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Energy, Nature and Society

The life contest is primarily a competition for available energy.

— Ludwig Boltzman (1886)

Other factors remaining constant, culture evolves as the amount of energy harnessed per capita per year is increased, or as the efficiency of the instrumental means of putting the energy to work is increased. We may now sketch the history of cultural development from this standpoint.

— Leslie White (1949)

[T]he ability to control energy, whether it be making wood fires or building power plants, is a prerequisite for civilization.

— Isaac Asimov (1991)

We live in a universe pulsing with energy; however, only a limited amount of that energy is available for our use. We humans have recently discovered a temporary energy subsidy in the forms of coal, oil, and natural gas, and that momentary energy bonanza has fueled the creation of modern industrial societies. We tend to take that subsidy for granted, but can no longer afford to do so. Emerging circumstances will require us to think much more clearly, critically, and contextually about energy than we have ever done before.

In this chapter we will first review some basic facts about energy and the ways in which nature and human societies function in relation to it. We will follow this discussion of principles with an exploration of the history of the United States' rise to global power, showing the central role of energy resources in that process.

The first section below includes information that may already be familiar to many readers from high-school or college courses in physics, chemistry, and biology. I begin with this material because it is absolutely essential to the understanding of all that follows throughout the book. Have patience. We will soon arrive in new (and disturbing) intellectual territory.

Energy and Earth: The Rules of the Game

Few understand exactly what energy is. And yet we know that it exists; indeed, without it, *nothing* would exist.

We commonly use the word *energy* in at least two ways. A literary or music critic might say that a particular poem or performance has energy, meaning that it has a dynamic quality. Similarly, we might remark that a puppy or a toddler has a lot of energy. In those cases we would be using the term intuitively, impressionistically, even mystically — though not incorrectly. Physicists and engineers use the word to more practical effect. They have found ways to measure energy quite precisely in terms of ergs, watts, calories, and joules. Still, physicists have no more insight into energy's ultimate essence than do poets or philosophers. They therefore define energy not in terms of what it is, but by what it does: as "the ability to do work" or "the capacity to move or change matter." It is this quantifiable meaning of the term *energy* that concerns us in this book. Though we are considering something inherently elusive (we cannot, after all, hold a jar of pure energy in our hands or describe its shape or color), energy is nevertheless a demonstrable reality. Without energy, nothing happens.

In the 19th century, physicists formulated two fundamental laws of energy that appear to be true for all times and places. These are commonly known as the First and Second Laws of Thermodynamics. The first, known as the Conservation Law, states that energy cannot be created or destroyed, only transformed. However, energy is never actually "transformed" in the sense that its fundamental nature is changed. It is more accurate to think of energy as a singular reality that manifests itself in various forms — nuclear, mechanical, chemical, thermal, electromagnetic, and gravitational — which can be converted from one to another.

The Second Law of Thermodynamics states that whenever energy is converted from one form to another, at least some of it is dissipated, typically as heat. Though that dissipated energy still exists, it is now diffuse and scattered, and thus less available. If we could gather it up and re-concentrate it, it could still work for us; but the act of re-concentrating it would itself require more energy. Thus, in effect, available energy is always being lost. The Second Law is known as the law of entropy — a term coined by the German physicist Rudolf Clausius in 1868 as a measure of the amount of energy no longer practically capable of conversion into work. The Second Law tells us that the entropy within an isolated system inevitably increases over time. Since it takes work to create and maintain order within a system, the entropy law tells us that, in the battle between order and chaos, it is chaos that ultimately will win.

It is easy to think of examples of entropy. Anyone who makes the effort to keep a house clean or who tries keeping an old car repaired and on the road knows about entropy. It takes work — thus energy — to keep chaos at bay. However, it is also easy to think of examples in which order seems naturally to increase. Living things are incredibly complex, and they manage not only to maintain themselves but to produce offspring as well; technological gadgets (such as computers) are always becoming more sophisticated and capable; and human societies seem to become larger, more complex, and more powerful over time. These phenomena all appear to violate the law of entropy. The key to seeing why they actually don't lies in the study of systems.

The Second Law states that it is the entropy in an *isolated system* that will always increase. An isolated system is one that exchanges no energy or matter with its environment. The only truly isolated system that we know of is the universe. But there are two other possible types of energy systems: *closed systems* (they exchange energy with their environment, but not matter) and *open systems* (they exchange both energy and matter with their environment). The Earth is, for the most part, a closed system: it receives energy from the Sun and re-radiates much of that energy back out into space; however, aside from the absorption of an occasional asteroid or comet fragment, the Earth exchanges comparatively little matter with its cosmic environment. Living organisms, on the other hand, are examples of open systems: they constantly receive both energy and matter from their environment, and also give off both energy and matter.

It is because living things are open systems, with energy and matter continually flowing through them, that they can afford to create and sustain order. Take away their sources of usable energy or matter, and they soon die and begin to disintegrate. This is also true of human societies and technologies: they are open systems that depend upon the flow of energy and matter to create temporary islands of order. Take away a society's energy sources, and "progress"

— advances in technology and the growth of complex institutions — quickly ceases. Living systems can increase their level of order and complexity by increasing their energy flow-through; but by doing so, they also inevitably increase the entropy within the larger system of which they are a part.

Matter is capable of storing energy through its chemical order and complexity. This stored energy can be released through chemical processes, such as combustion or, in the case of living things, digestion. Materials that store energy are called *fuels*.

The law of entropy holds true for matter as well as for energy. When energy is dissipated, the result is called *heat death*. When matter is eroded or degraded, the result is called *matter chaos*. In both cases, the result is a randomization that makes both matter and energy less available and useful.

In past decades, a simplistic understanding of entropy led many scientists to conclude that order is an anomaly in the universe — a belief that made it difficult to explain how biological evolution has proceeded from the simple to the complex, from bacteria to baleen whales. In recent years, more sophisticated understandings have developed, centered mostly around chaos theory and Ilya Prigogine's theory of dissipative structures. Now it is known that, even within apparently chaotic systems, deeper forms of order may lurk. However, none of these advances in the understanding of living systems and the nature of entropy circumvents the First or Second Laws of Thermodynamics. Order always has an energy cost.

Because the Earth is a closed system, its matter is subject to entropy and is thus continually being degraded. Even though the planet constantly receives energy from its environment, and even though the ecosystems within it recycle materials as efficiently as they can, useful concentrations of matter (such as metal ores) are always being dispersed and made unusable.

On Earth, nearly all the energy available to fuel life comes from the Sun. There are a very few exceptions; for example, oceanographers have discovered organisms living deep in ocean trenches, thriving on heat emanating from the Earth's core. But when we consider the energy flows that support the biosphere as a whole, sources originating within the planet itself are trivial.

The Sun continually gives off an almost unimaginable amount of energy — the equivalent of roughly 100 billion hydrogen bombs going off each second —radiating it in all directions into space. The Earth, 93 million miles away, is a comparatively tiny target for that energy, receiving only an infinitesimal fraction of what our local star radiates. Still, in terms that concern us, that's plenty: our planet is constantly bathed in 1,372 watts of sunlight energy per square meter. The total influx of solar energy to the Earth is more than 10,000 times the total amount of energy humankind presently derives from fossil fuels, hydro power, and nuclear power combined. The relative vastness of this solar-energy influx as compared with society's energy needs might suggest that humans will never face a true energy shortage. But only some of this solar energy is actually available for our use: much is re-radiated into space (30 percent is immediately reflected from clouds and ice), and nearly all of the rest is already doing important work, such as driving the weather by heating the atmosphere and oceans and fueling life throughout the biosphere.

Some organisms — green plants, including algae and phytoplankton — are able to take in energy directly from sunlight. Biologists call these organisms *producers*, or *autotrophs* ("self-feeders"), because they make their own food from inorganic compounds in their environments.[1] Producers trap solar energy through photosynthesis, a process in which chlorophyll molecules convert sunlight into chemical energy. Most of us tend to assume that green plants are mostly made up of materials from the soil drawn up through the plants' roots. This is only partly true: plants do require minerals from the soil, but most of their mass is actually derived from air, water and sunlight, via photosynthesis. Hundreds of chemical changes are involved in this process, the results of which can be summarized as follows:

$$\text{carbon dioxide} + \text{water} + \text{solar energy} \rightarrow \text{glucose} + \text{oxygen}$$
$$6CO_2 + 6H_2O + \text{solar energy} \rightarrow C_6H_{12}O_6 + 6O_2$$

Glucose — a sugar, or carbohydrate — serves as food for plants and can be converted into materials from which the plants build their tissues. Plants absorb only about half of the solar energy that falls on them; of that, they are able to convert only about one to five percent into chemical energy. Still, even at this low level of efficiency, photosynthetic organisms each year capture a little more than twice the total amount of energy used annually by human beings. (However, within the US, the total amount of energy captured in photosynthesis amounts to only about half of the energy used by humans.)

All nonproducing organisms are classifiable as *consumers*, or *heterotrophs* ("other-feeders"). By digesting glucose and other complex organic compounds that were produced through photosynthesis, consumers absorb the energy previously locked into chemical order by green plants. In the process, they produce waste — less-ordered material — which they excrete into the environment. In effect, consumers feed on order and excrete chaos in order to survive. All animals are consumers.

There are several categories of consumers: *herbivores*, which eat plants; *carnivores*, which eat other consumers (primary carnivores eat herbivores, secondary carnivores eat other carnivores, and tertiary carnivores eat carnivores that eat carnivores); *scavengers*, which eat dead organisms that were killed by other organisms or died naturally; *detritovores*, which eat cast-off fragments and wastes of living organisms; and *decomposers*, consisting mostly of certain kinds of bacteria and fungi, which complete the final breakdown and recycling of the remains and wastes of all organisms. Human beings — like foxes, bears, rats, pigs, and cockroaches — are *omnivores*, eating both plants and animals.[2]

Both producers and consumers use the chemical energy stored in glucose and other organic compounds to fuel their life processes. In most cells, this is accomplished through aerobic respiration, a process with a net chemical change opposite that of photosynthesis:

$$\begin{array}{lllllllll} \text{glucose} & + & \text{oxygen} & \rightarrow & \text{carbon dioxide} & + & \text{water} & + & \text{energy} \\ C_6H_{12}O_6 & + & 6O_2 & \rightarrow & 6CO_2 & + & 6H_2O & + & \text{energy} \end{array}$$

Some decomposers get energy through anaerobic respiration, or fermentation. Instead of carbon dioxide and water, the end products are compounds such as methane gas (a simple hydrocarbon) and ethyl alcohol. Normally, in the decay of organic materials, a chemical process based on aerobic respiration occurs, with carbon-based organic material combining with oxygen to yield carbon dioxide and water. However, if there is no additional oxygen available because of an anaerobic environment — such as exists if organic matter is buried under sediment or stagnant water — then anaerobic decomposers go to work. Plant and animal remains are transformed into hydrocarbons as oxygen atoms are removed from the carbohydrate organic matter. This is the chemical basis for the formation of fossil fuels. It is now believed that most oil comes from a few brief epochs of extreme global warming over quite short spans of geological time. The process began long ago and today yields fuels — chemically stored sunlight — that are energy-dense and highly usable.

Energy in Ecosystems: Eating and Being Eaten

Just as individual organisms use energy, so do complex systems made up of thousands or millions of organisms. The understanding of how they do so has been one of the central projects of the science of ecology.

The term *ecology* was coined in 1869 by German biologist Ernst Haeckel from the Greek roots *oikos* ("house" or "dwelling") and *logos* ("word" or "study of"). However, the discipline of ecology — which is the study of how organisms interact with one another and their surroundings — did not really flourish until the beginning of the 20th century.

At first, ecologists studied food chains — big fish eating little fish. Quickly, however, they realized that since big fish die and are subsequently eaten by scavengers and microbes that are then eaten by still other organisms, it is more appropriate to speak of food *cycles* or *webs*. Further analysis yielded the insight that all of nature is continually engaged in the cycling and recycling of matter and energy. There are carbon cycles, nitrogen cycles, phosphorus cycles, sulfur cycles, and water cycles. Of fundamental importance, however, are *energy flows* — which tend to drive matter cycles and which, as we have seen, begin in nearly all cases with sunlight.

Energy is the basic currency of ecosystems, passing from green plants to herbivores to carnivores, with decomposers participating along the way. With each transfer of energy, some is lost to the environment as low-quality heat. Typically, when a caterpillar eats a leaf, when a thrush eats the caterpillar, or when a hawk eats the thrush, only 5 to 20 percent of usable energy is transferred from one level to the next. Thus, if green plants in a given area capture, for example, 10,000 units of solar energy, then roughly 1,000 units will be available to support herbivores, even if they eat all of the plants; only 100 units will be available to support primary carnivores; only 10 to support secondary carnivores; and only one to support tertiary carnivores. The more energy-transfer levels there are in the system, the greater the cumulative energy losses. In every ecosystem, most of the chemically bound energy is contained among the producers, which also account for most of the *biomass*. The herbivores present will account for a much smaller fraction of the biomass, and the carnivores for yet a still smaller fraction. Thus the energy flow in ecosystems is typically represented by a pyramid, with producers on the bottom and tertiary carnivores at the top.

The energy available in an ecosystem is one of the most important factors in determining its *carrying capacity*, that is the maximum population load of any given species that is able to be supported by its environment on an ongoing basis. Energy is not the only factor, however; the operative principle in determining carrying capacity is known as Liebig's Law (after the 19th-century German scientist Justus von Liebig), which states that whatever necessity is least abundant, relative to per-capita requirements, sets the environment's limit for the population of any given species. For a plant, the limiting factor may be heat, sunlight, water, nitrogen, or phosphorus. Sometimes too much of a limiting factor restricts the carrying capacity, as when plants are killed by too much water or too much soil acidity. The limiting factor for any population may change over time. For herbivores and carnivores, the most common limiting factor is food-energy. This is why ecologists pay so much attention to food webs: when we understand the energy flows within an ecosystem, the dynamics of the system as a whole become clear.

These days the term *ecology* is often understood to be used merely in a scientific critique of human society's negative impact on nature. There are two reasons for this. The first is that early ecologists soon realized that, since humans are organisms, ecology should include the study of the relationship between people and the rest of the biosphere. The second is that, as early ecologists cataloged and monitored various natural systems, they found that it was becoming increasingly difficult to study such systems in an undisturbed state; everywhere, nature was being impacted by the human presence.

This impact itself became a focus of investigation, and soon ecologists realized that disturbed and undisturbed systems differ in clear ways. Ecosystems that have not been disturbed significantly for long periods of time (whether by humans or by natural disasters) tend to reach a state of dynamic equilibrium which ecologists call a *climax phase*, meaning that organisms have adapted themselves to one another in such a way as to maintain relatively constant population levels, to avoid direct competition, to keep energy flow-through to a minimum, and to recycle available energy and nutrients as completely as possible. They have formed, to use an anthropomorphic term, a *community*.

Biological communities are kept in equilibrium through balancing *feedback loops*. A useful technological example of a balancing feedback loop is a thermostat: if a room gets too cold, the thermostat triggers the furnace to turn on; when the room achieves the set temperature, the thermostat turns the furnace off. The temperature of the room varies, but only narrowly. Similarly, feedback loops in ecosystems — such as predator-prey relationships — tend to keep varying population levels within narrow ranges. If the vole population increases, fox and hawk populations will soon expand to take advantage of this food-energy surplus. The increase in the hawk and fox populations will then reduce the vole population, whose diminution will eventually lead to a reduction in the numbers of hawks and foxes as well.

The more mature the ecosystem, the more thoroughly the organisms in it use the available energy. Waste from one organism becomes food for another. Moreover, in order not to expend energy unnecessarily, organisms will tend to avoid direct competition through any of several strategies: by dividing the habitat into niches, by specializing (for example, if two species depend upon the same food source, they may evolve to feed at different times of day), or by periodic migration. Territorial animals avoid wasting energy in fights by learning to predict one another's behavior from signals like posture, vocalizations, and scent marks.[3] As a result, climax ecosystems give the appearance of cooperation and harmony among member species. The degree of mutual interdependence achieved can be astounding, with differing species relying on one another for food, shelter, transportation, warnings of danger, cleaning, or protection from predators. As biologist Lewis Thomas once put it, "The urge to form partnerships, to link up in collaborative arrangements, is perhaps the oldest, strongest, and most fundamental force in Nature. There are no solitary, free-living creatures, every form of life is dependent on other forms."[4]

In climax ecosystems, population levels are kept relatively in check not only through predators culling prey species, but also through species acting on their own to limit their numbers via internal feedback mechanisms. These internal mechanisms are seen in elephants, for example, which regulate their population densities through delays in the onset of maturity as well as among smaller animals such as mice, where females typically ovulate more slowly or cease ovulation altogether if populations become too dense. In many bird species, much of the adult population simply does not breed when there is no food-energy available to support population growth.

