was heated to form steam, were interested in building engines to do mechanical work. Thomas Savery built the first heat engine as early as 1697. Although his and other early engines were crude and inefficient, they could do a lot of work, and they attracted the attention of the leading scientists of the time. Classical thermodynamics as we know it now evolved in the early 1800s with concerns about the states and properties of everyday matter including energy, work, and heat. Sadi Carnot, the "father of thermodynamics," published in 1824 the paper that marked the start of thermodynamics as a modern science. Its title was "Reflections on the Motive Power of Fire, a discourse on heat, power, and engine efficiency" which outlined the basic energetic relations among the Carnot engine, the Carnot cycle, and motive power. This small volume gave for the first time the basic relations between input energy and the necessary transformation of a part of it to heat as work was done. It also derived a means of calculating the maximum efficiency that a machine could obtain as a relation between the temperature of the input energy and the temperature of the environmental sink to which the final heat was exhausted:

$$W = (Ts - Te)/Ts$$

The Carnot efficiency of heat-to-work conversion of an ideal heat engine that receives heat of high absolute temperature, Ts, from a source (e.g., a furnace) and rejects heat of lower temperature $Te < Ts$ to a sink (e.g., a river). By definition, it cannot exceed 1. This equation explains why despite the vast amount of heat stored in, for example, the surface of the North Sea in summer so little work can be done from it: the difference between the surface temperature (30 degrees) and the deepest water (2 degrees) is too small compared to, say, the temperature difference in an oil fired power plant, where temperatures at the turbine entrance may reach 817 degrees C and the cooling water might be from 6 degrees (winter) to 17 degrees (summer). It also explains why power plants are slightly more efficient in winter.

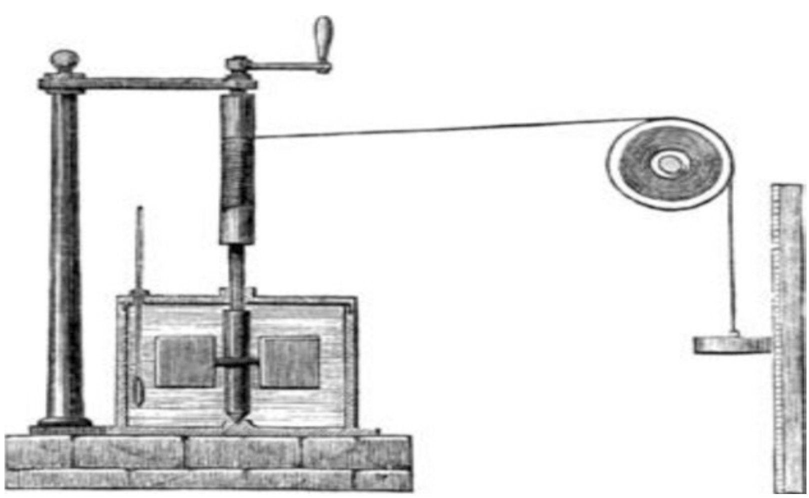
Only a few hundred copies were published, and Carnot died thinking his work had had no impact. But a few copies were found by others who developed the concepts further. The term *thermodynamics* was coined by James Joule in 1849 to designate the science of relations between heat and power. By 1858, "thermodynamics," as a functional term, was used in William Thomson's paper "An

Account of Carnot's Theory of the Motive Power of Heat" [1]. The first thermodynamic textbook was written in 1859 by William Rankine, originally trained as a physicist and a civil and mechanical engineering professor at the University of Glasgow.

The quantitative study of the relation between heat and mechanical work was undertaken further by Joule and Benjamin Thompson (also known as Count Rumford) who was astonished when he found that by immersing newly cast brass cannon into water while boring the hole in them using horse drawn power, he could actually make the water boil. He and other onlookers were astonished that they could generate heat without fire. The fact that the water would boil for as long as the horse kept turning the drill killed the earlier dominant "phlogiston" theory that heat was a substance that flowed from one object to another—because it never ran out! Great progress was made in understanding energy relations by Julius von Mayer and James Joule who measured "the mechanical equivalent of heat" by taking a pulley and rope, attaching a weight to one end and wrapping the other end of the rope around a shaft that went into an insulated water chamber where it operated a paddle wheel (◘ Fig. 14.1). As the weight dropped (doing so many kilogram meters of mechanical work), the increase of temperature inside the chamber could be measured. By doing so, Joule found that one newton-meter of work (or 7.2 foot pounds) was equivalent to 1 joule of heat energy. We now use the joule as the preferred unit of energy. It is equal to about the energy of picking up a newspaper.

More commonly we use larger units. The kilojoule (kJ) is equal to one thousand joules. The average amount of solar energy received per second by one square meter of the Earth's surface is 239 joules (i.e., the solar constant ± the albedo (reflectance) divided by 4, the ratio of Earth's surface to Earth's cross section). Thus, one kilojoule is about the amount of solar radiation received by one square meter of the Earth in about 4 s. The megajoule (MJ) is equal to one million joules or approximately the kinetic energy of a one-ton vehicle moving at 160 km/h (100 mph). The gigajoule (GJ) is equal to one billion joules. A gigajoule is about the amount of chemical energy in 7 gallons of oil. A barrel of oil has about 6.1 GJ.

Also in England and France, another very important discovery was made in the 1770s, that of oxygen. Probably Joseph Priestly in England discovered oxygen a little earlier than did Antoine Lavoisier in France, although the latter probably understood its significance better while quantifying its abundance and reactions (◘ Fig. 14.2). Both derived oxygen by heating oxides of mercury. Lavoisier discovered that the atmosphere contained oxygen or "eminently breathable air" by showing that an animal lived longer in a container of pure oxygen than in a container of air. He also clarified the role of oxygen in combustion and the rusting of metal and its role in animal respiration, recognizing that respiration was "slow burning." He also came up with the basis for the law of conservation of matter by showing that after a chemical reaction the elements always weighed the same as they did before the reaction.



◘ **Fig. 14.1** Joule's machine for measuring the mechanical equivalent of heat or perhaps better said as the quantity of heat released per unit of mechanical work done (Source: 2009 ► citizendia.org)

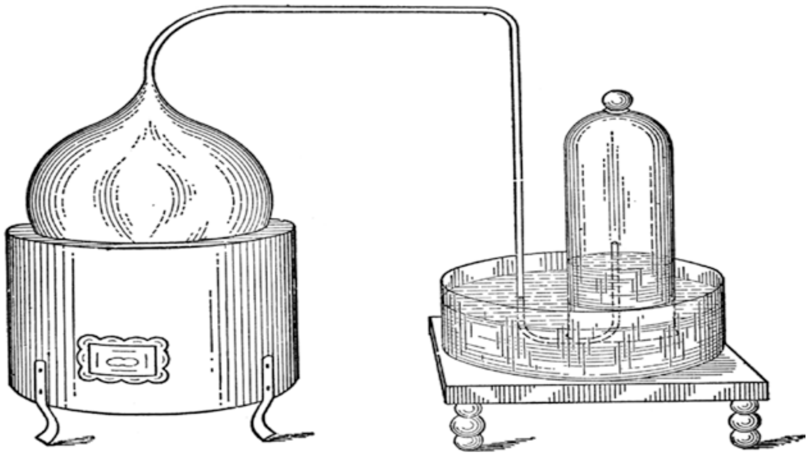


Fig. 14.2 Lavoisier's experimental approach to measuring the oxygen content of the atmosphere (Source: Florida Center for Instructional Technology)

These earlier investigators of energy turned what had been a complete mystery into a well understood and quantifiable science, and we owe a great deal to their work. Except for Albert Einstein's discovery of the equation for turning mass into energy (and vice versa, as in the Big Bang) and the development of quantum physics, there has, arguably perhaps, not been any comparable discoveries of the basic physics of energy, especially that can be represented readily by simple equations. However, as we shall see, perhaps the most important discoveries came with applying basic energy laws and ideas to more complex systems, including ecology and economics.