All of this contrasts with ecosystems that have recently been seriously disturbed, or whose balances have been upset by the arrival of a new species.

Fires, floods, and earthquakes are high-energy events that can overwhelm the energy balances of climax ecosystems. Disturbed ecosystems are characterized by disequilibrium and change. First, *pioneer species* appear — and proliferate wildly. They then give way to various secondary species. The environment passes through a series of phases, known collectively as *ecological succession*, until it arrives again at a climax phase. During these successive phases, earlier organisms transform the environment so that conditions are favorable for organisms that appear later. For example, after a forest fire, tough, annual, weedy, ground-cover plants spring up first. During the second or third season, perennial shrubs begin to dominate; a few years later, young trees will have grown tall enough to shade out the shrubs. In some cases, this first generation of trees may eventually be replaced by other tree species that grow taller. It may take many decades or even centuries for the land to again become a climax forest ecosystem. If we accept the view that the Earth can itself be treated as a living being, as has been proposed by biologists James Lovelock and Lynn Margulis[5], then it might be appropriate to think of succession as the Earth's method of healing its wounded surface.

In other instances, balances in ecosystems can be upset as a result of the appearance of *exotic species*. These days, the arrival of most exotic species is due to the actions of humans importing plants and animals for food, decoration, or as pets. But sometimes new arrivals appear on a freak wind current or a piece of flotsam. Most newcomers, having evolved in other environments, are unfit for life in their new surroundings and quickly perish; but occasionally, an exotic species finds itself in an environment with plenty of available food and with no predators to limit its numbers. In such instances, the species becomes an *invader* or *colonizer* and can compete directly with indigenous species. Most Americans are familiar with Scotch broom, starlings, and kudzu vine — all of which are successful, persistent, and profuse colonizers.

Many colonizing species are parasites or disease-causing organisms: bacteria, protozoa, or viruses. When such organisms initially invade a host species, they are often especially virulent because the host has not yet developed the proper antibodies to ward off infection. But the death of the host is no more in the interest of the microbe than it is in the interest of the host itself since the former is dependent on the latter for food and habitat. Thus, over time, disease organisms and their hosts typically co-evolve, so that diseases which initially were fatal eventually become relatively innocuous childhood diseases like measles, mumps, or chickenpox.

Not all feedback loops create balance, however; in *reinforcing feedback* loops, change in one direction causes more change in the same direction. A technological example would be a microphone held too close to the speaker of the amplifier to which it is attached. The microphone picks up sound coming from the speaker, then feeds it back to the amplifier, which amplifies the sound and sends it back through the speaker, and so on. The result is a loud, unpleasant squeal.

Colonizing species sometimes create reinforcing feedback loops within natural systems. While population levels among species in climax ecosystems are relatively balanced and stable, populations in disturbed or colonized ecosystems go through dramatic swings. When there is lots of food-energy available to the colonizing species, its population *blooms*. Suppose the organism in question is the rabbit, and the environment is Australia — a place previously devoid of rabbits, where there is plenty of food and no natural predator capable of restraining rabbit population growth. Each rabbit adds (on average) ten new baby rabbits to the population. This means that if we began with ten rabbits, we will soon have 110. Each of these adds ten more, and before we know it, we have 1,210 rabbits. More rabbits cause more babies, which cause more rabbits, which cause more babies.

Obviously, this cannot go on forever. The food supply for the rabbits is ultimately limited, and eventually there will be more rabbits than there is food to support them. Over the long term, a balance will be struck between rabbits and food. However, that balance may take a while to be achieved. The momentum of population increase may lead the rabbits to *overshoot* their carrying capacity. The likelihood of overshoot is increased by the fact that the environment's carrying capacity for rabbits is not static. Since the proliferating rabbits may eat available vegetation at a faster rate than it can naturally be regenerated, the rabbits may actually reduce their environment's rabbit-carrying capacity even as their numbers are still increasing. If this occurs, the rabbit population will not simply gradually diminish until balance is achieved; instead, it will rapidly *crash* — that is, the rabbits will *die off*.

At this point, depending on how seriously the rabbits have altered their environment's carrying capacity, they will either adapt or die out altogether. If they have not eaten available food plants to the point that those plants can no longer survive and reproduce, the rabbit population will stabilize at a lower level. For a time, population levels will undergo more seasonal swings of bloom, overshoot, and die-off as food plants recover and are again eaten back. Typically, those swings will slowly diminish as a balance is achieved and as the rabbits become incorporated into the ecosystem. This is, in fact, what has begun to happen in Australia since the introduction of rabbits by Europeans in 1859. However, if the rabbits were ever to eat food plants to the point of total elimination, they would reduce the rabbit-carrying capacity of their environment to zero. At that point, the rabbits would die out altogether.

Since successful invaders change their environments, usually overpopulating their surroundings and overshooting their ecosystem's carrying capacity, colonized ecosystems are typically characterized by reduced diversity and increased energy flow-through. As colonizers proliferate, energy that would ordinarily be intercepted by other organisms and passed on through the food web goes unused. But this is always a temporary state of affairs: living systems don't like to see energy go to waste, and sooner or later some species will evolve or arrive on the scene to use whatever energy is available.

These are the rules of the game with regard to energy and life: energy supplies are always limited; there is no free ride. In the long run, it is in every species' interest to learn to use energy frugally. Competition, though it certainly exists in Nature, is temporary and limited; Nature prefers stable arrangements that entail self-limitation, recycling, and cooperation. Energy subsidies (resulting from the disturbance of existing environments or the colonization of new ones) and the ensuing population blooms provide giddy moments of extravagance for some species, but crashes and die-offs usually follow. Balance eventually returns.

Social Leveraging Strategies: How to Gain an Energy Subsidy

We don't often tend to think about the social sciences (history, economics, and politics) as subcategories of ecology. But since people are organisms, it is apparent that we must first understand the principles of ecology if we are to make sense of events in the human world.

Anthropological data confirm that humans are capable of living in balance and harmony as long-term members of climax ecosystems. For most of our existence as a species, we survived by gathering wild plants and hunting wild animals. We lived within the energy balance of climax ecosystems — altering our environment (as every species does), yet maintaining homeostatic, reciprocally limiting relationships with both our prey and our predators.

However, humans are also capable of acting as colonizers, dominating and disrupting the ecosystems they encounter. And there is evidence that we began to do this many millennia ago, long before Europeans set out deliberately to colonize the rest of the world.

Like all organisms, humans seek to capture solar energy. Humans have certain disadvantages as well as advantages in this regard. Our disadvantages include our lack of thick fur, which would allow us to live in a wide range of climates, and our upright posture, which hampers our ability to outrun bears and lions. Our advantages include our adaptability, our flexible and grasping hands, and our ability to communicate abstract ideas by means of complex vocalizations — that is, by language.

We have made the most of our advantages. By exploiting them in ever more ingenious ways, we have developed five important strategies for gaining energy subsidies and thereby expanding the human carrying capacity of our environments:

- *takeover,*
- *tool use,*
- *specialization,*
- *scope enlargement,* and
- *drawdown.*[6]

While other creatures have adopted some of these strategies to a limited degree, modern industrial humans have become masters of all of them, combining and leveraging their advantages. Through an examination of these strategies we can begin to understand how and why *Homo sapiens* — one species among millions — has come to dominate the planetary biosphere.

Takeover

The first and most basic strategy that we have used to increase the human carrying capacity of our environments is one that William Catton, in his pathbreaking book *Overshoot* (1980), called *takeover*. It consists, in his words,

> ... of diverting some fraction of the earth's life-supporting capacity from supporting other kinds of life to supporting our kind. Our pre-*Sapiens* ancestors, with their simple stone tools and fire, took over for human use organic materials that would otherwise have been consumed by insects, carnivores, or bacteria. From about 10,000 years ago, our earliest horticulturalist ancestors began taking over *land* upon which to grow crops for human consumption. That land would otherwise have supported trees, shrubs, or wild grasses, and all the animals dependent thereon — but fewer humans. As the expanding generations replaced each other, *Homo sapiens* took over more and more of the surface of this planet, essentially at the expense of its other inhabitants.[7]

Takeover is a strategy composed of substrategies. The most basic of these entailed simply moving to new habitats. *Homo sapiens* presumably evolved in Africa; probably because of population pressure (which, in turn, may have been due to natural disasters or climate change), early humans left their African homeland and gradually began to fan out around the globe — first to Asia and Europe, and then to Australia, the Pacific Islands, and the Americas. As humans arrived in new habitats, they inevitably took over food-energy from other organisms, as all successful colonizing species do. They hunted for wild game that might otherwise have been prey for wolves, lions, or bears; and they foraged for roots, berries, seeds, and tubers that were already nourishment to a host of herbivores.

Meanwhile, humans were themselves prey to large carnivores. Hence, humans and the existing members of their newfound ecosystem communities went through a process of mutual adjustment. The archaeological evidence suggests that the adjustment was sometimes a painful one: humans often upset local balances dramatically, appropriating so much of the food supply that they caused or hastened the extinction of many animal species.[8]

Humans facilitated the takeover process by the use of fire — a rapid release of chemically stored energy. This constituted a second substrategy of takeover. In addition to keeping people warm at night, fire also served to increase their food supply. Early humans often carried fire sticks with them, deliberately igniting underbrush both to flush out game and to encourage the growth of edible shoots and grasses. The Native Americans and Aborignals of Australia were still using fire this way when European colonists first arrived. It is interesting to note that at least one nonhuman animal has adopted the same tactic: the black kite of India is known as the "fire hawk" because of its habit of picking up smoldering sticks from fires, dropping them on dry grass, and then waiting to catch small animals that flee.[9]

When humans arrived in Australia roughly 60,000 years ago, their use of fire so disrupted the normal growth cycles of shrubs and trees that large indigenous birds and mammals, including giant kangaroos and flightless ostrich-like birds, were deprived of food. According to recent paleontological research, roughly 85 percent of the Australian animals weighing more than 100 pounds disappeared within a few millennia of the first human appearance on the scene.[10]

The first humans to arrive in the Americas and the Pacific Islands provide similar examples: there, too, animal extinctions closely followed human arrival. In North America, the mammoth, mastodon, native horse, four-pronged antelope, native camel, giant beaver, ground sloth, mountain deer, and giant peccary all succumbed about 12,000 to 10,000 years ago, at a time when humans were migrating rapidly from Asia through present-day Alaska and southward into vast territories opened up by retreating ice sheets. Similarly, the Polynesian peoples extinguished the large, flightless moa bird soon after arriving in New Zealand.

But it is important to note what happened next in many of these places. In ancient Australia, over a period of tens of thousands of years, human beings and their adopted environment achieved a relative balance. The Aboriginals developed myths, rites, and taboos: overhunting was forbidden, and burning was permitted only in certain seasons of the year. Meanwhile, native species adjusted themselves to the presence of humans. All of the surviving species — humans, animals, and plants — co-evolved. By the time European colonizers arrived, once again upsetting the balance, Australia — people and all — had the characteristics of a climax ecosystem. Many native Australian trees and shrubs had so adjusted themselves to the Aboriginals' "fire-farming" practices that they could no longer reproduce properly in the absence of deliberate burning. Moreover, the Aboriginals had learned the necessity of limiting their own population levels through extended lactation, the use of contraceptive herbs, or, if necessary, infanticide.

In North America, native peoples had come to regard as sacred the animals and plants they used as food. According to Luther Standing Bear in his 1928 book *My People the Sioux*, Native Americans recognized a human responsibility to the rest of nature and regarded "the four-leggeds, the wingeds, the star people of the heavens, and all things as relatives."[11] Overhunting or the wanton destruction of ecosystems had come to be viewed by these people as an act with negative moral as well as practical implications.

In addition to the colonization of new territories and the use of fire, humans have pursued takeover through yet another substrategy: the appropriation of ever greater amounts of the total food web to human use, first through horticulture (gardening with a hoe or digging stick), then through agriculture (the planting of field crops, usually entailing the use of plows and draft animals). The deliberate planting and tending of food plants probably began gradually and somewhat inadvertently at a time when humans had already populated many habitable areas of the world as densely as they could. When people live by hunting and gathering, they require large territories; in this case, the human carrying capacity of a typical environment may be considerably less than one person per square mile. Horticulture yielded more food from a given land area, permitting population densities of several individuals per square mile.

Agriculture was yet more productive, permitting even greater population densities, though it also resulted in a reduction in the variety and nutritional quality of the human food supply: paleoanthropologists have found that the skeletons of early agriculturalists are usually smaller and show more evidence of degenerative diseases than those of earlier hunter-gatherers.

Agriculture entailed the deliberate simplification of ecosystems. Humans learned to grow only a few domesticated food crops while discouraging competitors to their food plants (weeds) and killing any organisms that competed with humans for access to those food plants (pests).

The domestication of animals constituted yet another variation on the takeover strategy. Animals could be useful for extracting energy from ecosystems in two ways: first, by concentrating and making available food energy from otherwise inedible fibrous plants; and second, by providing traction to pull plows, carts, and carriages. By helping to intensify agricultural production and assisting in overland transportation, domesticated animals facilitated the conquest of ecosystems and continents.

Though the takeover strategy was applied at first to other species, soon some humans began to use it in relation to other humans. Typically, societies with denser populations and more powerful weapons took over the territories of, or enslaved, groups with less intensive demands on the environment. This last substrategy achieved its apotheosis in the European takeover of most of the rest of the planet throughout the past 500 years.

Tool Use

Over the millennia, we humans facilitated our takeover of new ecosystems and other societies with an expanding kit of tools — from fire-drills, spears, knives, baskets, and pots to plows, carts, sailboats, machine guns, steam shovels, and computers.

This second basic strategy — the design, making, and use of tools — has ancient roots: archaeological evidence suggests that humans have been using tools for at least a hundred thousand years, perhaps much longer. Moreover, tool use is not absent among other animals: captive birds of the corvid family (which includes crows, ravens, and jays) have been reliably observed spontaneously constructing rakes out of available sticks or newspaper strips for pulling grain from outside their cage; placing stones in a drinking dish to raise the water to a drinkable level; or using a plastic cup to fetch and pour water on too-dry food.[12] Thus, the spectacular tools invented and used by modern industrial humans represent the development of a long-existing biological potential.

Nearly all tools assist in the harvesting or leveraging of ever-greater amounts of energy from the environment. The only notable exceptions are tools used purely for entertainment — which are also ancient, dating back at least to the oldest-recovered bone flute, made about 60,000 years ago.

It is often said that humans use tools to adapt and change their environments, and this is certainly true (recall the use of fire to thin out brush and thus clear space for the growth of food-yielding plants). However, it is just as accurate to say that we use tools to adapt *ourselves* to a variety of habitats. For example, we use shoes to adapt our feet to walking on rocky or uneven terrain.

Looked at this way, tools can be considered as functionally equivalent to detachable organs.[13] Another way of saying this is that tools are *prosthetic devices* we add to ourselves to replace or supplement our senses, limbs, or muscles. Usually the term *prosthesis* is used to describe a mechanical replacement for an absent organ or a supplement for a poorly functioning one (examples include artificial limbs, false teeth, iron lungs, and eyeglasses); however, it is possible to broaden the concept to include mechanical enhancements of perfectly healthy organs: wheels enhancing the mobility of legs and feet, bows and arrows effectively extending the reach of arms and hands, and so on. William Catton calls *Homo sapiens* "the prosthetic animal" and notes wryly that "when an airline pilot with thirty-three years of flying experience refers to the familiar act of buckling his cockpit seatbelt as 'strapping a DC-8 to my waist,' it is clear that even a modern jetliner can be seen as an elaborate prosthetic device."[14] Catton also notes that the "evolutionary and ecological significance of such prosthetic devices has been to facilitate the spread of mankind over a more extensive range than we could have occupied with only the equipment of our own bodies."[15]

Because tools are extensions of ourselves, they change us. The human-tool complex is effectively a different organism from a toolless human. We unconsciously tend to adapt ourselves to our tools in a myriad of ways — witness how industrial societies have adapted themselves to the automobile. Tool use also alters the mentality of entire societies. For example, the use of the technology of money tends to move whole cultures in the direction of an increased emphasis on calculation and quantification, powerfully intensifying any existing utilitarian attitudes toward natural resources and other humans by facilitating the accumulation of wealth. Similarly, as Marshall McLuhan and others have documented, the technology of writing reduces people's reliance upon memory while intensifying their use of abstract reasoning.[16] More recently, computers have sped up our lives while seeding our language with new metaphors: we now "process" experiences the way our computers process information; we get together with friends to "download" gossip; we complain that talkative individuals take up too much "bandwidth"; we go on vacations so that we can have "down time." Gone are the days of barnyard metaphors (chickens coming home to roost, foxes guarding the henhouse, grown children leaving the nest). As metaphors based on experiences of the natural world disappear from language and are replaced by mechanical or electronic referents, human consciousness may be subtly disengaging itself from its biological roots.

One way to better understand the evolution of technology through the millennia is to examine the relationship between tools and energy. All tools require energy for their use or manufacture — but that energy may come from human muscle power or some source external to the human body, such as animal muscle, wood fire, coal fire, or hydro-generated electricity. Some tools harness externally produced energy, making it available to other tools that then do work for us. Using energy source as a criterion, we can identify four basic categories of tools. These categories also correspond very roughly to four major watersheds in social evolution:

A. *Tools that require only human energy for their manufacture and use.* Examples include stone spearheads and arrowheads, grinding tools, baskets, and animal-skin clothing. These sorts of tools are found in all hunter-gatherer societies.

B. *Tools that require an external power source for their manufacture, but human power for their use.* Examples: all basic metal tools, such as knives, metal armor, and coins. These tools were the basis of the early agricultural civilizations centered in Mesopotamia, China, Egypt, and Rome.

C. *Tools that require only human energy for their manufacture, but harness an external energy source.* Examples: the wooden plow drawn by draft animals, the sailboat, the firedrill, the windmill, the water mill. The firedrill was used by hunter-gatherers, and the wooden plow and sailboat were developed in early agricultural societies; the windmill and water mill appeared at later stages of social evolution.

D. *Tools that require an external energy source for their manufacture and also harness or use an external energy source.* Examples: the steel plow, the gun, the steam engine, the internal combustion engine, the jet engine, the nuclear reactor, the hydroelectric turbine, the photovoltaic panel, the wind turbine, and all electrical devices. These tools and tool systems are the foundation of modern industrial societies —in fact, they define them.

This scheme of classification emphasizes the cumulative nature of technological and social development. Some Class A tools still persist in horticultural, agricultural, and even industrial societies (flint blades, for example, are, because of their extreme sharpness, occasionally used today by brain and eye surgeons for the most delicate operations), but Class D tools by and large did not exist in hunter-gatherer societies. However, the categories do overlap somewhat, and there are exceptions and anomalies: hunter-gatherers used fire to make some tools (for example, by cooking glues), thus turning them into Class C tools; the use of the metal plow (Class D) predated industrialism by three millennia; and a simple steam engine (Class D) was invented by the ancient Greeks, though they did not put it to practical use. Still, even if we allow for these inconsistencies, the scheme shows a clear trend: over time, tools and the societies that use them have increasingly captured energy from sources external to the human body and used that captured energy to fashion even more sophisticated energy-capturing and energy-reliant tools and tool systems.

Specialization

This third strategy is closely related to the second. Since a human-tool complex is effectively a different organism from a toolless human, humans using different tool complexes can become, in effect, different species from one another. As a society becomes composed of people working in different occupations, using different sets of tools, it becomes more complex; it develops its own technological-economic "ecosystem" that exists within, yet apart from, the larger biotic ecosystem.

We noted earlier that humans first applied the takeover strategy to other species and then to other humans; something similar happened with the tool-using strategy. At first, humans made tools out of stones and sticks, but eventually their increasingly utilitarian frame of mind led them to begin treating other human beings as tools. This scheme at first took the form of slavery. Some humans could capture the energy of others who had been seized in war, putting them to work at tasks too dangerous, dreary, or physically taxing for any free person to undertake voluntarily — tasks such as mining metal ores from beneath the Earth's surface. Those ores were, in turn, the raw materials from which were fashioned the chains and weapons that kept the slaves themselves in bondage. Eventually, metals also came to be used as money, a tool that would become the basis for a more subtle form of energy capture: wage labor. Through the payment of money, humans could be persuaded to give their energies to tasks organized by — and primarily benefiting — others. Some humans would become members of a permanent soldier class, which, through its conquests, could capture human slave-energy; others would become part of a peasant class, capturing solar energy through the growing of plants and animals for food for others. Compared to the raw energy of fire, human energy is of extremely high quality because it is intelligently directed. Only with the computer revolution of the late 20th century could inventors envision automatons capable of capturing and using energy in comparably sophisticated ways.

Just as the use of tools has affected our collective psychology, so has specialization. With a lifelong division of labor, many members of society became cut off from basic subsistence activities and processes; rather than enjoying a direct relationship with the natural world, they became, for their material existence, dependent upon the society's economic distribution system. This subtly fostered attitudes of conformity and subordination while undermining feelings of personal confidence and competence.

Scope Enlargement

To understand the nature of this fourth strategy for enlarging the human carrying capacity of environments, we must return to Liebig's Law, which states that for any given organism the carrying capacity of a region is limited by whatever indispensable substance or circumstance is in shortest supply.

Tools provided ways of getting around many limiting factors. For example, clothing permitted humans to live in climates that were otherwise too cold, whereas irrigation enabled humans to produce an abundance of food in regions that would otherwise have supported far fewer inhabitants. However, some limiting factors could be mitigated simply by transporting resources from one region to another. This sharing of resources among geographically circumscribed regions typically took the form of trade.

If one region had plenty of minerals but poor soil and another had good soil but no minerals, trade allowed both regions to prosper so that the total population of the two regions working together could far exceed what would be possible if they remained in isolation. William Catton calls this strategy *scope enlargement* and argues that

> a good many of the events of human history can be seen as efforts to implement [this principle] .... Progress in transport technology, together with advancements in the organization of commerce, often achieved only after conquest or political consolidation, have had the effect of enlarging the world's human carrying capacity by enabling more and more local populations (or their lifestyles) to be limited not by local scarcity, but by abundance at a distance.[17]

Local or regional catastrophes — famines, earthquakes, floods, droughts, plagues, etc. — have always been part of the human experience. With scope enlargement, their effects can be somewhat offset, as when aid is trucked or flown into a region experiencing famine. However, local populations then tend to become increasingly dependent on the system of trade and transport that connects them. If that system were itself ever to be threatened, many or all of the regions it encompasses would suddenly be put at risk.

In the past few decades, the strategy of scope enlargement has reached its logical culmination in a world system of trade and transport known as *globalization*. We who today live in industrialized countries are the ultimate heirs of the millennia-long process of scope enlargement. We have become globalized humans, daily eating foods grown hundreds or thousands of miles away, filling our cars with gasoline that may have originated in oil wells on the other side of the planet.

Drawdown

The fifth and final strategy that humans have used to increase their environment's carrying capacity is to find and draw down nature's stocks of nonrenewable energy resources: coal, oil, natural gas, and uranium. This strategy can only be pursued once societies are near the point of being able to invent, and produce in quantity, sophisticated Class D tools.

Drawdown dramatically improved the rates of return from the previous four strategies. It permitted

- the intensification of agriculture, with chemical fertilizers, pesticides, and herbicides increasing yields per acre, and with acreages devoted to the growing of food for humans increasing as a result of draft animals being replaced by tractors;
- the invention and utilization of a vast array of new tools that use energy more intensively;
- the development of more social roles and occupations based on specialized tool usage; and
- the rapid acceleration of transportation and trade.

Drawdown has been by far the most successful of the five strategies at increasing the human carrying capacity of the planet, and the degree of that success can be gauged in a single statistic, namely that of the world population growth since the beginning of the industrial revolution. The human population did not reach one billion until about 1820; in the less than two centuries since then, it has increased nearly six-fold. This is a rate of growth unprecedented in human history.

The exploitation of energy-bearing minerals created so much new carrying capacity, and so quickly, that much of that new capacity could be translated into increased wealth and a higher standard of living for a small but significant portion of the world's population. Previously, a parasitic increase of the standard of living for a wealthy few (kings, nobles, and lords) nearly always entailed a lessening of the standard of living of far more numerous serfs and peasants. Now, with power being liberated from fossil fuels, so much energy was available that the standard of living could be improved for large numbers of people, at least to a certain extent. Even though the majority of the world's population shared but little in this bonanza and continued to be exploited for cheap labor via takeover and specialization, virtually everyone shared in the expectation that the benefits of fuel-fed industrialism could eventually be spread to all. This expectation led in turn to a partial relaxation of the class-based social tensions that had plagued complex societies since their beginnings.

Americans, more than the people of any other region, have learned to take high-energy living standards for granted. In order to gain some perspective on this accustomed standard, it might be helpful to perform a little experiment. Try running up three flights of stairs in twenty seconds. If you weigh 150 pounds and the three flights go up forty feet, you will have done 6,000 foot-pounds of work in twenty seconds, or 300 foot-pounds per second. One horsepower equals 550 foot-pounds per second; therefore, you will have just generated a little over half a horsepower. But no one could sustain such a burst of muscle-energy all day long. The average sustained human power output is roughly one-twentieth of a horsepower.

This exercise is useful (even if performed only in imagination) in comparing human power with the power of the machines that maintain our modern way of life. Suppose human beings were powering a generator connected to one 150-watt light bulb. It would take five people's continuous work to keep the light burning. A 100-horsepower automobile cruising down the highway does the work of 2,000 people. If we were to add together the power of all of the fuel-fed machines that we rely on to light and heat our homes, transport us, and otherwise keep us in the style to which we have become accustomed, and then compare that total with the amount of power that can be generated by the human body, we would find that each American has the equivalent of over 150 "energy slaves" working for us 24 hours each day. In energy terms, each middle-class American is living a lifestyle so lavish as to make nearly any sultan or potentate in history swoon with envy.[18]

But if the payoffs of the drawdown strategy are spectacular, so are its dangers and liabilities. The latter can be grouped into three broad categories:

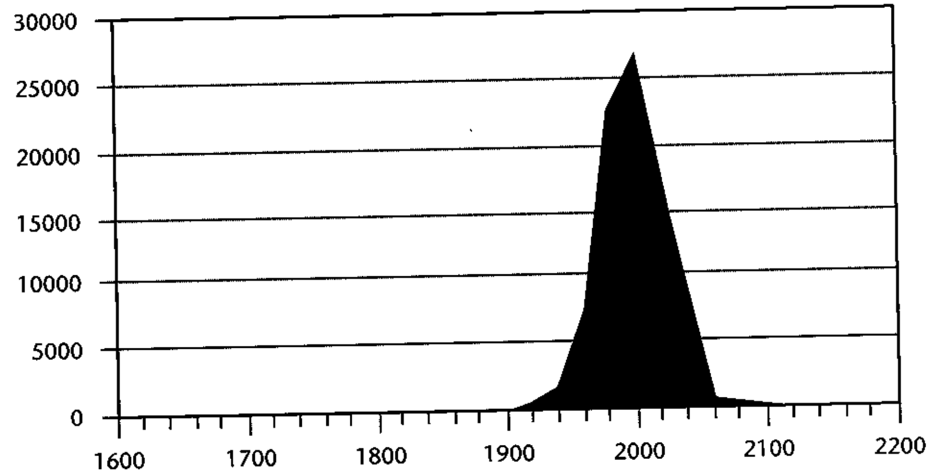

Figure 1. World oil production from 1600 to 2200, history and projection, in millions of barrels per year (Source: C. J. Campbell)

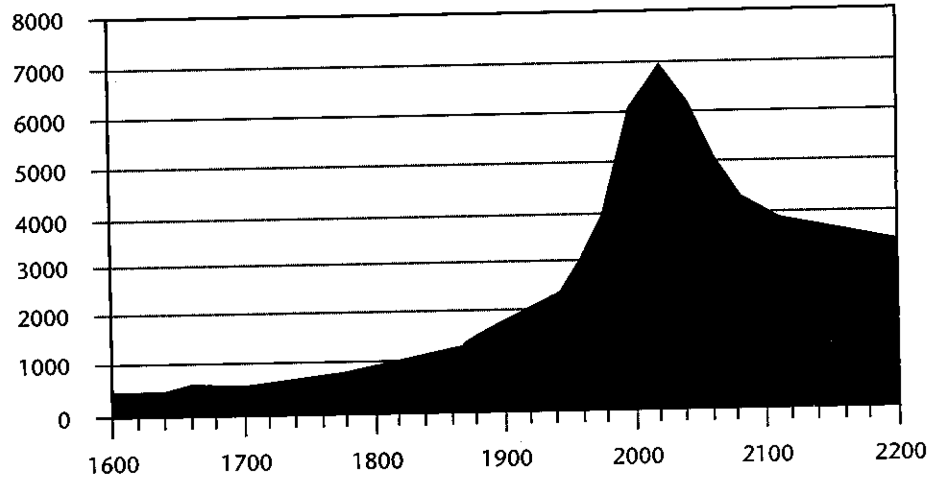

Figure 2. World population from 1600 to 2200, history and projection, assuming impacts from oil depletion, in millions (Source: C. J. Campbell)

environmental degradation, climate change, and increasing human dependency on a "phantom" carrying capacity.

Pollution was the first drawback of fossil fuel use to make itself apparent. Of course, pollution was hardly unknown before fossil fuels — it was apparent in the smoke of wood fires blackening winter skies over medieval cities, the horse manure clogging streets in 19th-century London and New York, and the tailings from mines ruining surrounding land and water throughout most of the civilized world since the dawn of civilization itself. But with the advent of the petrochemical industry, the toxic load on the environment has increased dramatically and quickly. Over the course of a few decades, chemical engineers synthesized tens of thousands of new, complex organic compounds for a wide variety of purposes. Few of these chemicals were safety-tested; of those that were, many turned out to have toxic effects on humans or other organisms. The undesirable consequences of the spread of these chemicals into the environment were sometimes dramatic, with rates of respiratory ailments and cancers soaring, and at other times more subtle, with estrogen-mimicking chemicals disrupting reproductive processes in fish, birds, amphibians, and mammals, including humans.[19]

The second danger of the drawdown method, which has more recently begun to make itself known, is climate change resulting from the global accumulation of greenhouse gases. The world's oil and coal fields represent vast stores of carbon that have been sequestered under the Earth's surface for hundreds of millions of years. With the advent of the industrial revolution, as these stores of carbon began to be mined and burned at an increasing rate, that carbon was released into the atmosphere as carbon dioxide (CO_2). There is strong evidence to suggest that elevated levels of carbon dioxide trap heat in the global atmosphere, creating a greenhouse effect that gradually warms the planet. Climate records derived from Greenland ice cores indicate a very close correlation between atmospheric carbon dioxide concentrations and global temperatures. Around the beginning of the 20th century, both CO_2 concentrations and global temperature began perceptibly to rise. For the previous 10,000 years, the amount of carbon in our atmosphere had remained constant at 280 parts per million. By 1998, that amount had increased to 360 ppm and was projected to increase to 560 ppm by the middle of the current century. Climate scientists have projected a consequent increase in the average global temperature of 3 to 7 degrees Fahrenheit (2 to 5 degrees Celsius).

Thus we have, unintentionally, begun to disturb massive planetary systems that have kept much of the world's climate relatively hospitable to civilization for the last 10,000 years. We are heating the deep oceans, which leads to more frequent and intense El Niño weather patterns. The timing of the seasons is noticeably altered and most of Earth's glaciers are retreating at accelerating rates. The potential effects are catastrophic. They include the drowning of coastal cities and whole island nations as a result of rising sea levels and intensified storms; the proliferation of disease-spreading insects into new regions, resulting in cases of malaria perhaps doubling in tropical regions and increasing 100-fold elsewhere; and the loss of forests and wildlife that depend upon a stable climate, leading to vastly increased extinction rates and the collapse of whole ecosystems.[20] The Earth's climate is so finely balanced that global warming could result in a rapid flip in weather regimes. For example, cold, fresh water from the melting of the arctic ice pack could halt the Gulf Stream, plunging Europe and North America into a new Ice Age.