14.5 What Is Energy?

A definition of energy turns out to be more difficult than what one might think. The high school physics definition "the ability to do work" does not take us very far. Robert Romer wrote a good physics textbook which was about using energy concepts to understand all the conventional material of physics because "all physics is about energy." Yet even he admitted that he was unable to give a satisfactory definition of energy. He said we can see its effects, we can measure it, but we don't really know what it is. Usually we detect energy being used because something is moved, a car, a basketball player, chemicals against a gradient, and so on. For our day-to-day purposes, energy is mostly either photons coming from the sun or chemically reduced (i.e., normally, hydrogen-rich) materials such as wood or oil that can be oxidized to generate work (i.e., move something) at some point in space and time, i.e., the process of combustion. In general, *reduced* means hydrogen rich and oxygen poor, so that a fuel is generally a hydrocarbon like oil or occasionally a carbohydrate such as alcohol (the "ate" on the end refers to the presence of oxygen, so that a carbohydrate will have somewhat less energy than a hydrocarbon per gram but still enough to be used as a fuel). When a reduced fuel is oxidized, energy is released, and the hydrogen is released as water (H_2O) and the carbon as carbon dioxide (CO_2). The general equation for combustion of a hydrocarbon is:

$$C_nH_{2n} + O_2 \rightarrow H_2O + CO_2$$

The exact numbers required to balance the equation depend upon the exact form of the hydrocarbon burned but are for oxidation of common biological foods about:

$$C_6H_{12}O_6 + 6\,O_2 \rightarrow 6\,CO_2 + 6\,H_2O + \text{energy}$$

The equation for photosynthesis is the same but runs from right to left.

Most of our energy comes into the Earth originally in the form of photon flux from the sun. Some small part of this energy is captured by plants in chemical bonds and then passed through food chains. Thus, we are able to use the energy in a hamburger by oxidizing the reduced matter in the animal tissue, through digestion within the body of the consumer. This energy initially was obtained by the cow when it ate grass that had in turn captured that energy from the photons, and then passed it as chemical bonds to the cow and then to us. Even when we are driving a car, we are oxidizing formerly reduced plant material (oil) that is constructed of high-energy chemical bonds originally made with energy captured from the sun by algae. All life is powered by organisms capturing energy by photosynthesis (where electrons are activated) or eating energy that originally came from the sun and passing those activated electrons along trophic (food) pathways, using some of that energy to run life processes, to a terminal electron acceptor, usually oxygen. It is analogous to electrons activated by a generator or a battery running along wires to a terminal electron acceptor (the ground or the pole of the battery).

Power refers to the rate at which energy is used. For example, a light bulb is rated in kilowatts, a unit of power, so that a 100 watt light bulb uses 360 kilojoules in an hour, equivalent to the energy in about 10 milliliters of oil. An automobile engine is rated in horsepower, roughly the rate at which a horse can do work, which was used to estimate the power of early steam engines. Since automobiles today typically have 100–200 horsepower engines, one can see how much fossil fueled engines have increased the ability of humans to do work (Table 6.2). If we want to know the total energy used, we multiply a measure of power (e.g., 100 watts) times the time of use (say 10 hours) to get the total energy use, in this case 1000 watt-hours or 1 kilowatt-hour).

The use of different terms to describe energy (e.g., calories, kcal, BTU, watt, joule, therm) may seem very confusing, but they all measure one thing: the quantity or rate of heat produced when all of the energy has been converted to heat. Table 14.1 gives many energy conversions as well as the metric prefixes that establish magnitude.

Table 14.1 Energy conversions as well as the metric prefixes that establish magnitude.

One calorie	4.1868 joule
One BTU	1.055 KJ
One KWh	3.6 MJ
One therm	105.5 MJ
One liter of oil	37.8 MJ
One gallon of oil	145.66 MJ
One barrel of oil	6.118 GJ
One ton of oil	41.9 GJ = 6.84 barrels

14.6 Quality of Energy

When considering energy as a resource in a general way, there are several critical things to think about. First of all, there is the *quantity* of it, how much there is at the disposal of the species or human society using it. For example, there is several times more coal in the world compared to oil. Second is the *quality* of that energy: that is, the form that it is in, which has a great deal to say about that energy's utility. The most obvious example is food. The energy in corn has obvious utility to us as food where the energy in wood or coal does not. There are many other aspects of quality. Corn, a grass, is a very productive crop so where the land is crowded people often eat nothing but corn (or other grasses such as wheat or rice) because it gives the most food production per hectare. But corn lacks a critical factor absolutely required for humans: the amino acid lysine. If the corn is fed to a cow, then the energy bonds in the corn will be transferred to energy bonds in the flesh of the cow. This animal protein has a full complement of amino acids and hence is a higher-quality food, at least from that perspective. Many relatively poor humans in Latin America (and elsewhere) eat mostly rice and beans. This is actually a very good diet because the rice and beans are cheap and they complement each other: the amino acid lysine is missing in rice but found abundantly in beans, while rice is basically carbohydrates, a good energy source, and beans are protein rich. Thus rice and beans provides an excellent diet for humans, although it is still missing one critical ingredient: vitamin C. Fortunately vitamin C is abundant in chile peppers, which is often used as a condiment by people who have a rice and bean diet. So cultural selection appears to be often associated with real dietary needs, all of which insures that the energy that fuels humans has the required quality.

We often say that the energy in the protein-rich beans, or a chicken that is fed rice, is of a higher *quality* than the rice because the animal food contains more protein, a food type absolutely necessary for humans and most animals that is in insufficient supply in many plant foods. Many would say it tastes better too. Thus people may feed rice or other grain to an animal to get a smaller quantity of higher-quality chicken. Likewise coal or oil can be burned to generate a smaller quantity (as measured by heating ability) of electricity. But this electricity has a higher quality in that it can be used to do things such as light a light bulb or run a computer that one cannot do with the oil or coal. We are willing to take roughly three heat units of coal or oil and turn it into one heat unit of electricity because it is more useful to us, that is, it can do more work and hence is more economic, in that form. We say the quality of the electricity is higher, and a special term, called *emergy*, has been derived to represent quality of energy in a comprehensive fashion [2].

A related aspect of energy is its ability to do work defined by physicists in a very careful, specific way. The term used here is exergy, which is that component of energy that can actually do the work, as opposed to being transferred into heat due to the minimal second law requirements for some to be turned into heat. In formal second law analysis and technical thermodynamics in physics and certain engineering, the terms exergy and enthalpy are used to measure quality [3].

There is a third component of energy, also related to its quality, which relates to the energy required to get that fuel. We normally measure this property as EROI, or energy return on investment, and this issue will be explored in much greater detail in ► Chap. 18. We often hear very bullish statements about the tremendous amounts of energy that are all around us just waiting for us to exploit. But there is a catch. The energy has to be of a high enough quality to make it worthwhile to exploit, and real fuels must have a very high EROI. For example, we normally can get only about a third of the energy out of an oil field simply because the remaining oil sticks tightly to the substrate. If we really wanted that oil, we could get it—we could dig a 2 mile deep hole and shovel it out of the ground and heat it in a giant pot. But obviously that would require far more energy than one would get from the oil. In fact we use steam, pressure chemicals and pumping, and to some degree it works. But at some point, getting more of the remaining oil out simply costs too much money for the energy to do it, and the well is closed off. Reduced carbon, a potential fuel, is extremely abundant in shale rocks throughout the world, and as such it represents, some say, a tremendous energy source. In certain very carbon-rich rocks, it is possible to get oil or gas out with a substantial energy profit. But for the majority of these rocks, more energy would be required to get this dilute carbon out of the rocks than the energy contained within it, so that rock cannot be considered a fuel. Similarly, the oceans contain a tremendous energy potential in the hydrogen found in the water molecule. But that hydrogen is not a fuel, for it takes more energy to separate it from the oxygen it is combined with than can be recovered by later burning it. EROI comes into play more generally when we examine our commonly used fuels. For example, the petroleum that flowed out of Spindletop probably had an EROI of far greater than 100:1. The EROI of all oil and gas production was initially low, about 20:1, then increased to about 30:1 in the 1950s, and then has declined to about 10:1 today. Finding and developing a brand new barrel of petroleum today (vs pumping out an existing stock) require perhaps one barrel for each three to five barrels found. Similar patterns have held for other fuels, such as for coal, over time, although for coal the numbers, although decreasing, are much higher. Thus in general as time goes by, the highest-quality fuels are used first, and the EROI declines. While it is true that occasionally brand new very high-grade petroleum resources are found, the probability for most of our main resources is vanishingly small because, according to Colin Campbell, the whole world has been seismically and otherwise explored and picked over for many decades.