The third danger of the drawdown strategy is one that is discussed less frequently than either pollution or global warming, though its ultimate implications for humankind may be even more dire. This is our increasing dependency on energy resources that are depleting within historically narrow time frames. There are now somewhere between two and five billion humans alive who probably would not exist but for fossil fuels. Thus if the availability of these fuels were to decline significantly without our having found effective replacements to maintain all their life-sustaining benefits, then the global human carrying capacity would plummet — perhaps even below its pre-industrial levels. When the flow of fuels begins to diminish, everyone might actually be worse off than they would have been had those fuels never been discovered because our pre-industrial survival skills will have been lost and there will be an intense competition for food and water among members of the now-unsupportable population (Chapter 5 provides a closer look at the likely consequences of the anticipated petroleum depletion.).

Complexity and Collapse: Societies in Energy Deficit

The five strategies humans have adopted for capturing increasing amounts of energy (takeover, tool use, specialization, scope enlargement, and drawdown) have permitted societies to grow in size, scope, and complexity. However, it is important to note that the ramp of history, rising upward from the simplest Paleolithic hunter-gatherer bands to the heights of globalized industrial civilization, has not been a smooth one. Many civilizations have expanded their scope and complexity dramatically, only to dissolve back into simpler forms of social organization.

Archaeologists have understandably given much attention to the study of collapsed complex societies since the ruins left by the ancient Egyptians, Romans, Mayas, Greeks, Minoans, Mesopotamians, Harappans, and Chacoans provide a wealth of material for investigation. Why would a group of people intelligent enough to have built impressive temples, roads, and cities suddenly lose the ability to maintain them? Why would a society capable of organizing itself into a far-flung empire, with communications networks and distribution systems, suddenly lose its ability to continue? Such questions — as much as the ruins left behind — contribute to a widespread and perennial fascination with lost civilizations.

The literature on the subject is voluminous and includes speculation on the causes of collapse ranging from class conflict to mismanagement. Undoubtedly, the best modern research on this subject was done by archaeologist Joseph Tainter, whose book *The Collapse of Complex Societies* (1988) is now widely recognized as the standard work on the topic. In his book and related essays, Tainter takes an ecological view of society as an energy-processing structure and concludes that complex societies tend to collapse because *their strategies for energy capture are subject to the law of diminishing returns.*

Tainter describes complexity as a problem-solving strategy used by civilizations and empires. "For the past 12,000 years," he writes, these societies "have seemed almost inexorably to grow more complex. For the most part this has been successful: complexity confers advantages, and one of the reasons for our success as a species has been our ability to increase rapidly the complexity of our behavior."[21]

When Tainter uses the term "complexity," he is referring to "such things as the size of a society, the number and distinctiveness of its parts, the variety of specialized roles that it incorporates, the number of distinct social personalities present, and the variety of mechanisms for organizing these into a coherent, functioning whole."[22] Hunter-gatherer societies, for example, may have no more than a few dozen distinct social personalities whereas a modern census recognizes many thousands of occupational roles. More complex societies, Tainter notes,

> are more costly to maintain than simpler ones, requiring greater support levels per capita. As societies increase in complexity, more networks are created among individuals, more hierarchical controls are created to regulate these networks, more information is processed, there is more centralization of information flow, there is increasing need to support specialists not directly involved in resource production, and the like. All of this complexity is dependent upon energy flow at a scale vastly greater than that characterizing small groups of self-sufficient foragers or agriculturalists. The result is that as a society evolves toward greater complexity, the support costs levied on each individual will also rise, so that the population as a whole must allocate increasing portions of its energy budget to maintaining organizational institutions. This is an immutable fact of societal evolution, and is not mitigated by type of energy source.[23]

Tainter offers the following diagram (Fig.3) as a schematic representation of the trajectory of a typical complex society. At first, incremental investments in social complexity, new technologies, and expanding scope yield impressive returns. Agricultural production increases, and wealth captured from conquest flows freely as the society's increasingly formidable army invades surrounding states. But gradually the rates of return tend to diminish, even as requirements for further investments in institutional support (including investments in legitimization and coercion) are still increasing. This eventually makes the strategy of complexity itself less palatable to the population. According to Tainter,

> a society that has reached this point cannot simply rest on its accomplishments, that is, attempt to maintain its marginal return at the status quo, without further deterioration. Complexity is a problem-solving strategy. The problems with which the universe can confront any society are, for practical purposes, infinite in number and endless in variety. As stresses necessarily arise, new organizational and economic solutions must be developed, typically at increasing cost and declining marginal return. The marginal return on investment in complexity accordingly deteriorates, at first gradually, then with accelerating force. At this point, a complex society reaches the phase where it becomes increasingly vulnerable to collapse.[24]

From the perspective of the average citizen, the burden of taxes and other costs is increasing while at the local level there are fewer benefits. The idea of being independent thus becomes more and more attractive. Collapse, then, may simply entail the decomposition of society, as individuals or groups decide to pursue their own immediate needs rather than the long-term goals of the leadership. In other situations, collapse may entail the takeover of a society that is stressed because of declining marginal returns by another society that is still enjoying higher rates of return on its investments in strategic leveraging.

Tainter discusses this theory in relation to the well-documented collapse of 17 different civilizations. Regarding the Roman Empire, he writes:

> The establishment of the Roman Empire produced an extraordinary return on investment, as the accumulated surpluses of the Mediterranean and adjacent lands were appropriated by the conquerors. Yet as the booty of new conquests ceased, Rome had to undertake administrative and garrisoning costs that lasted centuries. As the marginal return on investment in empire declined, major stress surges appeared that could scarcely be contained with yearly Imperial budgets. The Roman Empire made itself attractive to barbarian incursions merely by the fact of its existence. Dealing with stress surges required taxation and economic malfeasance so heavy that the productive capacity of the support population deteriorated. Weakening of the support base gave rise to further barbarian successes, so that very high investment in complexity yielded few benefits superior to collapse. In the later Empire the marginal return on investment in complexity was so low that the barbarian kingdoms began to seem preferable.[25]

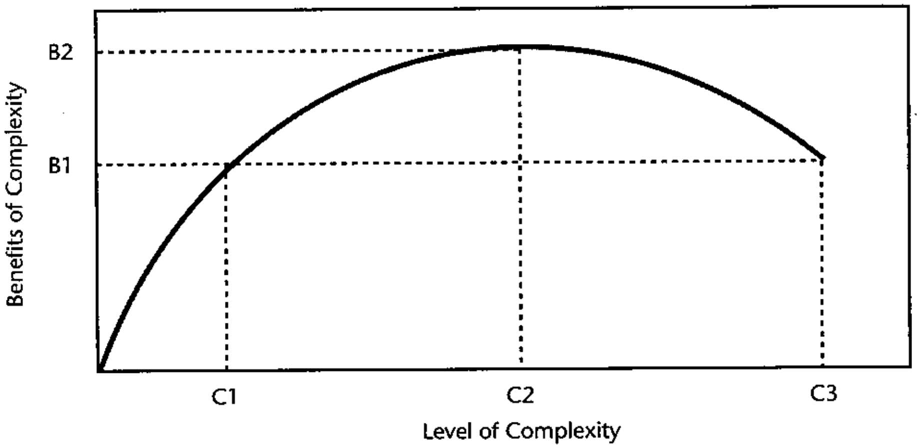

Figure 3: Benefits to a society from investments in complexity over time. Prior to point C1/B1, benefits are abundant; between points B1/C1 and B2/C2, returns on investments in complexity gradually diminish. After a society passes point B2/C2, its returns on investment become negative and it becomes vulnerable to collapse.

(Source: Joseph Tainter, "Complexity, Problem Solving, and Sustainable Societies")

This process of collapse is somewhat analogous to the phenomenon of population overshoot and die-off within a colonized ecosystem; indeed, the population of the city of Rome declined from over a million inhabitants in 100 AD to about 40,000 in 1100 AD.

Tainter's discussion of the Western Chou Empire, the Harappan Civilization, Mesopotamia, the Egyptian Old Kingdom, the Hittite Empire, the Classic Mayan civilization, and others shows a similarly tight fit between theory and historical data.

Western civilization from the Middle Ages to the present illustrates the theory in a somewhat different way. Rather than growing and declining in a simple curve, Western civilization has recovered and undergone at least two even greater growth surges due to its ability to find and exploit new energy subsidies at critical moments. The takeover of the Americas, Africa, India, and the Pacific Islands offered subsidies ranging from slave labor to new sources of metal ores and timber. The expansion of the Euro-American cultural and political influence that these new resources enabled, while impressive, probably could not have been sustained through the 20th century in the face of rising costs (e.g., for the maintenance of colonial administrations) and declining returns, had it not been for the discovery of fossil fuels, the greatest energy subsidy ever known. This discovery, as we have already seen, enabled the transformation of civilization itself into a form never before seen: industrialism.

The returns on early investments in drawdown and industrial production were staggering. Costs were extraordinary as well, but they could easily be borne. As Tainter puts it,

> with subsidies of inexpensive fossil fuels, for a long time many consequences of industrialism effectively did not matter. Industrial societies could afford them. When energy costs are met easily and painlessly, the benefit/cost ratio of social investments can be substantially ignored (as it has been in contemporary industrial agriculture). Fossil fuels made industrialism, and all that flowed from it (such as science, transportation, medicine, employment, consumerism, high-technology war, and contemporary political organization) a system of problem solving that was sustainable for several generations.[26]

This does not mean, however, that industrial civilization is immune to the law of diminishing returns. Tainter cites statistics indicating that already there have been steep reductions in returns on increasing US investments in education, military hardware, information processing, and scientific research. As we will see in more detail in Chapter 3, the drawdown of fossil fuels is itself subject to the law of diminishing returns. Early investments in drilling for oil yielded fabulous returns. But most of the largest and most productive oil fields were discovered within a century of the drilling of the first commercial well: rates of discovery peaked in the 1960s. And so, over time, the amount of energy that must be expended to find and extract each barrel of oil, or to mine each ton of coal, increases.

Tainter ends his book by drawing the following sobering conclusion: "However much we like to think of ourselves as something special in world history, in fact industrial societies are subject to the same principles that caused earlier societies to collapse."[27]

Applied Socio-Ecohistory: Explaining the American Success Story

So far in this chapter we have explored some of the basic energy principles at work in natural systems and human societies. In order to better illustrate these principles (and especially those discussed in the last two sections), let us use what we have learned to address a specific question that could add importantly to our understanding of global energy resource usage over the past two centuries: *Why is the United States of America currently the wealthiest and most powerful nation in the history of the world?*

Often this question is addressed through a discussion of ideas, personalities, and unique historical occurrences. We have all learned the names of early explorers, inventors, and politicians; we have been taught the importance of the American system of government, with its guarantees of freedoms and rights; and we have memorized the dates of important wars and other political events in US history. These are all of course essential to any explanation of US ascendancy. However, let us take an approach that focuses on energy and explore the extent to which America owes its prominent position in the world to energy resources and its people's ability to exploit them.

Such a discussion must begin with geology and geography. The North American continent, which Europeans began to explore and claim in the early 16th century, was a place of extraordinary biotic and mineral abundance. Early Spanish conquistadors found vast forests, animals for food and fur, fertile farmland, fresh water, iron, copper, silver, and gold — all in far greater quantities than existed in Europe. Eventually, the colonists' descendants also found an abundance of coal and petroleum. These energy resources proved to be especially valuable because they enabled the more intensive extraction and use of all other resources.

When Europeans first arrived in the New World, there were already other humans present. Why hadn't Native Americans taken more advantage of all these resources? Why was it not they who became world conquerors, sailing to Europe to claim it as a possession of the Iroquois, the Seminole, or the Lakota?

As Jared Diamond explains in his Pulitzer Prize-winning book *Guns, Germs, and Steel: The Fates of Human Societies*, Eurasia had been blessed with indigenous domesticable cereal grains and traction animals nonexistent in the Americas.[28] These permitted — perhaps even encouraged — the development of large-scale agriculture and stratified societies. The Europeans thus had a head start in applying the leveraging strategies discussed above. Their successes in expanding the carrying capacity of their environment meant that Europe, by the 16th century, was comparatively crowded and resource-depleted. Europeans were therefore highly motivated to expand their application of the takeover and scope-enlargement strategies by conquering and exploiting new lands. Most Europeans who came to America were not so much searching for freedom as escaping population pressure and resource depletion.

Still, things might have turned out differently: in the early 15th century, squadrons of large Chinese junks made several amazing voyages that carried them as far as Hormuz; had these expeditions continued, the Chinese might have become the first to circumnavigate Africa and sail the Atlantic and the Pacific. However, political troubles back home in China called a halt to the entire project; thus newly claimed territories in America acquired names like New Spain and New England, rather than New Beijing or New Canton.

As it turned out, the Europeans who arrived in North America regarded the land as essentially empty and saw the native peoples — who were making far fewer demands on resources than the Europeans themselves were accustomed to making — as unproductive savages. Europeans at first sought to enslave the natives, thus taking over the human muscle-energy of the continent in addition to its other resources. But many of the natives — millions, in fact; in some regions over 90 percent of the population — quickly succumbed to colonists' diseases, such as smallpox, measles, and influenza. These diseases were caused by microorganisms that had become integrated into the internal bodily ecosystems of Europeans through centuries of contact with domesticated animals; for the natives of the Americas, however, these microorganisms were exotic invasive species whose impact was utterly devastating.[29] In any case, the natives made poor slaves because most were accustomed to living in a more easy-going and egalitarian — namely less specialized and complex — social environment than were the Europeans, and often preferred death to lifelong servitude.

Nevertheless, it was clear that great wealth could be extracted from the continent if only there were sufficient energy available to farm the land and mine the ores. Quickly, Europeans seized upon the strategy of importing Africans as slaves. With the latter's intelligently directed muscle-power as motive force, the machinery of extraction went to work and produced great fortunes for thousands of colonists and their families — those, that is, who could afford to buy into this wealth-producing system. Because the Africans were typically kidnapped from kingdoms — complex societies — and then ripped from their cultural matrix (not only by transplanting them geographically but by preventing them from speaking their own languages and engaging in their own customs), they were somewhat more easily enslaved than were most Native Americans.

This discussion of "where" and "who" helps account for America's meteoric rise from colonial backwater to global superpower in a mere two centuries, but it is still not sufficient. We must also take into account the "when" of the US appearance on the world scene. Europeans had in fact arrived in North America several centuries before Columbus: the Norse and possibly the Irish made the voyage repeatedly between approximately 1000 and 1350 AD. However, all that ultimately resulted was the leaving behind of a few enigmatic stone inscriptions for future historians to puzzle over. As every musician knows, timing is of the essence. Jared Diamond notes that the

> second Eurasian attempt to colonize the Americas [in the 15th century] succeeded because it involved a source, target, latitude, and time that allowed Europe's potential advantages to be exerted. Spain, unlike Norway, was rich and populous enough to support exploration and subsidize colonies. Spanish landfalls in the Americas were at subtropical latitudes highly suitable for food production, based at first mostly on Native American crops but also on Eurasian domestic animals, especially cattle and horses. Spain's transatlantic colonial enterprise began in 1492, at the end of a century of rapid development of European oceangoing [Class C] ship technology, which by then incorporated advances in navigation, sails, and ship design developed by Old World societies (Islam, India, China, and Indonesia) in the Indian Ocean.[30]

Resources are of little benefit without the ability to exploit them. Imagine having several barrels of gasoline but no car or other motorized equipment with which to put that gasoline to use. This was essentially the situation not only of the Native Americans, but also, at first, of the invading Europeans with regard to America's energy minerals. Though the continent was rich in coal and petroleum, few people, if any, yet realized that fact.

However, the Europeans had spent many centuries making prior investments in tool making, and so the breakthrough to the production of Class D tools was for them merely the next step in a long evolution of strategic leveraging. As we have already noted, the entire process of industrialization was based on using fossil fuels (initially coal, later petroleum) to mechanize production and transport. Soon after the Industrial Revolution began in England, it became clear that North America in fact had a much greater natural abundance of energy minerals than did Europe. If the US had remained a colony, its energy resources would likely have been siphoned off to promote the production of still more wealth in the Old World. However, the American Revolutionary War had dissolved the former Crown Corporations of Virginia, Delaware, Massachusetts, etc., so that the people of the new nation of the United States of America were free to shape their own economic destiny by exploiting the continent's resources for their own benefit. Thus within a few decades the situation changed from being one in which Europe was taking resources from North America to one in which North America was taking industrial technology from Europe and putting it to more effective use due to its richer resource base. The US did not start the Industrial Revolution, but was poised to capitalize on it.

The history of the 19th century in America is a tale of snowballing invention, exploration, and extraction, each feeding the others. Political events were largely shaped by resource disputes. For example, the realization (by the industrial northern states) that America's future wealth lay far more in the extraction and use of concentrated fuels than in the continued reliance (by the agrarian southern states) on kidnapped African muscle-power may have played a role in the freeing of the slaves.