Similarly we have used up our highest-grade copper ores, so that the average grade mined fell from about 4% in 1900 to 0.4% in 2000. This lower-grade copper requires more energy to get a kg of pure copper out, and we can say that its RoE ([material] return on energy investment) is declining. Humans, usually being no economic fools, tend to use high-grade resources first, high-grade meaning more concentrated or easier to access. This important concept is called the *best first principle*, and it is very important as we consider the possibilities before us. The principle was also derived very clearly in economics by David Ricardo two centuries ago.

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14.7 What Are Fuels?

Fuels are normally energy-rich, reduced compounds of hydrogen and carbon which we call carbohydrates if they also contain some oxygen or hydrocarbons if they do not. We often think of fuels as energy *carriers*, for they store and allow energy to be moved from its source to where we wish to use it. Oil in the ground or even in the gas tank is not useful. Rather it becomes useful when it releases energy in the process of transfer from the reduced state to the oxidized state. Thus the utility of a fuel depends upon having a redox (reducing-oxidizing) gradient between the fuel and the final electron acceptor. A key to the way that organisms have evolved is that life has tended to break this process down into a series of tiny steps that captures or releases some of this energy step by step. Thus electrons are passed through energy capture devices, such as a membrane or a whole plethora of oxidized-reduced chemical compounds, which cycle from energy-rich reduced forms to energy-poor oxidized states and, as appropriate, the converse. In a way this flow of energy through biological food chains is not unlike the flow of electrons in a wire that we call electricity. Some energy sources, the sun for biology or a generator fueled by falling water or the combustion of fossil fuel, gives the electrons a boost, a kick in the pants as it were. In electricity the wire provides a circuit for the electrons to travel along, and the energy represented by their excited state can be used by a device such as a motor or light bulb put in the path way of the electrons flowing from the source to what we call a sink, which represents a place that the low-energy electrons can return, generally to be kicked into a high-energy state again. The energy provided by the kick is simply moved to the place where it is utilized in a light, motor or whatever. Similarly electrons that have received a "kick" from the sun in photosynthesis pass through the complex "wires" of biological circuits carrying the energy derived from the photon to reduced carbon compounds in a plant and then through food chains to various animals and decomposers. So when you eat your corn flakes or a hamburger, remember that the energy that allows you to run, jump, or just exist came from the sun through the magic of photosynthesis.

14.8 Why Energy Is So Important: Fighting Entropy

When we think about energy, it is normally from the perspective of going somewhere, or keeping warm in the winter, or some friend's high-energy level. But the reach of energy is far more pervasive. The principal reason is due to what is normally called *entropy*. Entropy is often used inaccurately or vaguely. Physically it describes, essentially, the tendency of the components of a physical system to spread as evenly as possible in space and over all states of motion. Entropy is the physical measure of disorder, that is, randomness. The concept of molecules arranged in a definite pattern (such as in a building or an animal) is the opposite of those molecules being spread out randomly. The natural tendency is for molecules to be arranged randomly, that is, to have high entropy. Some have called this property "the entropy law." While this concept may seem far removed from our day-to-day existence where we live surrounded by ordered structures (such as in the computer, I am using as I write this), it is in fact critical, for everything with which we deal is impacted by entropy, and everything that we own tends to degrade (i.e., become more random) over time: our cars (that's why we need to take it to the shop), our homes (that is why we need fire insurance, repainting, plumbers, termite controllers, and so on), our food (that is why we need refrigerators), our closets, and even ourselves (that is why we need to eat and why most of us require medical intervention at various times in our life). What all these things are—cars, houses, computers, and ourselves—is bits of negentropy, or negative entropy, that is an ordered structure of molecules, something that is by itself extremely unlikely. Life must be nonrandom to exist, that is, life consists of very specific aggregates of molecules that are completely different from the general environment within which it resides. But although by chance alone negentropy is extremely unlikely, in fact it is common around us, and this is due principally to natural selection that has generated life plans that extract energy from the environment and invests that energy into creating, maintaining, and reproducing life forms.

Thus the creation of negentropy requires energy to concentrate and organize molecules as well as a plan as to what reorganization will work. For life, the plan is a species's DNA, and analogously for a mechanic or plumber, it is the wiring or piping diagrams, shop manuals and so on, or his or her training and experience that allows the car or house to continue to exist. But without energy the plan is useless for it requires energy to take metals or other materials out of the ground and air to make new biomass or new brake drums or pads, cylinder blocks, pipes, faucets, and so on.

It even takes our personal energy expenditure to reduce the daily entropy of our closets. More generally life, including civilization, is about very specific structures, or construction according to a plan, and then the maintenance of that structure. Both of these things are energy demanding, the degree of which is a function of the complexity, size, and makeup of the plan. That is why we eat, why plants photosynthesize, and why modern civilization requires coal, gas, and oil: to get the energy necessary to maintain and in some cases build the very specific structures that we are and that characterizes all life and also our economies. An organism's DNA gives it the pattern or plan for the very specific structures, physiologies, and behaviors that have worked well in the environment—in which it is found—or at least have worked well up to the present. Those patterns that did work in the past may or may not work in the future, depending upon whether there are environmental changes or whether some other species has figured out a new way to exploit that environment. But all organisms are, in a sense, betting that what they have will work well enough for what life is all about—propelling genes into the future. It is a wonderful process, and the results are magnificent!

A simple example will help to think about this. Both a ham sandwich and your own self are extremely unlikely, nonrandom structures of molecules of carbon, nitrogen, phosphorus, and so on that have been developed by taking the elements and materials of nature, initially scattered more or less at random over the surface of the Earth, and concentrating these elements and their compounds into structures that would be extremely unlikely—except for the investment of energy into a plan—a wheat plant, a pig, and ourselves for starters and then additionally all that goes into a ham sandwich. Once the structure is made, energy must be continuously invested, or the materials of which it is composed will go back on their own toward entropy—i.e., a more random assemblage—and the structure will fall apart. A simple example is your ham sandwich. If that sandwich is put into a refrigerator, a device that uses energy to maintain the structures of its contents, the integrity of the sandwich will be maintained for some time. Pull the plug on the refrigerator (i.e., cut off the energy), and the sandwich begins to go into a more random assemblage, first smelly organic residues and then eventually carbon dioxide and simple nitrogen compounds such as ammonia. Pull the energy plug on yourself by not eating, and the same will happen to you, eventually. Likewise a car will not run without both fuel and the energy required for its repair; a city cannot run without its fuel supplies, power plants and many kinds of repair personnel, or an entire civilization without all of these things, which must be supplied essentially daily. Most past civilizations that have lost their main energy supplies became extinct, as we will develop later.

The practical meaning of this is that it is always necessary to find new energy resources to construct and maintain whatever structures we have, including houses, cars, civilizations, and ourselves. This is familiar to us in the shop costs, medical bills, and taxes we must pay to maintain our cars, ourselves, and our roads and bridges against the entropic forces of nature that would otherwise result in time in cracked and broken roads and bridges rusted to pieces. Curiously it is necessary to generate additional entropy to maintain areas of negentropy. The refrigerator must take high-grade electricity and turn it onto lower-grade (more entropic) heat in order to maintain the ham sandwich in its desired configuration, and each of us must take low-entropy food and turn it into high-entropy heat and waste products in order to maintain ourselves. Even the creation of this book, which hopefully represents highly ordered information, requires the generation of excess entropy around us, as a look at either of our offices will confirm.

14.9 Laws of Thermodynamics

Thermo means heat (or energy), and *dynamics* means changes. *Thermodynamics* is the study of the transformations that takes place as energy or fuels are used to do work. *Work* means that something is moved, including a rock or your leg lifted, a car driven, water evaporated or lifted up in the atmosphere, chemicals concentrated, or carbon dioxide transformed from the atmosphere into a green plant. There are two principle laws of thermodynamics, called the *first law of thermodynamics* and the *second law of thermodynamics*. Quite simply the first law says that energy (or for some particular considerations energy matter) can never be created nor destroyed but only changed in form. Thus the potential energy once found in a gallon of gasoline but then used to drive a car, say, 20 miles up a hill, is still found somewhere, as the momentum of the car, as heat dissipated by the radiator or where the tires met the road, or in the increased potential energy of the car at the top of the hill. Most of the original energy will be found as heat dissipated into the environment, where it is essentially impossible to get any additional work out of it. (Technically you could capture that waste heat and use some of it, but it would require the use of even more energy to do so.) But some fraction of the work done can be used again, for example, the automobile could be rolled back to its original downhill position using the force of gravity. The second law says that all real-life processes produce entropy. At every energy transformation, some of the initial high-grade energy (i.e., energy that has potential to do work) will be changed into low-grade heat barely above the temperature of the surrounding environment. In other words, the first law says that the *quantity* of energy always remains constant, but the second law says that the *quality* is degraded over time. The practical meaning of this is that with the exception of the reliable energy input from the sun, it is always necessary to find new energy resources to construct and maintain whatever structures we have, including houses, cars, civilizations, and ourselves. The implications of this have had overwhelming impacts upon all human enterprises and histories and constitute the remainder of this book.