Overall, the US made the most of its energy-resource advantage. At first, wood fueled the mills and factories of the Northeast; soon it also fueled the railroads that brought raw materials to the factories and manufactured goods to the frontier. In the latter decades of the 19th century, coal took the place of dwindling wood supplies; and then in the 20th, oil — flowing initially from Pennsylvania and Ohio, then from southern California, then Texas and Oklahoma, and finally the Gulf of Mexico and Alaska — in turn fueled the automobile industry, modern agriculture, and the modern chemical industry. While European nations had to colonize far-off places like Indonesia in order to fill their increasing appetite for energy resources, the US could extract all it needed from within its borders. Its energy-resource base was so great that, until 1943, it remained a net petroleum exporter.

In the 20th century, while the old colonial powers (such as England, Spain, and Portugal) were reaping diminishing returns from their investments in conquest and while other aspiring colonial powers (Germany, Japan, and Italy) were thwarted in gaining access to energy resources in other lands, the US found itself in the rare and enviable position of having both abundant indigenous resources and the expertise, technology, and freedom to exploit them for its own benefit. It invested the wealth from these resources both in further technological development and in the production of by far the most powerful and sophisticated weapons systems the world has ever seen. Thus by the end of the Second World War the US was, from both an economic and a military point of view, the most powerful nation in the history of the world.

This is not to say that the promise of political and religious freedom had played no role in drawing millions of skilled and highly motivated immigrants from Europe — though many were simply driven out by overcrowding at home. Nor can one deny the role of extraordinary personalities: inventors, politicians, military leaders, and explorers whose names and accomplishments fill history books. However, it is also indisputable that without its wealth of minerals and energy resources, the US could never have achieved its current position of global dominance.

But American resources, however vast, were nevertheless limited. Throughout the 20th century, geologists combed the North American continent for oil, coal, and natural gas reserves. The US quickly became the most explored region of the planet. Americans were encouraged through advertising to buy private automobiles in order to take advantage of these energy resources, and they did so at a rate unparalleled in the industrialized world. By mid-century, however, older oil wells were running dry and newer wells were proving to be less productive. The rate of discovery of new petroleum resources in the continental US peaked in the 1930s; the rate of extraction of those resources peaked in 1970. But the energy-based "American Way of Life" had to be maintained in order to avoid political and economic disaster; therefore, further energy resources had to come from elsewhere.

Understandably, industrial and political leaders adopted a time-tested strategy — scope enlargement, or trade and transport — in order to make up the difference. The US began to buy oil at first, and soon natural gas, from other nations. Its balance of trade — historically positive — soon became overwhelmingly negative. Formerly the world's foremost lender and investor, the US soon became the world's foremost debtor nation. Meanwhile it continued to develop its already awesome military capability with which to enforce its priorities on the rest of the world, more blatantly so following the demise of its only competitor for global hegemony: the Soviet Union, itself geologically blessed with energy resources but handicapped by early barriers in exploiting those resources and by an economic-social system that discouraged individual initiative.

Soon after US petroleum production had peaked, official policy began emphasizing "free trade" as a global panacea for unemployment, underdevelopment, despotism, and virtually every other economic or political ill. Through its manipulation of the rules of global trade, the US sought to maintain and increase its access to natural resources worldwide. Those rules — written primarily by US-based corporations and encoded in policies of the International Monetary Fund (IMF), the World Bank, and the World Trade Organization (WTO) as well as in treaties like the North American Free Trade Agreement (NAFTA) — essentially said that wherever resources lie, they must be available for sale to the highest bidder. In other words, whoever has the money to buy those resources has a legally defensible right to them. According to those rules, the oil of Venezuela belongs to the US every bit as much as if it lay under the soil of Texas or Missouri. Meanwhile technology, or "intellectual property," was regarded as proprietary; thus nations with prior investments in this strategy were at an advantage while "underdeveloped" nations were systematically discouraged from adopting it.

In the early 21st century, growing opposition to globalization — peaceful and otherwise — began to emerge in mass public demonstrations as well as in terrorist attacks. Most Americans, however, informed only by commercial media outlets owned by corporations with energy-resource interests, remained utterly in the dark as to what globalization was really about and why anyone would object to it.

* * *

In this first chapter, we have focused on energy principles in physics, chemistry, ecology, and sociology. We have noted how important energy is for the functioning of ecosystems and societies, and have traced its role in the history of the US rise to global dominance.

As we have just seen, America became the preeminent world power in the 20th century not just because of its professed ideals of freedom and democracy, its ingenuity, and the hard work of its people, but more importantly because of its immense wealth of natural energy resources and its ability to exploit them. For the past three decades, the depletion of those resources has been propelling US economic, political, and military policy in a certain definable direction, which we will explore further in Chapter 5.

In order to better understand these developments and their likely consequences, we need to examine more thoroughly the recent history of energy resources and their impact on societies around the globe. It is to this subject that we turn next.

2

Party Time: The Historic Interval of Cheap, Abundant Energy

In 1859 the human race discovered a huge treasure chest in its basement. This was oil and gas, a fantastically cheap and easily available source of energy. We did, or at least some of us did, what anybody does who discovers a treasure in the basement — live it up, and we have been spending this treasure with great enjoyment.

— Kenneth E. Boulding (1978)

Oil has literally made foreign and security policy for decades. Just since the turn of this century, it has provoked the division of the Middle East after World War I; aroused Germany and Japan to extend their tentacles beyond their borders; the Arab Oil Embargo; Iran versus Iraq; the Gulf War. This is all clear.

— Bill Richardson, Secretary of Energy (1999)

Whether we are talking of an individual citizen or a whole community, "cataclysmic wealth" can have disastrous consequences .... Its use rises sharply to create new habits and expectations. These habits are accompanied by an irrational lack of care about usefulness or waste. The process develops habits in individual people, and institutions in whole societies, which accustom them to operating on the basis of excess and wastefulness; and, although different episodes have different endings, one prospect sees the affected groups, long after the cloudburst of wealth has passed, trying every kind of expedient — borrowing, sponging, speculating — to try to ensure that the private habits or public institutions of excess and waste are maintained. The result is at best a measure of social disintegration; at worst, collapse.

— Barbara Ward (1977)

Forests to precede civilizations, deserts to follow.

— François René Chateaubriand (ca. 1840) (including the oil and automobile companies). By taking it, our politicians have simply followed the path of least resistance.

This may be understandable, but the consequences — if the economists are wrong and the physical scientists are right — will be devastating for nearly everyone.

It is therefore particularly important that we think long and hard about the path not taken before it disappears from sight altogether. What if the Cassandras are right?

Throughout the rest of this book — primarily because of what I see as the overwhelming hard evidence in its favor, but also for the reason just cited — I will assume as correct the Cassandras' prediction that global oil production (all liquids) will peak some time during the remainder of this decade.

If we take that as a given, can we still avoid catastrophe by switching to other technologies and fuels in the years ahead? What, precisely, are our options?

4

Non-Petroleum Energy Sources: Can the Party Continue?

Under the rule of the "free market" ideology, we have gone through two decades of an energy crisis without an effective energy policy .... We have no adequate policy for the development or use of other, less harmful forms of energy. We have no adequate system of public transportation.

— Wendell Berry (1992)

The pattern of preferences for using energy efficiency to decrease demand and [for renewable energy sources] to supply energy has been consistent in the poll data for 18 years. This is one of the strongest patterns identified in the entire data set on energy and the environment.

— Dr. Barbara Farhar (2000)

Nonrenewable resources should be exploited, but at a rate equal to the creation of renewable substitutes.

— Herman Daly (1992)

Continuing to increase our dependency on petroleum consumption is clearly a suicidal course of action. The only intelligent alternative is to begin reducing energy consumption and finding alternative energy sources to substitute for petroleum.

— Paul Ehrlich (1974)

Total energy consumption is projected to increase from 96.1 quadrillion British thermal units (BTU) to 127.0 quadrillion BTU between 1999 and 2020, an average annual increase of 1.3 percent.

— US Department of Energy (1999)

This chapter focuses exclusively on a single vital question: *To what degree can any given non-petroleum energy source, or combination of sources, enable industrial civilization to survive the end of oil?*

Before we can make this assessment, it is important that we clearly understand what has made oil such a valuable energy commodity. Oil is

- easily transported (liquid fuels are more economically transported than solids, such as coal, or gases, such as methane, and can be carried in ships far more easily than can gases);
- energy-dense (gasoline contains roughly 40 kilowatt-hours per gallon);
- capable of being refined into several fuels, including gasoline, kerosene, and diesel, suitable for a variety of applications; and
- suitable for a variety of uses, including transportation, heating, and the production of agricultural chemicals and other materials.

Moreover, historically petroleum has been easy to access, which has helped give it a very high energy return on energy invested (EROEI). Net energy — or EROEI — is a subject we will touch on frequently in this chapter. In assessing each of the non-petroleum energy sources, I will refer to net-energy figures from Howard T. Odum's *Environmental Accounting, Energy and Decision Making* (1996), and C. J. Cleveland, R. Costanza, C. A. S. Hall, and R. Kaufmann's "Energy and the U.S. Economy: A Biophysical Perspective" (1984).[1] Odum assigns imported oil a current EROEI of between 8.4 (that is, 8.4 units of energy returned on every unit of energy invested in exploration, drilling, building of drill rigs, transportation, the housing of production workers, etc.) and 11.1, depending on the source.

However, for the period between 1950 and 1970, he calculates that oil had an EROEI of 40. Cleveland *et al.* calculated a greater than 100-to-1 return for oil discoveries prior to 1950, which declined to a 30-to-1 return by the 1970s.

In this chapter we will examine each of the most prominent non-petroleum energy sources, starting with those that are closest to oil in their characteristics (i.e., the other fossil fuels: natural gas and coal), then moving to nuclear and geothermal power, the renewables (solar power, wind, biomass, tides, waves, and hydro), hydrogen, and exotic sources (cold fusion and "zero-point" energy). Finally, we will explore the potential for energy conservation (not a "source," but an essential strategy) to ensure the survival of industrial societies as the petroleum interval comes to a close.

Natural Gas

In some respects, natural gas appears to be an ideal replacement fuel for oil: it burns more cleanly (though it still produces CO_2); automobiles, trucks, and buses can be converted to run on it; and it is energy-dense and versatile. Its EROEI is quite high. It has long been used to create nitrogen fertilizers for agriculture (through the Haber-Bosch process), for industrial processes like glassmaking, for electricity generation, and for household cooking and heating. Currently, natural gas accounts for about 25 percent of US energy consumption; 17 percent of the gas extracted is used to generate electricity. Thus there already is an infrastructure in place to make use of this fuel.

Could extraction be increased to make up for the projected shortfalls in oil? Some organizations and individuals claim there is enough gas available globally to last for many decades. Estimates for total reserves vary from about 300 to 1,400 tcf (trillion cubic feet). With such a wide range of figures, it is clear that methods of reporting and estimating are imprecise and speculative. The number 1,100 tcf is often cited; this would represent 50 years' worth of reserves at current rates of global usage. The ever-optimistic US Energy Information Agency (EIA) reports that the US also has about 50 years' worth of natural gas, with proven reserves of 177.4 tcf in 2001. As of 2001, annual usage was in the range of 23 tcf.[2]

Clearly, the EIA is assuming considerable future discovery, as current proven reserves would last fewer than ten years at current usage rates. That assumption — that future discoveries will more than quadruple current proven reserves — is highly questionable; moreover, we should also ask: Does natural gas depletion follow a Hubbert-type curve, so that we should expect a peak of production and a long period of decline to occur long before the last cubic foot is extracted?

Many industry analysts believe the outlook for future discoveries in North America is far less favorable than EIA forecasts suggest. In the decade from 1977 to 1987, 9,000 new gas fields were discovered, but the following decade yielded only 2,500 new fields. This general downward trend in discovery is continuing, despite strenuous efforts on the part of the industry. Matthew Simmons has reported that the number of drilling rigs in the Gulf of Mexico grew by 40 percent between April 1996 and April 2000, yet production remained virtually flat. That is largely because the newer fields tend to be smaller; moreover, because of the application of new technology, they tend to be depleted faster than was the case only a decade or two ago: new wells average a 56 percent depletion rate *in the first year of production.*

In a story dated August 7, 2001, Associated Press business writer Brad Foss noted that in the previous year, "there were 16,000 new gas wells drilled, up nearly 60 percent from 10,400 drilled in 1999. But output only rose about 2 percent over the same period, according to estimates from the Energy Department. The industry is on pace to add 24,000 wells by the end of the year, with only a marginal uptick expected in production."[3]

In June 1999, *Oil & Gas Journal* described how the Texas gas industry, which produces one-third of the nation's gas, had to drill 6,400 new wells that year to keep production from plummeting. Just the previous year, only 4,000 wells had to be drilled to keep production steady.[4]

According to Randy Udall of the Community Office for Resource Efficiency in Aspen, Colorado, "[n]o one likes talking about [natural-gas] depletion; it is the crazy aunt in the attic, the emperor without clothes, the wolf at the door. But the truth is that drillers in Texas are chained to a treadmill, and they must run faster and faster each year to keep up."[5]

US natural gas production has been wavering for years; in order to make up for increasing shortfalls, the nation has had to increase its imports from Canada, and Canada is itself having to drill an increasing number of wells each year just to keep production steady — a sign of a downward trend in discovery. A May 31, 2002 article by Jeffrey Jones for Reuters, entitled "Canada Faces Struggle Pumping More Natgas to US," begins ominously: "Canadian natural gas production may have reached a plateau just as the country's role as supplier to the United States is becoming more crucial due to declining US gas output and rising demand ...."

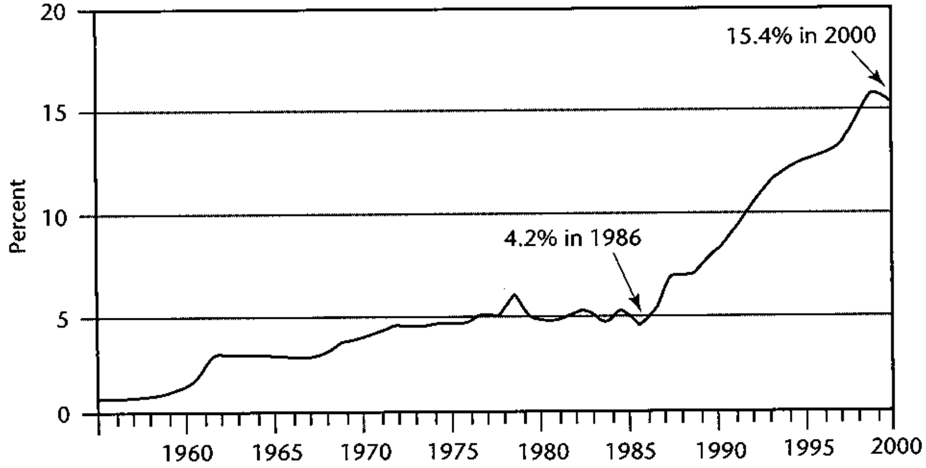

Figure 17. Net US imports of natural gas as share of consumption
(Source: US Energy Information Administration)

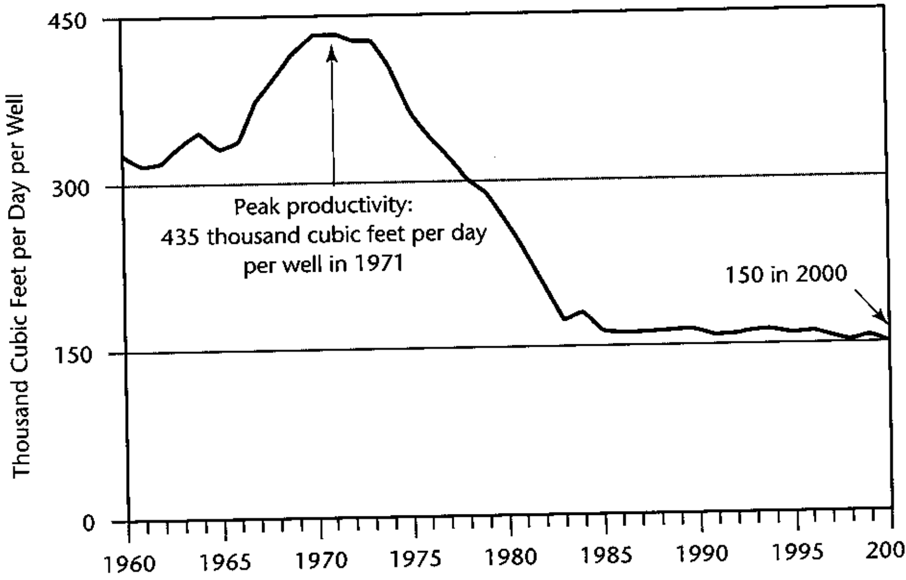

Figure 18a. US natural gas well productivity (Source: US Energy Information Administration)

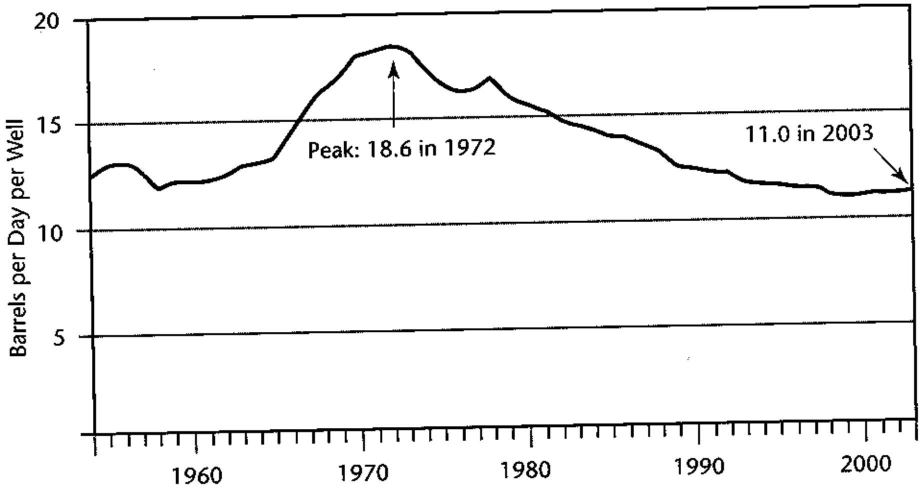

Figure 18b. Average oil well productivity, US 1950–2003 (Source: US Energy Information Administration)

Furthermore, Mexico has already cut its gas exports to the US to zero, and has become a net importer of the fuel.