To our knowledge, there are no examples of any action occurring on earth, or anywhere else for that matter, that is not subject to the laws of thermodynamics. The only possible exception, given in the first part of this chapter, is that that the law of conservation of energy needs to be expanded to the law of conservation of mass energy when nuclear reactions (in a star, nuclear bomb, or nuclear power plant) are considered. This is because mass can be converted to energy (and the converse) according to Einstein's famous equation: $E = MC^2$, which says that under special circumstances energy created equals mass times the speed of light squared. In other words in a nuclear conversion, a small amount of mass can be converted to a huge amount of energy, although this can take place only under very special conditions. This is an example of how science often moves forward. The first law of thermodynamics might seem to have been violated when we learned about nuclear reactions, but with Einstein's help, we only had to understand that while the first law works very well for everyday conditions, we have to expand it to include mass for the very special circumstances of a star, that is, we need to learn how to expand our law.

14.10 Types of Energy

Although energy is critical to all of our daily activities an actual definition, as we have said, is hard to come by. Energy is usually defined as the capacity to do work, where work implies something is moved (a rock or animal from here to there, chemicals concentrated, and so on. The most important routine work activities that take place within the human realm are driven by the sun (solar energies). These activities include the evaporation and lifting of water from the sea to provide us with rains and rivers that flow from mountains, the concentration of low-energy carbon from the atmosphere into higher-energy tissues of a plant through photosynthesis, the passing of this energy through food chains (e.g., with a deer or a cow eating plants), the generation of winds that moves atmospheric water from the ocean to the land and cleanse the local skies of pollutants, the generation of soils through complex processes of forests and grasslands, the running of many complex processes in natural ecosystems, and so on (Fig. 14.3). Increasingly we also use fossil (meaning old) fuels such as coal, oil, and natural gas. Energy that is being used at the time in question to undertake work is called *kinetic* energy, and energy that has the possibility to do work but that is not doing it now is called *potential* energy. Examples include a rock at the top of a hill, the energy in a pile of firewood, the concentrated energy within a flashlight battery not being used, and the chemical energy in a gallon of gasoline sitting in a gas tank. When the gasoline is used to move a car, the potential energy of the gasoline is changed into the kinetic energy of the automobile in motion and into heat. Most energy that we use is derived directly from the sun either at present (i.e., wind, the power of dry air to evaporate, and so on) or in the past (i.e., the gasoline came from petroleum that was once solar energy captured by small plants (phytoplankton) drifting in the sea. Other sources of energy besides the sun include the energy of planetary motions

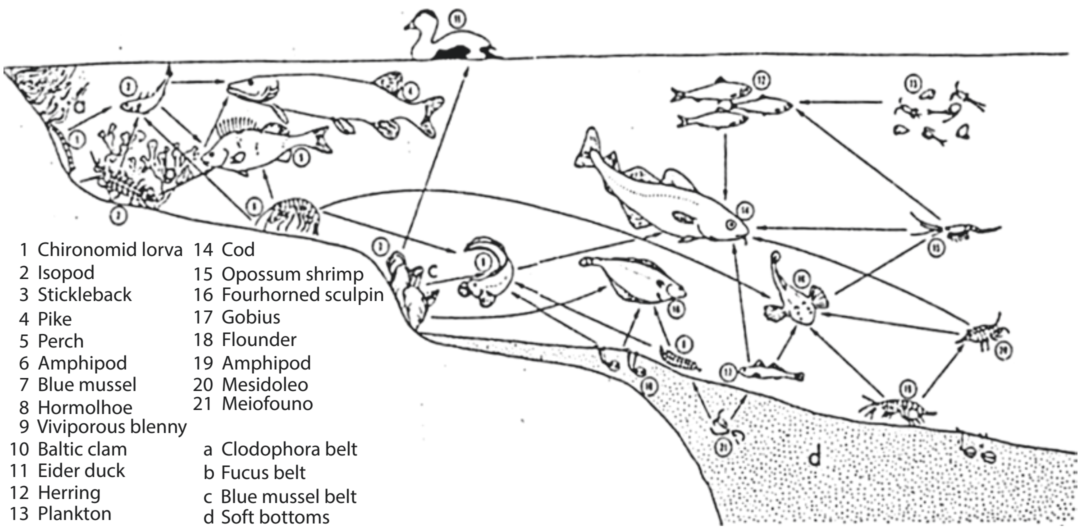

Fig. 14.3 Energy flow through a Baltic ecosystem. The energy that enters from the sun is captured by green plants and then is passed to herbivores and then carnivores through food chains (sometimes called food webs) (Source: Bengt-Owe Jansson)

(which causes tides), geological processes such as volcanoes and crustal movements and that of nuclear decay (which causes the interior of the earth to be hot).

Solar energy is especially important as it runs the whole "heat engine" of the earth (see next chapter). It also runs local weather. For example, when steady winds are forced upward by a mountain in their path, the air masses cool, generating a rainy region on the windward side (think Seattle, Washington) and a dry or even desert area on the leeward side (think Yakima, Washington). Thus the unequal interception of solar energy on different parts of the Earth's surface generates the world's winds, its wet and dry areas and, more generally its climatic zones. Solar energy also evaporates water from the surface of the ocean, lifting and purifying it in the process, moves it onto land masses while causing it to rain as solar-powered winds push the air masses up mountains, and in so doing generating the world's rains and rivers. While we may not appreciate a particular rainy day, the rains are essential to our purified water supplies and the growth of plants upon which all animal life, including our own, depends. An understanding and appreciation of the world's hydrological cycle and the critical role of energy in it is perhaps one of the most fundamental things we can learn about how the Earth, and hence our economy, operates. Curiously this process is not considered a part of most economics even though it is probably the most important step in the world economy, that is, the purifying of water and the lifting of it to the land and to the mountains that supply most of the world with its water for agriculture, for all economic activity, and for life itself. It is not considered by conventional economics because it is free, i.e., it does not enter into markets. But being free and indispensable makes it more, not less, valuable to our economy, and we need to think of it that way especially as we must pay more to compensate for the pollution and other abuse of water that is increasingly part of the hydrological cycle.

14.11 Energy and Life in More Detail…

Life, in all of its manifestations, runs principally on contemporary sunlight that enters the top of our atmosphere at approximately 1400 watts (1.4 kilowatts or 5.04 MJ per hour) per square meter for a point perpendicular to the sun's rays. Roughly one quarter of that amount reaches the Earth's surface. This sunlight does the enormous amount of work that is the thermodynamic consequence of this energy input and that is necessary for all life, including human life even when isolated from nature in cities and buildings. The principal work that this sunlight does on the Earth's surface is to evaporate water from that surface (evaporation) or from plant tissues (transpiration) which in turn generates elevated water that falls eventually back on the Earth's surface as rain, especially at higher elevations. The rain in turn generates rivers, lakes, and estuaries and provides water that nurtures plants and animals. Differential heating of the Earth's surface generates winds that cycle the evaporated water around the world, and sunlight of course maintains habitable temperatures and is the basis for photosynthesis in both natural and human-dominated ecosystems. These basic resources have barely changed since the evolution of humans (except for the impacts of the ice ages) so that preindustrial humans were essentially dependent upon this limited, or perhaps more accurately diffuse, although predictable energy base.