A gas pipeline from Alaska could help, but not much. A three-foot-diameter pipeline would deliver only two percent of the projected needs for the year 2020.

Nearly all of the natural gas used in the US is extracted in North America. While gas is more abundant in the Middle East, which has over a third of the world's reserves, the amount that could be transported by ship to the American market is limited. The shipment process itself is feasible (there is only a 15 percent energy penalty from cooling and transportation), but the US has only four liquified natural gas offloading terminals at present, and it will take time and considerable investment to build more.

Moreover, nearly all of the existing LNG shipping capacity is spoken for by Japan, Korea, and Taiwan through long-term contracts. Europe and the Far East may be able to depend on gas from the Middle East and Russia for several decades to come, but that is probably not a realistic prospect for the US.

The public got its first hint of a natural gas supply problem in the latter months of 2000, when the wellhead price shot up by 400 percent. This was a more dramatic energy price increase than even the oil spikes of the 1970s. Homeowners, businesses, and industry all suffered. This gas crisis, together with simultaneous oil price hikes, helped throw the nation — and the world — into recession. Farmland Industries shut down some of its fertilizer plants because it could not afford to use expensive natural gas to make cheap fertilizer; many consumers were dismayed to find that their utility bills had doubled. A frenzy of new drilling resulted, which, together with a scaling back of demand due to the recession, enabled the natural gas market to recover so that prices eased back. Yet by the spring of 2001, wellhead gas prices were still twice what they had been twelve months earlier, and gas in storage had reached its lowest level ever. The nation narrowly averted serious shortages again in 2003; however, unusually mild winter and summer weather in 2004 enabled the refilling of underground gas storage reservoirs. The US has managed to avoid a train wreck so far, but given declining production, the event seems inevitable, whether it occurs this year or next.

The increasing demand for gas is coming largely from an increasing demand for electricity. To meet growing electricity needs, utilities in 2000–2001 ordered 180,000 megawatts of gas-fired power plants to be installed by 2005. This strategy seemed perfectly logical to the utilities' managers since burning gas is currently the cheapest and cleanest way to convert fossil fuel into electricity. But apparently no one in the industry had bothered to inquire whether there will be enough gas available to fire all of those new generators over their useful lifetime. Many exploration geologists are doubtful. By mid-2002, plans for many of those new gas-fired plants were being cancelled or delayed.

Does natural gas extraction follow the same Hubbert curve as does oil extraction? Oil wells are depleted relatively slowly, whereas, as we have seen, gas wells — especially newer ones — often deplete much more quickly. The typical natural gas well production profile rises from zero, plateaus for some time, and then drops off sharply. However, in aggregate, combining all of the natural gas wells in a country or large geographical region, extraction does follow a modified Hubbert curve, with the right-hand side of the curve being somewhat steeper than that for crude.

Hence, natural gas will not solve the energy-supply problem caused by oil depletion; rather, it may actually *compound* that problem. Our society is already highly dependent on natural gas and becoming more so each year. But soon we are likely to see a fairly rapid crash in production. As my colleague Julian Darley has written in his book *High Noon for Natural Gas: The New Energy Crisis*, "The coming shortage of natural gas in the United States and Canada, compounded by the global oil peak and decline, will try the energy and economic systems of both countries to their limits. It will plunge first the United States, then Canada, into a carbon chasm, a hydrocarbon hole, from which they will be hard put to emerge unscathed."[6]

Many alternative energy advocates have described natural gas as a "transition fuel" whose increased usage can enable the nation to buy time for a switch to renewable energy sources. However, in view of the precarious status of North American gas supplies, it seems more likely that any attempt to shift to natural gas as an intermediate fuel would simply waste time and capital in the enlargement of an infrastructure that will soon be obsolete anyway — while also quickly burning up a natural resource of potential value to future generations.

Coal

Currently, the US derives about as much energy from coal as it does from natural gas. Approximately 90 percent of coal mined and burned is used to generate electricity.

Coal is the most abundant of the fossil fuels, but also the most controversial one because of environmental destruction caused by coal mining, emissions from burning coal (including carbon dioxide and acid rain-causing sulphur oxides), and its inefficiency as an energy source. Coal producers typically fight all attempts to regulate emissions or to improve efficiency, and nearly all progress in these areas has come from government research in cooperation with electric utility companies.

Demand for coal has increased over the past few decades at an average pace of about 2.4 percent per year (meaning that, at current rates of increase, total usage doubles every 30 years). The EIA estimates that recoverable reserves in the US amount to about 275 billion short tons (bst), representing roughly 25 percent of total world reserves. Production in 1998 amounted to about 1.1 bst; at that rate of usage, current reserves could theoretically last 250 years. However, the EIA also notes that "much of this may not be mined because of sulfur content, unfavorable quality, mining costs and/or transportation infrastructure."

Even given these caveats, and also taking into account the fact that rates of usage are projected to continue growing, it might seem safe to assume that there are theoretically still several decades' worth of coal reserves in the US. Moreover, these reserves are already known and mapped; expensive exploration is not needed in order to locate them.

With coal, impending shortage does not appear to be as much of a problem as with oil and natural gas; however, its inefficiency, pollution, and declining net energy yield cast a pall on prospects for the increased use of coal to replace dwindling oil. Currently, we use oil to mine coal. Most of the increased coal production during the past three decades has been from opencut (open-pit) mines that are worked by relatively few miners using giant earth-moving machines that can consume as much as 100 gallons of diesel fuel per hour. As petroleum becomes less available, the energy used to mine coal will have to come from coal or some other source.

At the same time, the most easily accessed coal beds will have become depleted: like cheap oil, cheap coal relies on reserves that lie relatively close to the surface, but these represent only a small percentage of the world's total coal resources. As those are exhausted, producers will have to return to traditional underground mining. But many underground mines have been run down and allowed to flood. Moreover, most skilled miners have lost their jobs and have been routed into other occupations. Mining is difficult, dreary work, and few miners want their children to follow in their footsteps. In areas of the Western world where underground coal mining is still practiced, the average age of miners is over 40. Thus, in order to maintain or grow coal production in the future, the industry will have to find new workers as well as develop new methods of production. As this occurs, society will be deriving less net energy from the process.

In their book *Beyond Oil*, John Gever *et. al.* describe coal's depletion profile and decreasing net energy yield as follows:

> Because the United States has used only a small fraction of its total coal supply, a Hubbert analysis is only speculative ....
>
> Besides glossing over the environmental damage resulting from heavy coal use (acid rain, particulate pollution, carbon dioxide buildup in the atmosphere), optimistic projections have been based on total coal resources and have ignored the fact that substantially less net energy may ultimately be obtained from these supplies. The quality of mined coal is falling, from an energy profit ratio of 177 in 1954 to 98 in 1977 .... These estimates include only fuel used at the mine, however, and do not include the considerable amounts of energy used to build the machines used in the mines, to move the coal away from the mines, and to process it. When these costs are included, the shape of the energy profit ratio curve changes .... [and drops] to 20 in 1977... If it continues to drop at this rate, the energy profit ratio of coal will slide to 0.5 by 2040.[7]

The authors' last statement deserves some emphasis: an energy profit ratio of 0.5 means that twice as much energy would be expended in coal production as would be yielded to do useful work. Coal has a relatively low energy density to begin with, and as miners exhaust the more favorable seams and then move on, the average heat content of a pound of coal is gradually dropping. If the study by Gever and his co-authors is correct, from a net-energy standpoint *coal may cease to serve as a useful energy source in only two or three decades.*

A recently published Hubbert analysis of coal production in the US predicts that, depending on the rate of demand, production will peak between 2032 and 2060.[8]

It is theoretically possible to use coal as the raw material from which to make synthetic liquid fuels that could directly replace petroleum. The process has already been tested and used; after all, it kept the Germans going during World War II, and an improved version is currently employed by the Sasol Company in South Africal. But the net energy yield from coal-derived liquids is extremely low and will only decline further as the net energy from coal itself dwindles. Walter Youngquist writes:

> If coal were to be used in the United States as a substantial substitute for oil by liquefying it, the cost of putting in place the physical plants which would be needed to supply the United States with oil as we use it now would be enormous. And to mine the coal which would have to go into these plants would involve the largest mining operation the world has ever seen.[9]

It may be possible to improve the efficiency of the process of releasing coal's stored energy. The most promising proposal in this regard comes from the Zero Emission Coal Alliance (ZECA), a program started at New Mexico's Los Alamos National Laboratory. ZECA has designed a coal power plant that extracts hydrogen from coal and water and then uses the hydrogen to power a fuel cell (we will discuss hydrogen and fuel cells in more detail below). The ZECA plants would attempt to recycle nearly all waste products and heat. Promoters claim that ZECA plants could produce electricity with an efficiency of 70 percent, compared to an average efficiency of about 34 percent at current combustion-based coal power plants (though newer combustion technology already yields greater efficiencies, in the range of 55 percent). That would mean releasing twice the energy from the same amount of coal, as compared to the present average. ZECA's system is not truly zero-emission (no energy production system is), but does represent a significant potential improvement over combustion-based technologies. However, ZECA's process for the sequestration of CO_2 will probably constitute a significant drain on net energy yields, and designers say the necessary fuel-cell technology is still at least five years away from commercial application.

Abundant coal, used to generate electricity, will enable us to keep the lights burning for a few more years; but, taking into account its other limitations — and especially its rapidly declining net energy yield — we cannot expect it to do much more for us in the future than it is already doing.

Nuclear Power

In a nuclear-powered electrical generating plant, uranium fuel rods are brought together under highly controlled conditions to create an atomic chain reaction that produces great heat. That heat is transferred to water, changing it to steam, which turns turbines to generate electricity.

The first commercial plant built in the US was the Shippingport, Pennsylvania, Atomic Power Station of the Department of Energy and the Duquesne Light Company. In a dramatic high-tech dedication ceremony, ground was broken in 1954 by President Dwight D. Eisenhower, who also opened the plant on May 26, 1958. Nuclear power was hailed as the nation's route to permanent prosperity; in reality, however, the DoE's highly touted "Atoms for Peace" program was a direct outgrowth of the nation's nuclear weapons program and served both as a public relations exercise and as a source for fissile materials for warheads.

Many nuclear power stations were built during the 1960s and '70s; today, 103 are operational in the US. In the 1950s, promoters promised that nuclear power would be so cheap as to be essentially free; but experience proved otherwise. Today, electricity from nuclear plants is inexpensive — the industry sometimes cites costs as low as two cents per kilowatt-hour — but this is true if *only* direct costs are considered. If the immense expenditures for plant construction and safety, reactor decomissioning, and waste storage are taken into account, nuclear power is very expensive indeed.

During the 1970s and '80s, an antinuclear citizens' movement was successful in swaying public opinion against nuclear technology and in discouraging the further growth of the industry. The movement's warnings about the dangers of nuclear power were underscored by serious reactor accidents at Three Mile Island in Pennsylvania and Chernobyl in the Soviet Union; other less-publicized accidents have plagued the industry from its inception and continue to do so. As a result of both greater-than-anticipated expenses and public wariness, no orders for new plants have been placed in the US since the 1970s.

Nuclear power plants produced 3.6 percent of all the energy consumed in the US in 1980; by 2000, that number had climbed to 8.1 percent. This increase was due not to the building of new reactors, but to increased efficiency in the operation of existing plants. In 2000, the industry achieved a record overall average capacity factor (the percentage of potential output actually achieved on average) of nearly 86 percent, up from 58 percent 20 years earlier.

Today about 20 percent of all the electricity generated in the US comes from nuclear sources. Globally, 12 percent of the world's electricity, and 5 percent of the total energy consumed, are nuclear-generated. Some nations derive much more of their energy from nuclear plants than does the US: France, for example, gets 77 percent of its electricity from atomic energy, Belgium 56 percent, and Sweden 49 percent. There are currently 442 reactors operating worldwide. In Western Europe, France is the only country still building nuclear plants; only in Asia is the nuclear-power industry expected to expand significantly in the foreseeable future.

Could nuclear power take up the slack as energy from petroleum production declines? Those who argue that it could claim that nuclear power is:

Abundant: There is a virtually limitless supply of fuel (assuming breeder reactors, which reprocess spent fuel);

Clean: It is non-polluting, having no CO_2 emissions; wastes are produced in small quantities and the problem of their disposal will be solved once a single permanent repository is created;

Practical: Nuclear fuel has the highest energy density of any fuel known; further, nuclear power is inexpensive, the produced electricity being cheaper than energy from coal; and

Safe: It is safer than many people believe, and becoming safer all the time. The likelihood of a person dying from a nuclear accident is already far lower than that of dying in an airplane crash, while new technology on the drawing boards will make nuclear power virtually 100 percent safe in the future.

However, when these claims are examined in detail, a very different picture emerges.

Abundant? The fuel supply for nuclear power is virtually limitless if we use fast-breeder reactors to produce plutonium — which is one of the most poisonous materials known and is used to make nuclear weapons. But only a few fast-breeder reactors have been constructed, and they have proved to be prohibitively expensive, largely as a result of the need for special safety systems.

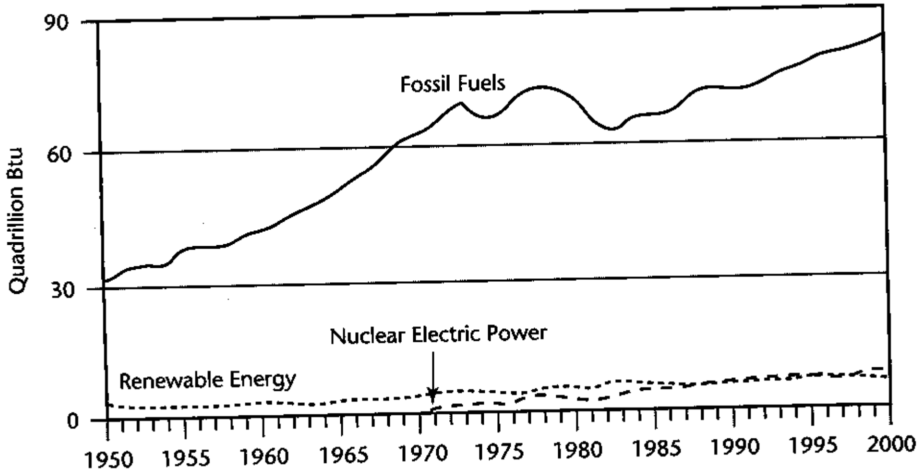

Figure 19. US energy consumption by source
(Source: US Energy Information Administration)

These reactors generate an extraordinary amount of heat in a very small space and use molten metals or liquid sodium to remove the heat. Designing reactors to take these properties into account has made them costly to build and maintain. It also makes them susceptible to serious fires and long shutdowns: the French Superphoenix reactor operated for less than one year during the first ten years after it had been commissioned.