In *photosynthesis* energy from the sun is captured by green plants using chlorophyll, a very special compound similar in structure to the hemoglobin in our blood. Chlorophyll appears green to our eyes because it uses (i.e., absorbs) the shorter red and longer blue wavelengths from the sun and reflects back the green wavelengths that it does not use. A thick layer of green plants cover the earth wherever temperatures are moderate and water is abundant The amount of energy trapped by photosynthesis is immense, roughly 3000 exajoules per year, which is about six times larger than the energy use of all human activities (488 exajoules per year). The first step occurs in the center of the chlorophyll molecule where electrons circling the magnesium-nitrogen compound in the center of the molecule are "hit" by a photon from the sun and "pushed" into a larger orbit, which allows them to store more energy and then pass it to special chemical compounds. This is similar to how a professional skater stores energy in her outstretched arms when her partner gives her a well-aimed push, and then uses that stored energy to speed up her spin by pulling her arms back to her sides. Free electrons are normally made available from reduced compounds and move through biological circuits to fuel biotic processes. That energy is first stored temporarily in reduced compounds in plants such as NADP, which are then used to split water to get hydrogen and an excited electron, and CO_2 to get carbon. Plants then combine the carbon and hydrogen to make reduced, energy-rich compounds such as sugar. Eventually, the electron is passed to an electron acceptor, normally oxygen, but occasionally sulfur or some other element. These electrons are reenergized when green plants give a new kick to the electrons when a photon from the sun again drives photosynthesis. And hence the process continues, with the energy from solar-derived photons driving every biological activity including the movement of my fingertips on this keyboard. It is incredible!

The chemistry of photosynthesis is based on the energy from photons being used to split carbon dioxide and also water to get or *fix* reduced carbon and hydrogen which is then used to generate sugars with oxygen as a waste product:

$$6\,CO_2 + 6\,H_2O \rightarrow C_6H_{12}O_6 + 6\,O_2$$

The sugars are then synthesized into the more complex compounds of life. These include cellulose (the basic structural material of wood, which is just a lot of sugars attached one to another into a network of the same materials called a *polymer*) and, with the addition of nitrogen, the proteins of animal and many plant tissues. This same equation is "run backward" by animals and decomposers that use the chemical compounds. When green plants first evolved, some three billion years ago, and especially one billion years ago when plants colonized the land, they changed the atmosphere from an anaerobic one to an aerobic one. This can be seen in, for example, the rocks of Glacier National Park where there are green layers of iron containing rock that were laid down before the oxygenation of the atmosphere and similar "rusted" red rocks that were laid down later after the evolution of an oxygenated atmosphere.

What about animals? Take a look at most wild or domestic animals. Usually they are eating, i.e., getting energy, or trying to position themselves to do so (◘ Fig. 14.4). If they are not eating, they tend to be resting, conserving energy. In the breeding season, obviously things get a bit more complicated. Plants too are spending most of their time dealing with energy: for example, they are photosynthesizing any time the sun is shining and in various ways attempting to protect themselves from energy losses by, e.g., making natural pesticides. Humans are a bit different because food energy is (at this time in our history) so abundant and cheap, at least for the richer half of humanity, that we have to invest relatively little time or

Fig. 14.4 Herbivores grazing in Kenya (Source: Kathy Wooster)

personal energy to feed ourselves. We are also different now because our energy requirements are only about half of what they were when we were more active. For example, early New England farmers had to eat (and drink, especially ale!) about 7000 kilocalories (30 MJ) each day to fuel their hard agricultural work, although many hard workers in poorer countries get by on less than half that. Any of us today who ate that many calories would become huge!

The study of biology, from biochemistry to ecosystem biology, is very much about the study of how energy is passed from one chemical entity to another. Biochemists often focus on the importance of the energy storage materials NADPH and ATP, scientists who study at the level of one organism often consider feeding behaviors, and the physiology of energy transfer within and across the gut wall, whereas ecosystem biologists talk about the transfer of energy from plants to herbivores to predators. The importance of energy in biotic function has captured the attention of many of our great biological thinkers, for example, Alfred Lotka, Harold Morowitz, Max Kleiber, Howard Odum, and others. And what do they conclude? Basically, that life, or more specifically the individual organisms and species that constitute the packages of life, is about capturing as much energy as possible per unit time with as little expenditure or investment as possible per unit gained, using that net energy gained to sequester more energy and other resources, to use to create structures and fuel behaviors to propel their genes into the future.

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As far as we know, this is entirely the result of the uncaring processes of natural selection, those organisms and, ultimately, genes that were successful at this pattern were those that tended to survive, prosper, and eventually be relatively dominant on the Earth's surface. Some people prefer to use the more general term "resources" rather than just "energy resources" when discussing these issues, and there is occasionally a good case to be made for that. Obviously water is a critical resource for plant growth, and all the solar energy a plant could ask for might be available in an Arizona desert although water is very much limiting. In other situations some specific nutrient, such as phosphorus or nitrogen, may be limiting, but even these limitations can be mitigated by the plant investing more of its energy into growing longer roots to exploit more soil or transferring molecules across fine roots. Thus for most of the earth, the critical issue is energy, and life seems to be very good at expanding to capture as much of the available energy around it as possible.

Two important concepts here are *energy investments* and *energy opportunity costs*. The former means that life must always invest energy into fighting entropy, getting other resources, reproducing, and so on. The second means that since every organism has only a limited energy supply at any one time, and any particular investment into one process means that there is that much less energy to invest elsewhere. If a tree invests more energy in growing long roots to get more water or nutrients, then less will be available for growing tall, and it might be shaded by a competitor or eaten by an insect. If more energy is diverted into making natural pesticides (such as caffeine, mustard oils, or various alkaloids) then less is available for growing roots, and so on. Likewise if a civilization invests more energy into military activities, or expanding office space, or building fancy homes, or looking for oil, then less energy is left for repairing bridges or education. Politics is all about how to make energy investment decisions, although it is done through deciding where to spend money. In both trees and politics, there is a tendency to invest in a way that can capture more energy (through plant or economic growth), but that can work only when there are additional energy resources that can be exploited by using less energy than that gained. If the energy resources become restricted, then investing in growth can be self-defeating, a situation that many of the world's economies now face.

14.12 Energy Storage

Life is of course about much more than simply gaining and using energy, for life must use energy when and where it needs it in order to help the organism adjust to a continuously changing environment. Just as a motor or light needs a switch to turn it off and on as needed, life too must have switches. As a simple example, if our muscles were firing all the time, they would be useless, and in fact such a condition is a pathology called tetanus. Thus life has evolved a whole series of complex controls and switches that use available energy from the sun or food a little at a time, storing it and releasing it as needed and as controlled by hormones and the nervous system operating through very complex biochemistry. The general solution that has evolved for the storage and on/off problem has been through the use of various storage reservoirs. This allows for the capture, storage, transport, and release of the energy made available to the organism by photosynthesis or by ingesting food. The most common such compound for *short-term storage* is adenosine triphosphate (ATP) and its less energized form ADP. Whenever the body needs energy, quickly it calls on ATP to deliver that. These compounds are ubiquitous to life and are critical to all activities that an organism does. *Medium-term storage* is the glycogen in our liver, and *longer-term storage* is all too familiar to us as body fat.

14.13 A Big Jump in the Earth's Energy Supplies for Life

Thus free oxygen increased with the first massive increase in land plants as a waste product of their photosynthesis that split water and carbon dioxide to generate the carbon and hydrogen needed to produce reduced carbohydrates such as sugars. For all the existing plants and animals and microbes on the Earth this free oxygen, itself extremely reactive, was initially a severe toxic threat, a widespread and dangerous pollutant. Some say that the evolution of oxygen-releasing green plants was the greatest environmental impact the earth has ever faced! Some have argued that the mitochondria were initially evolved (or as we said above "captured") to sequester the dangerous oxygen before it destroyed other parts of the organism, and only later developed the capacity to enhance the metabolic activity of the host cell. Over time natural selection created organisms (including humans) with protective skins that require oxygen to live and to use completely their food. But even today there are many environments where oxygen is not present. They are normally obvious to us from their smell of hydrogen sulfide, characteristic of, for example, the mud of a marsh or the inside of our intestines, which would not be a good place to have oxygen for then the energy in our food would be used up before it got to do us any good! In these environments oxygen remains a poison for many of the organisms.

Thus, it appears that evolution has operated in many complex ways, such as incorporating oxygen-using organelles (i.e., mitochondria) in all animals that live in an oxygen-rich environment, to derive means of using energy more powerfully. Apparently the main ways to do this were worked out very long ago in the evolution of life since nearly all life has the same internal energy structures and uses the same basic phosphorus-based chemistry for storage and quick release. Biochemist Paul Falkowski makes an elegant argument that in many ways the biochemistry that life depends upon now is inappropriate for our existing oxidized environment. It can be understood only as a "holdover" from life's anaerobic past—that is, the anaerobic mechanisms that worked in the past were too deeply engrained into the processes of life for life to abandon, and so were retained and modified even if not perfectly suited for the new aerobic environment. Although complete oxidation of food using mitochondria allows the most complete use of food, many different approaches to utilizing food energy have evolved, and these different pathways are still used variously by different species and in response to different environmental conditions. If oxygen is not present, the less thorough but quite adequate energy release process called fermentation still can be used, and this process generates energy-intermediate alcoholic residues which we have exploited to generate beer and wine. The partial transformation of the grain or fruit into usable energy leaves as residues alcohol and CO_2, which generates the bubbles in beer.

A more general perspective is that energy is passed through and among organisms in a series of complex *redox* (reducing-oxidizing) reactions, until the full food value is extracted and some or all of the carbon base is turned into CO_2. Energy is passed from one organism to another through an ecosystem along food chains and food webs. Plants capture the energy from the sun and turn a portion of it into their own tissues, leaves, stems, roots, and so on. Then some of that energy is passed to herbivores (plant eaters) and then carnivores (meat eaters) and decomposers. The word trophic means food, and trophic dynamics is the study within ecology of how energy is passed along food chains within an ecosystem and what happens to that energy. An important thing that happens is that energy is lost (actually turned into heat) at every step as necessitated by the second law of thermodynamics. Most of the energy that is lost was actually used by the organism itself for its own maintenance metabolism. This is due to the necessity for each organism to "fight entropy" through energy investments, and the necessary losses to heat arising from the second law of thermodynamics. Usually only a small proportion, very roughly 10%, is passed from one trophic level (such as plants) to the next (herbivores). This is one reason there are few top carnivores—if there are four or more trophic levels each passing on only 10% of the energy, then only a very small amount of the original energy captured by photosynthesis makes it to the top carnivore.

While it is obvious that an organism must get enough *quantity* of energy to maintain itself, it is also necessary for it to get sufficient *quality* of energy. Most generally the missing ingredient in vegetative material for humans or for other animals is sufficient protein. Kwashiorkor is a common disease of people on an insufficient protein diet, characterized by cinnamon-colored hair and a protruding belly, as well as many personal metabolic problems restricting the ability of people to work. Once in the 1950s well-meaning nutritionists made a large effort to increase protein production of certain groups of people who had this disease, for example, feeding existing grains to chickens and fish, to try to increase the protein available to these people. But the program backfired because the people were actually energy-starved, and their bodies were burning the proteins for fuel, not using them for structural development. In other words our bodies have an even greater need for energy than for structural building and repair. So, feeding energy-rich grains to animals to produce a smaller quantity of protein actually exacerbated the problem by reducing the energy available to the people, even though they got more protein, their desperate bodies had to use it for fuel, not maintenance or growth of new tissues! But where calories are sufficient protein is critical for normal healthy development, thus the quality of energy is often as important as the quantity. Obviously in our food, quality is a much more complex issue than simply protein or not.

Proteins are foods made of amino acids that are based upon nitrogen as well as carbon. One can think of a hamburger: the bun is a carbohydrate made of carbon, hydrogen, and oxygen, and the beef is protein, which has those elements and much nitrogen as well. While we normally think of protein as meat, there are many other sources. For example, ecologists have found that many of the animals of an estuary or a forest are dependent upon detrital food chains, that is, food that has been dead a relatively longtime before being consumed (as opposed to grazing or browsing living materials). Dead plant material is mostly carbon and as such contains little nitrogen, which is critical for the protein needs of the animals that feed upon it. But in estuaries and forest floors much of the decomposition of this material occurs by bacteria, and certain bacteria can do something that most other organisms cannot: they can fix nitrogen from the air and turn it into protein. Thus, the animals that eat microbially mediated food get much better nutrition because there tends to be more protein. This may sound repulsive to humans, but maybe it is much less so if you think about the microbially mediated foods we eat: bread, cheese, beer, wine, salami, sour cream, and so on. In fact most of our party foods are microbially mediated!

14.14 More on Energy and Evolution

Plants and animals in nature have been subjected to fierce selective pressure to do the "right thing" energetically, that is, to insure that whatever major activity that they did, and do, gained more energy than it cost and generally got a larger energy net return than alternative activities. Biology in the last century had, appropriately enough, focused mostly on fitness, that is, on the ability of organisms to survive and reproduce, in other words to propel their genes into the future. While it is a no brainer that a cheetah, for example, has to catch more energy in its prey than it takes to run it down, and considerably more to make it through lean times and also to reproduce, it took the development of double-labeled isotopes and the exquisite experimental procedures by the likes of Donald Thomas and his colleagues [4] to show how powerfully net energy controlled fitness. They studied tits (chickadees) in France and Corsica, and they found that those birds that timed their migrations, nest building, and births of their young to coincide with the seasonal availability of large caterpillars, which in turn were dependent upon the timing of the development of the oak leaves they fed upon, had a much greater surplus energy than their counterparties that missed the caterpillars. They fledged more, larger, and hence more-likely-to-survive young while also greatly increasing their own probability to return the next year to breed again. Those of their offspring that inherited the proper "calendar" for migration and nesting were in turn far more likely to have successful mating and so on. Thomas et al. also showed how the natural evolutionary pattern was being disrupted by climate change, so that the tits tended to get to their nesting sites too late to capitalize upon the caterpillars, who were emerging earlier in response to earlier leaf out. Presumably if and as climate warming continues natural selection will favor those tits which happened to have genes that told them to move north a bit earlier.

14.15 Maximum Power

Howard Odum has taken these concepts one step further by arguing that it is not just the net energy obtained but the *power*, that is, the *useful energy per unit time*, that is critical. Odum argued that there is generally a trade-off between the rate and the efficiency for any given process; that is, the more rapidly a process occurs, the lower its efficiency and vice versa. Under a given set of environmental conditions, it is not advantageous to be extremely efficient at the expense of the rate of exploitation nor to be extremely rapid at the expense of efficiency [5, 6]. For example, in a series of elegant observations and experiments, Smith and Li [5] found that a trout that feeds on drifting food in a rapidly flowing stream will acquire large amounts of food drifting by but at a low net efficiency; i.e., much of the energy surplus created by the consumption of this large amount of food is spent in muscle contraction for the trout so that it can fight the faster current. Likewise a trout in slow water can be very efficient because its swimming costs are lower, but the slower water brings with it less food, and thus the overall energy surplus will be limited by the lower rate at which food is provided. Dominant trout will pick an optimum intermediate current speed, which will result in faster growth and more offspring. Subdominant trout will be found in water moving a little faster or a little slower. In some experiments trout with no competitive power would be found drifting aimlessly in still water slowly starving to death.

Of course life in all of its diversity also has a diversity of energy lifestyles that have been selected for—sloths are just as evolutionarily successful as cheetahs, while warm-blooded animals pay for their superior ability to forage in cold weather with a higher energy cost to maintain an elevated body temperature—the list is endless.

Nevertheless each lifestyle must be able to turn in an energy profit sufficient to survive, reproduce, and make it through tough times. There are few, if any, examples of extant species that barely make an energy profit—for each has to pay for not only their maintenance metabolism but also their "depreciation" and "research and development" (i.e., evolution), just as a business must, out of current income. Thus their energy profit must be sufficient to mate, raise their young, "pay" the predators and the pathogens, and adjust to environmental change through sufficient surplus reproduction to allow evolution. Only those organisms with a sufficient net output and sufficient power (i.e., useful energy gained per time) are able to undertake this process through evolutionary time, and indeed some 99 plus percent of all species that have ever lived on the planet are no longer with us—their "technology" was not adequate, or adequately flexible, to supply sufficient net energy to balance gains against losses as their environment changed. Given losses to predation, nesting failures, and the requirements of energy for many other things, the energy surplus needs to be quite substantial for the species to survive in time.

14.16 Natural Economies

Of course in nature, plants and animals do not exist in isolation but combined in complex arrangements that we call ecosystems, tied together by the movement of energy and materials from one species to another in what is often referred to as food chains or food webs. We call the green plants that capture the solar energy *primary producers*, the animals that eat the grass *herbivores*, the animals that eat other animals *carnivores,* and so on. Eventually all plant and animal material ends up as dead organic material, often called detritus, and this material is then broken down into very simple materials or even elements by bacteria and other decomposers. We call the study of these relations *trophic* (meaning food) analysis and each successive step from the sun trophic levels. It is rather amazing to think that all the energy necessary for all the animals and all the decomposers, and even the plants at night and in the nongrowing season, comes from the photosynthesis during the daylight hours during the growing season.