France and the UK, despite having pursued breeder programs for several decades, have no plans for constructing more such plants. Japan has not restarted its Monju reactor, which was shut down after a sodium fire in December 1995. Among countries that have constructed breeders, Russia alone supports further development.

It is also possible to reprocess spent fuel into a form known as MOX (mixed oxide), which consists of a mixture of plutonium and uranium oxides. Reprocessed MOX fuel can then be used to replace conventional uranium fuel in power plants. However, only two MOX plants have been built (one in the UK, the other in France), and both have turned out to be environmental and financial nightmares.[10]

Uranium — the usual fuel for conventional reactors — must be mined, and it exists in finite quantities. The US currently possesses enough uranium to fuel existing nuclear reactors for the next 40 years.[11] The mining process is wasteful, polluting, and dangerous: the early New Mexico uranium mines, which employed mostly Navajo workers, ruined thousands of acres of Native lands and poisoned workers and their families. The entire episode constitutes a horrific and permanent blot on the industry's record.[12]

Further, much of the energy needed to mine uranium currently comes from oil. As petroleum becomes more scarce and expensive, the mining process will likewise become more costly and will yield less net energy.

Clean? Vice President Dick Cheney told CNN on May 8, 2001, that nuclear power "doesn't emit any carbon dioxide at all."[13] But this is true only in the sense that the nuclear chain reaction itself doesn't create such emissions. Mining uranium ore, refining it, and concentrating it to make it fissionable are all highly polluting processes. If the whole fuel cycle is taken into account, nuclear power produces several times as much CO_2 as renewable energy sources.

The assertion that nuclear waste is only produced in small quantities is misleading. Direct wastes include roughly 1,000 metric tons of high- and low-level waste per plant per year — hardly a trivial amount, given that much of this waste will pose hazards for thousands or tens of thousands of years to come. Further-more, this figure does not include uranium mill tailings, which are also radioactive and can amount to 100,000 metric tons per nuclear power plant per year.[14]

Can the problem of nuclear waste be solved by the creation of a permanent repository? To assume so is to indulge in wishful thinking. After nearly five decades of the development and use of atomic energy, no country in the world has yet succeeded in building a permanent high-level nuclear waste repository. Moreover, the transporting of wastes to such a central repository would create extra dangers.[15]

Practical? It is true that nuclear fuel has an extraordinarily high energy density, but this is the case only for uranium that has already been separated from tailings and been processed — which itself is a far more hazardous and energy-intensive procedure than drilling for oil or mining coal.

The costs typically quoted for nuclear-generated electricity (1.8¢-2.2¢/kWh) are operating costs only, including fuel, maintenance, and personnel. As noted earlier, such figures omit costs for research and development, plant amortization and decommissioning, and spent-fuel storage. Fully costed, nuclear power is by far our most expensive conventional energy source. Indeed, total costs are so high that, following the passage of energy deregulation bills in several states, nuclear plants were deemed unable to compete, and so utility companies like California's PG&E had to be bailed out by consumers for nuclear-related "stranded costs."[16] Germany has decided to phase out nuclear power for both economic and environmental reasons.

If nuclear energy is not cheap, is it at least reliable? Certainly more so than it was two or three decades ago. However, it is worth noting that problems at the Diablo Canyon and San Onofre reactors contributed significantly to California's energy crisis in 2001. Nuclear power plants are extremely complex — many things can go wrong. When technical failures occur, repair costs can be much higher than is the case with other types of generating plants.

Safe? For the general public, safety is probably the foremost concern about nuclear power. Siting nuclear plants has always been a challenge, as communities typically fear becoming the next Three Mile Island or Chernobyl. Earthquake zones must be ruled out, along with most urban areas (due to evacuation problems). While the statistical likelihood of any given individual dying in a nuclear accident is quite low, if a truly catastrophic accident were to occur many thousands or even millions could be sickened or die as a result. Nuclear power's record of mishaps is long and disturbing. It is a telling fact that the industry has required special legislation (the Price-Anderson Act) to limit the liability of nuclear-power plant operators in the event of a major accident. If the technology were as safe as that in conventional generating plants, no such measure would be needed. Following the terrorist attacks of September 11, many commentators pointed out that if the airplane hijackers had targeted nuclear power plants rather than office buildings, the resulting human toll would have been vastly greater.

Extraordinary safety claims have been made for a new design of high-temperature reactor, the Pebble Bed Modular Reactor. However, this technology is strictly theoretical, never yet having been tested in practice. Even the International Atomic Energy Agency's International Nuclear Safety Advisory Group has expressed misgivings about claims that the ceramic coating of the fuel "pebbles" can take the place of a normal reactor containment building. This coating consists mostly of graphite; and though graphite has a very high melting point, it can burn in air (graphite burned in the Chernobyl disaster as well as in the 1957 Windscale fire), so it is important to exclude air from the reactor. Current assertions that these untested technologies will be "100 percent safe" are probably about as believable as claims made in the 1950s that nuclear-generated electricity would be "too cheap to meter."[17]

These are all important concerns in assessing to what extent the deployment of nuclear power has been successful or even acceptable so far. But in deciding whether this energy source can help us through the transition away from oil and natural gas, we need to consider three other questions: Can the technology be scaled up quickly enough? What is its EROEI? And to what extent can it substitute for petroleum in the latter's current primary uses, such as in transportation and agriculture?

Scaling up the production of electricity from nuclear power would be slow and costly. In the US, just to replace current electricity generated by oil and natural gas, we would need to increase nuclear power generation by 50 percent, requiring roughly 50 new plants of current average capacity. But this would do nothing to replace losses of energy to transportation and agriculture as petroleum becomes less available.

Since coal is currently used mostly for electricity generation, nuclear power could conceivably substitute for coal; in that case, nuclear generation would have to increase by 250 percent — requiring the construction of roughly 250 new atomic power plants.

But using atomic energy as a replacement for petroleum is much more problematic. To replace the total amount of energy used in transportation with nuclear-generated electricity would require a vast increase (on the order of 500 percent) in nuclear generation capacity. Moreover, the replacement of oil — gasoline, diesel, and kerosene — with electricity in the more than 700 million vehicles worldwide constitutes a technical and economic problem of mammoth proportions. Current storage batteries are expensive, they are almost useless in very cold weather, and they need to be replaced after a few years of use. Currently, there are no batteries available that can effectively move heavy farm machinery or propel passenger-carrying aircraft across the oceans. (We will return to the problem of storing electrical energy later in this chapter, in discussions about hydrogen and fuel cells.)

Finally, the EROEI for nuclear power — when plant construction and decommissioning, waste storage, uranium mining, and all other aspects of production are taken into account — is fairly low. Industrial societies have, in energy terms, been able to afford to invent and use nuclear technologies primarily because of the availability of cheap fossil fuels with which to subsidize the effort.

For all of these reasons, it would be a disastrous error to assume that nuclear power can enable us to maintain business as usual when energy shortages arise due to the depletion of fossil fuels. New nuclear plants will no doubt be proposed and built as energy shortages arise; however, the associated costs will be too high to permit the construction of enough plants, and quickly enough, to offset the decline of cheap fossil fuels.

Wind

As we saw in Chapters 1 and 2, the capture of energy from wind — first by sails for transportation over water, and then by mills used to grind grain or pump water — predates industrialism. Today, sleek high-tech turbines with airplane propeller-like blades turn in response to variable breezes, generating an increasing portion of the world's electricity.

Winds arise from the uneven heating of the Earth's atmosphere by the Sun, as well as from Earth's surface irregularities and its axial rotation. Winds are generally strongest in mountain passes and along coastlines. The world's best coastal wind resources are in Denmark, the Netherlands, California, India, southern Argentina, and China; "wind farms" have been developed in all of these places.

Wind is a limited but renewable energy resource: unlike fossil fuels, winds are not permanently "drawn down" by their use. Once a wind turbine is installed, costs are incurred primarily for its maintenance; wind itself is, of course, free.

Of all renewables, wind is the one that, on a global level, is being developed the fastest. Wind power is approaching 40 gigawatts in installed capacity worldwide, out of the total electrical generating capacity of 3000 gW. Germany and Spain have recently become the world leaders in installed wind generating capacity. In the US, growth in the industry slowed in the 1990s but began a resurgence in 2000; about one percent of all electricity generated in the nation now comes from wind.

Wind-turbine technology has advanced dramatically in the past few years. Only a decade ago, engineers envisioned turbines with a maximum capacity of 300 kW, and blade rotation speeds were such that many areas had to be excluded from siting consideration for environmental reasons (turbine blades sometimes kill endangered birds, which tend to migrate along coastal areas). The optimum wind speeds for the turbines produced then were 15 to 25 MPH and only about 20 percent of actual wind energy could be converted to electricity.

Turbines that are being developed and installed today have capacities in the range of two to three megawatts. Blade rotation is much slower (resulting in less likelihood of bird kill), and efficiencies have been improved significantly. Moreover, the newer turbines can operate in more variable winds — with speeds ranging from about 7 to 50 MPH.

The cost of wind-generated electrical power is declining quickly. The National Renewable Energy Laboratory (NREL) estimates that by 2010 average prices will be in the range of 3.5¢/kilowatt-hour. The Lake Benton Wind Farm in

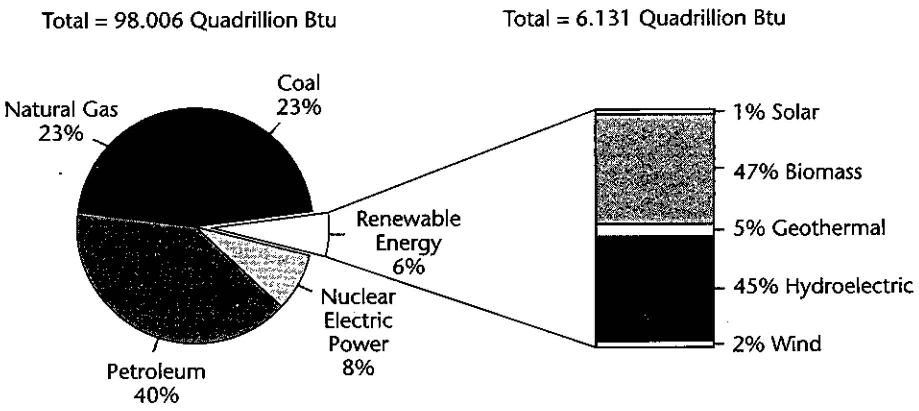

Figure 20. US energy consumption by source, showing renewables, 2003

(Source: US Energy Information Administration)

Minnesota, operational as of 2002 and using 1 mW turbines, produces wind-generated electrical power at 3.2¢/kWh. Another large project, on the Oregon/Washington border, is expected to produce power at 2.5¢/kWh. These prices are already competitive with other generating sources; and as the EROEI of coal declines and natural gas supplies dry up, wind power will look even more inviting.

New vertical-axis turbine designs being developed at Lawrence Berkeley Laboratories in cooperation with the Makeyev State Rocket Center in Miass, Russia, could make wind power more feasible in a wider range of situations. Prototypes feature vertical fiberglass blades that rotate around a central mast. The company that has been formed to commercialize the design, Wind Sail, expects to market small turbines to homeowners. Previous horizontal-axis designs were noisier and had a tendency to kill birds — problems solved by the new design. Vertical-axis turbines are also potentially more efficient than similar-sized horizontal-axis turbines.[18]

How much energy could be derived from wind? Theoretically, a great deal. A good guide is a 1993 study by NREL that concluded that about 15 quads (quadrillion BTU) of energy could be produced in the US per year. Since the newer turbines are capable of operating in a wider range of wind conditions, that potential could conceivably now be in the range of 60 quads. Total energy usage in the US is about 100 quads.[19]

However, the realization of that potential will require huge investments and a strong commitment on the part of policymakers. Investment will be required not just for the turbines themselves, but also for new transmission lines: a 1991 California study estimated that only 12 percent of the "gross technical potential" for wind power in that state could be realized given the existing transmission infrastructure.

In addition, it will be necessary to solve technical problems arising from wind power's intermittent daily, monthly, and seasonal availability. Often, peak availability of wind does not correspond with peak energy demand. This is not an insurmountable problem: energy storage systems (such as the Regenesys regenerative electrochemical fuel cell) are in development that may in the future eliminate the daily variability of electricity generation from wind.[20] Also, peak wind generation that exceeds momentary demand could be used to produce hydrogen (see 167).

Over the short term, the problem of intermittency should not simply be shrugged off. Germany, which now leads the world in installed wind electrical generation capacity (14,350 Megawatts at the end of 2003), therefore also has the most experience with the practical problems associated with wind energy. A recent report from EON, the largest grid operator in Germany, points out that it is necessary to have 80 percent of wind capacity available at all times from power stations that can produce on-demand energy (i.e., coal, nuclear, hydro, geothermal, or natural gas plants). In addition, according to the report, "if wind power forecast differs from the actual infeed, the transmission system operator must cover the difference by utilizing reserve capacity. This requires reserve capacities amounting to 50 to 60 percent of the installed wind capacity." The report's authors also point out that wind power often requires the construction of new grid capacity to transport the electricity from remote areas, where the wind farms operate, to populated areas where the electricity is consumed.[21]

Though the siting of wind turbines presents a challenge, imaginative solutions are being proposed. Most of the best sites are privately owned and in use for other purposes — principally, for agriculture. However, wind turbines do not take up exorbitant amounts of space, and wind farms and conventional farms need not be mutually exclusive. A Minnesota farmer earning less than $30 per acre per year from livestock and $250 per acre from crops might earn $1,000 per acre from land rental for a wind farm and continue to use most of the land for cattle or corn.

At the moment, the EROEI for wind is the best for any of the renewables that has much opportunity for expansion. While Odum gives a figure of 2+, a Danish study suggests an energy payback period of only two to three months, which might translate to an EROEI of 50 or more.[22] Though even the latter number may be relatively low when compared to the EROEI for oil and natural gas during the expansion phase of industrial civilization (when it occasionally surpassed 100-to-1), it probably already exceeds the EROEI for these fossil fuels as their net energy yield gradually wanes due to depletion.

Wind can deliver net energy; the challenge for industrial societies is to scale up production quickly enough to make up for the energy decline from dwindling oil and natural gas supplies. Just to produce 18 quads of wind power in the US by 2030 (never mind the 60 quads of theoretical potential) would require the installation of something like half a million state-of-the-art turbines, or roughly 20,000 per year starting now. That is five times the present world production capacity for turbines. This feat could be accomplished, but it would require a significant reallocation of economic resources. Meanwhile, most of the energy needed for that undertaking would have to come from dwindling fossil fuels.

Thus even if current policymakers had the political will to undertake such a transition, industrial societies would still face a wrenching adjustment to a lower-energy regime. This sobering assessment is underscored by the difficulty of substituting wind-generated electricity for oil's current uses. As we saw in the previous section on nuclear power, electricity is not well suited to the powering of our current transportation and agriculture infrastructure. The rebuilding of that infrastructure is itself a gargantuan task in both economic and energy terms, and one that is still beset by technical challenges.

Nevertheless, it is clear that, of the alternatives we have surveyed so far, wind is probably the most practicable.

Solar Power

Since virtually all terrestrial energy sources derive ultimately from the Sun, the development of direct means of capturing usable energy from sunlight seems an obvious way to satisfy industrial societies' prodigious appetites for power. There is, after all, plenty of solar energy available: the average solar energy influx in North America is about 22 watts per square foot (200 watts per square meter), which means that the typical suburban house in the US continuously receives the equivalent of over 25 horsepower in energy from the Sun. However, there are technical obstacles to gathering that energy, converting it to useful forms, and storing it for times when the Sun is not shining.

Solar energy is most easily harvested and used in the form of heat. For millennia, people have oriented their homes to take advantage of the Sun's warming rays; today, the design of houses to maximize passive solar heating is still one of the most effective ways to increase energy efficiency. Simple rooftop collectors for home hot water or swimming pool heating also take advantage of free solar heat.