We can call all of these trophic interactions collectively *natural economies*. In other words, nature too, just like human economic systems, is all about production, exchange within and between species, and eventual degradation. Of course natural ecosystems are different from modern human economies in that there is no money—but the economy exists just fine without the money, as might conceivably ours (i.e., many economies are based on barter alone). This idea that nature too has economies is a very powerful one for it allows us to focus on just what are the essential features of an economy when we strip it of the human additions of money, debt, credit, and so on.

14.17 Summary So Far: Surplus Energy and Biological Evolution

The interplay of biological evolution and surplus energy is far more general, as emphasized a half century ago by Kleiber [7], Morowitz [8], Odum [9], and others. Plants and animals are subjected to fierce selective pressure to do the "right thing" energetically; that is, to insure that whatever major activity that they undertake gains more energy than it costs and beyond that gets a larger energy net return than either alternative activities or their competitors. It is obvious that a cheetah, for example, has to catch more energy in its prey than it takes to stalk it and run it down and considerably more to make it through lean times and also to reproduce. Plants too must produce an energy surplus to supply net resources for growth and reproduction, as can be seen easily in most clearings in evergreen forests where living boughs on a tree that are in the clearing are usually lower down than they are in the more densely forested and hence shaded side of the tree. If the bough does not carry its weight energetically, that is, if its photosynthesis is not greater than the respiratory maintenance metabolism of supporting that bough, the bough will die (or perhaps even be sloughed off by the rest of the tree).

Every plant and every animal must conform to this "iron law of evolutionary energetics": if you are to survive, you must produce or capture more energy than you use to obtain it; if you are to reproduce, you must have a large surplus beyond metabolic needs; and if your species are to prosper over evolutionary time, you must have a very large surplus for the average individual to compensate for the large losses that occur to the majority of the population. In other words, every surviving individual and species needs to do things that gain more energy than they cost, and those species that are successful in an evolutionary sense are those that generate a great deal of surplus energy that allows them to become abundant and to spread.

While probably most biologists tacitly accept this law (if they have thought about the issue), it is not particularly emphasized in biological teaching. Instead biology in the last century focused mostly on fitness, that is, on the ability of organisms to propel their genes into the future through continuation and expansion of populations of species. But in fact energetics is an essential consideration as to what is, and what is not fit, and many believe that the total energy balance of an organism is the key to understanding fitness.

14.18 Energy and Economics in Early and Contemporary Human Economies

Humans are no different from the rest of nature in being completely dependent upon sunlight and food chains for our own energy requirements and nutrition, and on being part of complex interactions among very complex food chains leading to ourselves. Human populations, like those of any other species, must capture sufficient net energy to survive, reproduce, and adapt to changing conditions in the area in which they live. Humans must first feed themselves before attending to other issues. For at least 98% of the million years that we have been recognizably human, the principal technology by which we as humans have fed ourselves, that is, obtained the energy we need for life, has been that of hunting and gathering. Contemporary hunter gathers –such as the !Kung of Kalahari desert in Southern Africa that we introduced in ► Chap. 7—are probably as close to our long-term ancestors as we will be able to understand. Most hunter-gatherer humans were probably similar to other species in that their principal economic focus is on obtaining sufficient surplus energy as food gained directly from their environment. Studies by anthropologists such as Lee [10] and Rapaport [11] confirmed that indeed present-day (or at least recent) hunter-gatherers and shifting cultivators acted in ways that appeared to maximize their own energy return on investment, perhaps 10 joules returned for each one invested. Angel found that agriculture actually decreased the average physical fitness of humans [12].

Human evolution, broadening the definition to include social evolution, is different from other species, for the human brain, language and the written word have allowed for much more rapid cultural evolution. The most important of these changes, as developed in ► Chap. 6, were energy related: the development of energy-concentrating spear points and knife blades, agriculture as a means to concentrate solar energy for human use, and more recently the exploitation of wind and water power and, of course, fossil fuels. What is important from our perspective is that each of these cultural adaptations is part of a continuum in which humans invest some of their energy to increase the rate at which they exploit additional resources from nature, including both energy and nonenergy resources.

For a particularly good example, the development of agriculture allowed the redirection of the photosynthetic energy captured on the land from the many diverse species in a natural ecosystem to the few species of plants (called cultivars) that humans can and wish to eat, or to the grazing animals that humans controlled. It also allowed the development of cities, bureaucracies, hierarchies, the arts, more potent warfare, and so on—that is, all that we call civilization, as nicely developed by Jared Diamond in his book *Guns, Germs, and Steel*.

A human as a machine works at about 20% efficiency, that is, the power output of a human (i.e., his/her muscular work) is about 20% of the food energy input to that machine. Thus, over a 10-hour day, a human can deliver about one half to one horsepower hours or about 5–10% of what a horse can do (and on about 5–10% of the food) [13]. Put another way, the power output of a human at rest is about 60 watts, and at peak performance, a strong worker might generate about 300 usable watts, although that rate cannot be sustained for very long. A very strong person might be able to deliver 100 watts or 1 kilowatt-hour (3.6 MJ) over a 10 hour day. The human machine cannot deliver this power if the temperature is above 20–25 °C, so that other things being equal it is more difficult to generate surplus wealth in the hot tropics [14]. A horse can generate about 3 kilowatts. By comparison a four-cylinder standard automobile engine generates about 1000 kilowatts and a jet turbine engine about one million kilowatts. Clearly the world now has at its disposal a tremendous amount of power compared to the past (◘ Tables 14.2, 14.3, 14.4).

Anthropologist Leslie White once noted that a bomber flying over Europe during the Second World War consumed more energy in a single flight than had been consumed by all the people

Table 14.2 The energy cost of various things. The ratio of energy to GDP changes year to year mostly as a function of inflation but also as the economy appears to becoming more efficient

U. S. approximate energy use per unit of economic activity (in 2016) when GDP was 18.569 trillion dollars:

$$\text{Energy per \$GDP} = -\frac{90.6\ \text{Exajoules}(e18)}{18.569\ \text{trillion}(e12)\text{dollars}} = \frac{4.88\ e6\ \text{joules}}{\text{dollar}} = 4.88\text{Mega joules per dollar}$$

One dollar of economic activity requires	4.88 MJ = 0.03 gallon of oil
One thousand dollars requires	4.88 GJ (0.79 BOE)
One million dollars requires	4.88 terajoules (790 BOE)
One billion dollars requires	4.88 petajoules (790 thousand BOE)
One trillion dollars requires	4.88 exajoules (790 million BOE)
18.57 trillion dollars requires	18.57 e12 * 4.88 MJ/$ = 90.6 EJ (14.8 e9 BOE)

Source: US Dept. Commerce; US EIA BOE = barrels of oil energy equivalent

Table 14.3 Selected fuels and their heat equivalents

Fuel	Heat equivalent (MJ)
Residual oil (1 barrel)	6626.5
Crude oil (1 barrel)	6163.8
Distillate oil (1 barrel)	6139.6
Gasoline (1 gallon)	131.8
Electricity (1 kilowatt-hour)	3.6
Natural gas (1 cubic foot)	1.1

Source: State of Oregon DOE

Table 14.4 MJ used per 2005 dollar spent in select sectors of the economy

Sector	MJ
Oil and gas field machinery and equipment	7.36
Petroleum lubricating oil and grease manufacturing	61.30
Cement manufacturing	68.4
Rolled steel shape manufacturing	15.60
Fabricated pipe and pipe fitting manufacturing	9.84
Water transportation	48.80
Other miscellaneous chemical product manufacturing	16.30
Other basic organic chemical manufacturing	21.70
Explosives manufacturing	22.70
Watch, clock, and other measuring device manufacturing	5.65
Oil and gas extraction	9.26
Drilling oil and gas wells	9.87
Support activities for oil and gas operations	6.98

Source: Economic Input-Output Life Cycle Assessment Model developed by the Green Design Institute at Carnegie Mellon University (We do not know exactly how these were calculated so are simply passing them on. We also suspect that the nominal precision used does not reflect reality)

of Europe during the Paleolithic, or Old Stone Age, who existed when people lived entirely by hunting and gathering wild foods [15]. White estimated that such societies could produce only about 1/20 horsepower per person—an amount that today would not suffice for even a fleeting moment of industrial life. Over time, humans increased their control of energy through technology, although for thousands of years most of the energy used was animate—people or draft animals—and derived from recent solar energy. A second very important source of energy was from wood, which has been recounted in fascinating detail in Ponting [16], Smil [17], and especially Perlin [18]. Perlin estimates that by 1880, about 140 million cords of wood were being used in the world per year. Massive areas of the Earth's surface—Peloponnesia, India, China, parts of England, and many others—have been deforested three or more times as civilizations have cut down the trees for fuel or materials, prospered from the newly cleared agricultural land and then collapsed as fuel and soil become depleted. Archeologist Joseph Tainter [19] recounts the general tendency of humans to build up civilizations of increasing reach and infrastructure and complexity that, again and again, have eventually exceeded the energy available to that society.

People have understood how to get energy from winds or from a stream for millennia to, for example, grind grain, but the technology and incentives to do so increased rapidly from about 1750 onward. Fred Cottrell [13] gives a thorough review of the importance of the increased use of energy by civilization, to which he, rightly in our opinion, attributes most other advances in civilization. Water power was especially important in, for example, New England in the early years of this country. But the real push in the development of "modern" civilization came with learning how to burn coal to do many things, but especially to make iron and to run steam locomotives. With these inventions, mostly in England in the 1800s, industrial development really took off, and this led to what most people call "the industrial revolution." It was not simply the development of the use of coal but a whole suite of financial, chemical, metallurgical, and other developments that accelerated each other and led to the enormous production of wealth that took place in England, Scotland, and Germany during the 1800s. For example, James Watt could not develop his famous steam engine until his friend William Wilkinson had perfected the iron refining and drilling technologies that allowed for the construction of the perfectly round cylinder needed for Watt's steam engine. Even their interactions required the social environment of the Scottish *enlightenment* for their ideas to evolve and to come to fruition as actual components of society. Most thinking people at that time believed that these were wonderful inventions that would finally free people from the drudgery of every day existence and allow them to build a better society through rational thinking.

At the same time, many of the English Romantic poets, notably William Wordsworth, were horrified by the smoke and grime and repetitive jobs of the industrial revolution and pined for the bucolic preindustrial England. Our societies today need such vast amounts of energy that we provide it by mining stocks of solar energy accumulated eons ago, and converted into coal, natural gas, and petroleum. Without these stocks, our populations would be much less, and we could not live as we do. Clearly the world now has at its disposal a tremendous amount of power compared to the past.

In summary, it seems obvious that both natural biological systems subject to natural selection and the cultures and civilizations that preceded our own were highly dependent upon maintaining not just a bare energy surplus from organic sources but rather a substantial energy surplus that allowed for the support of the entire system in question—whether of an evolving natural population or a civilization. Most of the earlier civilizations that left artifacts that we now visit and marvel at—pyramids, ancient cities, beautiful buildings and rooms, monuments, and so on—had to have had a huge energy surplus for this to happen, although we can hardly calculate what that was. Certainly massive works from the past represented small net surpluses from thousands or millions of people carefully organized or brutally forced to do this work. Archeologist and historian Joseph Tainter has written elegantly about the role of surplus energy in constructing and maintaining ancient empires—Mayan, Roman, and so on [19]. Tainter argues that as empires get larger, they can spend more and more energy impressing potential adversaries and that the construction of impressive capital cities in itself shows potential competitors that the empire has so much surplus wealth that it makes much more sense for them to knuckle under, become part, and pay tribute than to fight the empire. The ever-expanding frontiers, however, and the need for ever more surplus energy as the distance needed to bring in food and other resources from increasingly distant provinces, increasingly decrease the net energy delivered to the center. Eventually the empire falls in on itself and collapses from its very need for the complexity, and its energy costs, required to generate the necessary surplus energy. This has happened again and again in antiquity and more recently with the collapse of the German Third Reich, the British Empire, and the Soviet Union. An important question for today is to what degree does the critical importance of surplus energy apply to contemporary civilization with its massive, although possibly threatened, energy surpluses? At what point have we developed so much infrastructure that it requires all the surplus energy we can get just for maintenance metabolism, so that growth is impossible?

Contemporary industrial civilizations are dependent upon the sun and in addition on fossil fuels. Today fossil fuels are mined around the world, refined and sent to centers of consumption. For many industrial countries, the original sources of fossil fuels were from their own domestic resources. The United States, Mexico, and Canada are good examples. However, since many of these industrial nations have been in the energy extraction business for a long time, they tend to have both the most sophisticated technology and the most depleted fuel resources, at least relative to many countries with more recently developed fuel resources. For example, in 2010 the United States, originally endowed with some of the world's largest oil provinces, was producing only about 40% of the oil that it was in the peak year of 1970, Canada had begun a serious decline in the production of conventional oil, and Mexico in 2006 was startled to find that its giant Cantarell Field, once the world's second largest, had begun a steep decline in production at least a decade ahead of schedule. (See previous chapter for an update.) Howard Odum's "maximum power" hypothesis is a very powerful and insightful way to think about the evolution of nature and of human society. Odum explains, for example, how oil-rich nations gained ascendancy over solar-based societies—at least for as long as their oil lasted. But it also suggests that countries that waste their energy or are unable to come to grips with the finite nature of premium energy will not be selected for. A scary thought is that it does not take an enormous amount of energy to generate horrific war – all of World War II, in which more than 50 million people lost their lives and a billion more were seriously compromised, was fought on 7 billion barrels of oil, about the quantity that the United States uses in 1 year at relative peace.

Thus, as we face the inevitable contraction in the availability of our most important fuels and as the difficulties of generating alternatives at the scale required seem to mount day by day, we must face the possibility that our own economy and civilization, which is almost universally based on the concept of continual growth of just about everything, may need a massive rethinking for planning for the future—in other words a new economics. This book is meant to give you the conceptual tools to begin that process [20].

14

Questions

1. If energy is so important, why are most people unaware of most of the energy that they use?
2. What is meant by "the mechanical equivalent of heat"? How was this demonstrated?
3. Can you explain Carnot's equation: $W = (Ts - Te)/Ts$? What implications does this have for the limits with which we can turn fuel into work?
4. Why, if the amount of energy stored in the surface of the North Sea is so great, is it not possible to extract this energy for use by society?
5. What is oxygen? If oxygen is so reactive, why do we have oxygen in the atmosphere?
6. What is the law of the conservation of matter?
7. What is energy? Do you think it has been defined adequately?
8. What is combustion? Can you give an example of an equation representing combustion?
9. What is the relation between energy and power?
10. Energy is often given in different units such as therms, kilowatt-hours, joules, calories, and so on. How are these units different? How are they the same? Which unit should you use? Why?
11. Define the relation between energy quantity and energy quality. Can you give an example where it is important?
12. Explain the differences among energy, exergy, and emergy.
13. What are fuels?
14. What is entropy? What is negentropy? Can you give an example from everyday life? What is the relation between energy and entropy?

15. What is the relation between negentropy and a plan? Can you give several examples?
16. How does negentropy relate to biotic evolution?
17. Why does the maintenance of negentropy generate entropy?
18. What is the first law of thermodynamics?
19. What is the second law of thermodynamics?
20. Can you define the first and second laws of thermodynamics using the words quantity and quality?
21. What might be considered an exception to the laws of thermodynamics? In your opinion, is this really an exception?
22. What is the difference between kinetic and potential energy? How are they related?
23. How is the surface of the Earth a heat engine?
24. Give the basic equation for photosynthesis.
25. What is the relation between energy investments and energy opportunity costs?
26. What are some of the biotic chemical compounds in which energy is stored?
27. Discuss the terms aerobic and anaerobic in relation to the Earth's evolutionary history.
28. According to Paul Falkowski, why do organisms carry within them inappropriate chemistry for today's environment?
29. If a metabolic process produced alcohol or vinegar, what does this tell you about the efficiency of the use of the original plant material?
30. What does redox mean?
31. Define trophic dynamics and give an example. What does this tell us about the efficiency of ecosystem processes?
32. What element characterizes proteins and makes them different from carbohydrates?
33. Relate energy to evolution.
34. What does the maximum power principle tell us about the efficiency of a biological or physical process?
35. Does nature have economies? How so? Do you think it is accurate to describe nature in that way?
36. What is the "iron law of evolutionary energetics"?
37. Relate the principles learned in the earlier part of this chapter to human societies.
38. How did wood use precede the industrial revolution?
39. Summarize your views on how natural and human societies use energy to survive and prosper.
40. Do you think that technology will make the end of the oil era of little concern? Why or why not?

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