The ancient Greeks and Chinese used glass and mirrors to focus the Sun's rays in order to start fires. Modern solar-thermal electrical generation technologies use the same principle to produce electrical power by heating water or other fluids to temperatures high enough to turn an electrical generator. Several distinct types of solar-thermal generating systems have been developed (including dish concentrators driving Stirling engine generators; trough concentrators heating a liquid-to-gas system driving a turbine generator; solar towers using large reflector arrays to heat molten salts which, through a heat exchanger, drive steam turbines; and plastic film collectors that work much like trough concentrators, but are much cheaper to build). Relatively few such systems of any type are in use, but ambitious plans are on the drawing boards, including some that integrate solar-thermal systems into the roofs of commercial and industrial buildings.

The photovoltaic effect, in which an electrical current is directly generated by sunlight falling upon the boundary between certain dissimilar substances, was discovered in 1839 by a nineteen-year-old French experimental physicist named Edmund Becquerel. Albert Einstein won the Nobel Prize in 1923 for explaining the effect. The first silicon solar-electric cells were made in the 1950s by researchers at Bell Laboratories, who achieved an initial conversion efficiency of only 4.5 percent. The development of photovoltaic (PV) technologies soon received a significant boost from research undertaken by the US space program, which used solar cells to power satellites. By 1960, efficiencies had been boosted to nearly 15 percent. In the 1970s, alternative energy enthusiasts began to envision a solar future in which photovoltaics would play a significant role in powering a post-petroleum energy regime.

Today there is roughly 1 gW of PV generating capacity installed worldwide (versus roughly 3000 gW of capacity in conventional power plants). Power-conversion efficiencies are now as high as 30 percent, and the cost of solar cells — initially astronomical — has fallen a hundred-fold. A typical small system now costs as little as $6 per watt of production capacity, whereas on large-scale projects costs as low as $3 are possible; at the latter price, with financing of the system at 5 percent interest over 30 years, the price of produced PV electricity amounts to roughly 11¢/kWh — though few installations actually achieve such a low cost. Photovoltaic electricity is still expensive.

PV technologies have the advantage of being able to provide electricity wherever there is sufficient sunlight, so they are ideal for powering remote homes or villages that are difficult to connect to a power grid. With a PV system, homeowners can become independent of electrical utility companies altogether. The disadvantage of such "stand-alone" systems is that a means must be provided to store electrical power for use when the Sun isn't shining — at night or on cloudy days. The typical solution is a bank of batteries, which require maintenance and add substantially to the system's cost. A complete system normally includes a collector array, a controller, an inverter (to change the generated current from DC to AC), and a battery bank, which altogether may represent an investment of more than $20,000 for even an energy-conserving home. In many states, businesses and homeowners can tie their PV panels directly to a power grid; by doing so, they avoid both electric bills and the need for batteries (though an inverter is still required). In this case, the system owner becomes an independent commercial electricity generator, selling power to the local utility company. Such grid-tied systems are typically much less expensive than stand-alone systems.

Two technical improvements in PV technology that are now in the developmental stage — thin-film panels and PV dye coatings — seem especially promising for reducing the cost of photovoltaic electricity. To date, the biggest obstacle to further implementation of the technology has been that production costs are high. The fabrication of even the simplest semiconductor cell is a complex process that has to take place under exactly controlled conditions, such as a high vacuum and temperatures between 750 and 2550 degrees Fahrenheit (400 and 1400 degrees Celsius). These new technical improvements promise to lower production costs dramatically.

Researchers are now experimenting with the use of hybrid materials that are inexpensive and allow for the use of flexible substrates, such as plastics. Manufacturers of such thin-film PV collectors claim a possible production cost of electricity of 7¢/kWh. There are three forms of thin-film PV technology in commercial production: amorphous silicon (a-Si), cadmium telluride (CdTe), and copper indium diselenide (CuInSe2, or CIS). There are two more on the way: spheral and CIGS (copper indium gallium diselenide).[23] Already, amorphous silicon accounts for more than 15 percent of the worldwide PV production. Amorphous silicon technology holds great promise in building-integrated systems, replacing tinted glass with semi-transparent modules; however, the efficiency is low: while some experimental a-Si modules have exceeded 10 percent efficiency, commercial modules operate in the 5 to 7 percent range. Cadmium Telluride laboratory devices have approached 16 percent efficiency, though production modules have achieved only about 7 percent. Copper Indium has reached a research efficiency of 17.7 percent, with a prototype power module reaching 10.2 percent, but production problems have so far prevented any commercial development.

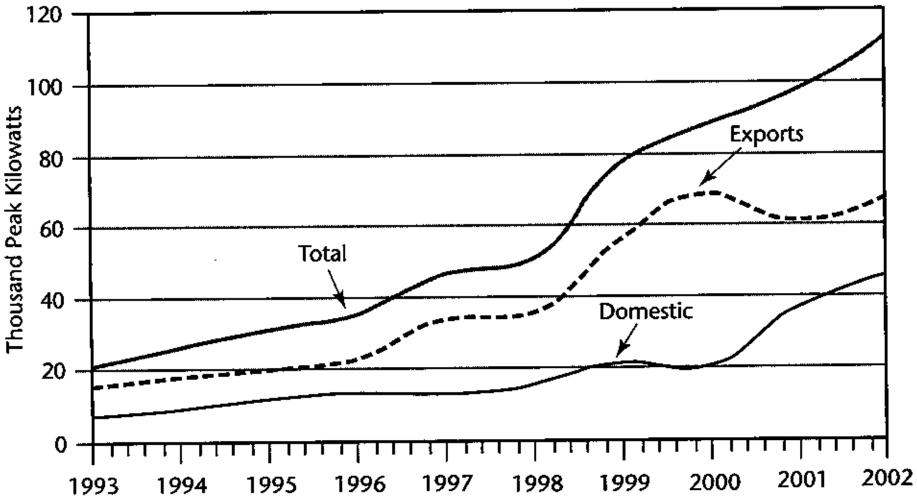

Figure 21. Shipments of PV cells and modules, 1993 - 2002

(Source: International Energy Agency)

Meanwhile, scientists at Switzerland's École Polytechnique de Lausanne have developed a fundamentally different solar pholtovoltaic cell that may eventually result in the cheapest PV devices of all. The production process uses common materials and low temperatures: a photosensitive dye, whose properties enable it to perform what the technology's promoters call "artificial photosynthesis," is simply silkscreened onto a substrate, such as glass. The resulting cells, known as Titania Dye Sensitised Cells (Titania DSC), can be assembled into colored opaque or translucent modules that could potentially be incorporated into the walls of buildings or the sunroofs of cars. Titania DS cells demonstrate performance in low light and at high temperatures that far surpasses that of silicon cells. Titania cells are currently only 10 percent efficient in energy conversion.[24] In this case, lower efficiency (relative to silicon-crystal cells) may not be much of a problem because of the potential for enormous cost savings: it may not matter much if a solar cell is inefficient if it can be put where otherwise only tarpaper, a sheet of plywood, or glass would go.

Nanosolar, a startup company in Palo Alto, California, is planning to commercialize this new technology, with its first product slated to hit the market in 2006. The production process will involve spraying a combination of alcohol, surfactants (substances like those used in detergents), and titanium compounds on a metal foil. A *Technology Review* article describes what happens next: "As the alcohol evaporates, the surfactant molecules bunch together into elongated tubes, erecting a molecular scaffold around which the titanium compounds gather and fuse. In just 30 seconds, a block of titanium oxide bored through with holes just a few nanometers wide rises from the foil. Fill the holes with a conductive polymer, add electrodes, cover the whole block with a transparent plastic, and you have a highly efficient solar cell."[25] Nanosolar hopes to reduce the cost of solar electricity by up to two thirds, making it competitive with commercial grid electricity rates. Eventually, it may be possible to paint a photovoltaic material directly onto buildings, cars, and other objects.

Still another new solar photovoltaic technology, this one involving organic materials, was recently announced by researchers at the Georgia Institute of Technology.[26] Using a crystalline organic film, pentacene, together with C_60, a form of carbon more popularly known as "buckyballs," the research group was able to convert sunlight into electricity with 2.7 percent efficiency, and they hope to reach 5 percent efficiency in the near future. Though the efficiency of the material is likely to remain low, its flexibility and minimal weight would allow it to be used on nearly any surface, including tents and clothing. The developers estimate that commercial residential applications are five years away, though versions to power small devices could be marketed within two years.

Net-energy calculations for current photovoltaic technologies are a matter of some controversy. Clearly, conventional silicon-crystal cells have so far had a relatively low return for the energy invested in their manufacture, even though promoters of the technology staunchly claim a favorable figure (typically, they exclude from their analyses the energy expended in transportation as well as that embodied in production facilities). In this instance at least, net-energy payback appears to be highly sensitive to the volume of production: PV modules are still manufactured on a very small scale; if demand were to surge, the energy returned on investment would likely rise very noticeably. It is likely that, even if the most pessimistic assessments of silicon-crystal cells — which suggest a *current* net return of less than 1:1 — are correct, the newer thin-film and DSC technologies may be able to achieve a substantially more favorable EROEI (the more optimistic assessments of silicon-crystal cells suggest a current net return of roughly 10).[27] At some point the net energy available from PV electricity will overtake the EROEI that can be derived from petroleum, as the latter is depleted.

However, solar photovoltaic and thermal-electric technologies present us once again with the problem we noted concerning nuclear power and wind: electricity cannot easily be made to power our current transportation and agriculture infrastructure. What is needed is some efficient medium for storing electrical energy that also renders that energy transportable and capable of efficiently moving large vehicles.

Many people believe that the solution lies in the simplest and most abundant element in the universe.

Hydrogen

Hydrogen is the lightest element, and it combines readily with oxygen; when it does so, it burns hot; and its combustion product is water — no greenhouse gases, no particulate matter or other pollutants. For these and other reasons, hydrogen would seem to be an attractive alternative to fossil fuels.

However, there are no exploitable underground reservoirs of hydrogen. Usable hydrogen has to be manufactured from hydrocarbon sources, such as natural gas or coal (a gallon of gasoline actually contains more hydrogen than does a gallon of liquid hydrogen), or extracted from water through electrolysis. Hydrogen production from algae and from sewage wastes has been demonstrated in the laboratory, but it is unclear whether these processes can ever be scaled up for commercial application. The crux, however, is this: *The process of hydrogen production always uses more energy than the resulting hydrogen will yield.* Hydrogen is thus not an energy *source*, but an energy *carrier*.

Still, many people foresee a prominent role for hydrogen as a means to enable renewable wind- and photovoltaic-generated electricity to be stored and transported. Proposals for a "hydrogen economy" have been circulating for decades (a 1976 study by the Stanford Research Institute was entitled *The Hydrogen Economy: A Preliminary Technology Assessment*), and in recent years a chorus of proponents has proclaimed the desirability and inevitability of a full transition from fossil fuels to an energy regime based on renewables and hydrogen. "Hydrogen-powered fuel cells promise to solve just about every energy problem on the horizon," writes David Stipp in an article called "The Coming Hydrogen Economy."[28] At the Hyforum held in Munich, Germany, in September 2000, T. Nejat Veziroglu, President of the International Association for Hydrogen Energy, proclaimed, "It is expected that the petroleum and natural gas production fueling this economic boom will peak around the years 2010 to 2020 and then start to decline. Hydrogen is the logical next stage, because it is renewable, clean, and very efficient."[29]

Much of the optimism surrounding the hydrogen-economy vision — whose boosters occasionally exhibit a techno-utopianism of almost messianic intensity — derives from recent developmental work on fuel cells, which chemically produce electrical energy from hydrogen without burning it. Fuel cells have more in common with batteries than with combustion engines.

Hydrogen is not the only substance that can be used to power fuel cells. The Regenesys fuel cell uses two electrolyte salt solutions; it will be useful alongside conventional and renewable commercial power plants to store output and

Nonrenewable and Renewable Energy Sources

Nonrenewable	Renewable
Oil	Hydroelectric
Natural Gas	Wind
Coal	Solar Power
Nuclear Power	Biomass, including biodiesel and ethanol
Geothermal Power (geysers)	Tides
	Waves
	Geothermal (ground-water heat pumps)

Net Energy Compared

Below are the summarized results of two comprehensive comparative studies of net energy (EROEI), one by Cleveland, Costanza, Hall, and Kaufmann (1984), the other by Odum (1996). Cleveland and Kaufmann have criticized Odum's methodology (see www.oilanalytics.com), but have not published an updated study of their own. Time is relevant to EROEI studies because the net-energy yield for a given energy source may change with the introduction of technological refinements or the depletion of a resource base.

Process	Energy Profit Ratio
Nonrenewable	
Oil and gas (domestic wellhead)	
1940s	Discoveries > 100.0
1970s	Production 23.0, discoveries 8.0
Coal (mine mouth)	
1950s	80.0
1970s	30.0
Oil shale	0.7 to 13.3
Coal liquefaction	0.5 to 8.2
Geopressured gas	1.0 to 5.0
Renewable	
Ethanol (sugarcane)	0.8 to 1.7
Ethanol (corn)	1.3
Ethanol (corn residues)	0.7 to 1.8 ☞
Methanol (wood)	2.6
Solar space heat (fossil backup)	
Flat-plate collector	1.9
Concentrating collector	1.6
Electricity production	
Coal	
US average	9.0
Western surface coal	
No scrubbers	6.0
Scrubbers	2.5
Hydropower	11.2
Nuclear (light-water reactor)	4.0
Solar	
Power satellite	2.0
Power tower	4.2
Photovoltaics	1.7 to 10.0
Geothermal	
Liquid dominated	4.0
Hot dry rock	1.9 to 13.0

(Source: From C. J. Cleveland, R. Costanza, C. A. S. Hall, and R. Kaufmann, "Energy and the U.S. Economy: A Biophysical Perspective," *Science* 225 (1984), pp. 890-97.)

Item	Energy Yield Ratio
Dependent Sources, No Emergy Yield	
Farm windmill, 17 MPH wind	0.03
Solar water heater	0.18
Solar voltaic cell electricity	0.41
Fuels, Yielding Net Emergy	
Palm oil	1.06
Energy-intensive corn	1.10
Sugarcane alcohol	1.14
Plantation wood	2.1 ☞

Item	Energy Yield Ratio
Lignite at mine	6.8
Natural gas, offshore	6.8
Oil Mideast purchase	8.4
Natural gas, onshore	10.3
Coal, Wyoming	10.5
Oil, Alaska	11.1
Rainforest wood, 100 years growth	12.0
Sources of Electric Power, Yielding Net Emergy	
Ocean-thermal power plant	1.5
Wind electro-power	2-?
Coal-fired power plant	2.5
Rainforest wood power plant	3.6
Nuclear electricity	4.5
Hydroelectricity	10.0
Geothermal	13.0
Tidal electric, 25 ft. tidal range	15.0

(Source: From Howard T. Odum, *Environmental Accounting, Emergy, and Decision Making* (John Wiley, 1996). Note: In that book, Odum explains the meaning of his term "emergy." If you think of it as shorthand for "embodied energy," you will not be far from the mark, though Odum's technical definition of the term is far more rigorous and complicated.) ■

release it when needed. In addition, zinc-air fuel cells are in development which, if the promotional literature is to be believed, are much cheaper to make than hydrogen fuel cells, use a solid fuel that has twice the energy density of hydrogen, and have an electricity-to-electricity efficiency in the range of 40 to 60 percent.[30] Zinc "fuel" will come in the form of small pellets. The chemical reaction in zinc fuel cells produces zinc oxide, a non-toxic white powder. When all or part of the zinc has been transformed into zinc oxide, the user refuels the cell by removing the zinc oxide and adding fresh zinc pellets and electrolyte. The zinc oxide is then reprocessed into new zinc pellets and oxygen in a separate, stand-alone recycling unit, using electrolysis. Thus, the process is a closed cycle that can theoretically be continued indefinitely. Each cycle consumes energy; but we must remember that the real purpose of the fuel cell is not to *produce* net energy, but rather to make stored energy available for convenient use.

But back to hydrogen. At present, on a global scale, about 40 million tons of hydrogen are produced commercially per year. This represents slightly more than one percent of the world's energy budget. Most of this commercially produced hydrogen is now made from natural gas.

There are reasons to be hopeful about hydrogen's potential. The electric drive train of a fuel cell-driven car would be much lighter than a conventional gasoline or diesel drive train. Emissions from burning hydrogen in fuel cells consist only of water and heat; thus many pollution problems — including the production of greenhouse gases — could be reduced dramatically by the widespread use of hydrogen. Even if the source of hydrogen is coal or natural gas, fewer emissions are produced in the coal or gas reformation process (the production of hydrogen) than in the direct burning of these fossil fuels for energy.

Several major car manufacturing companies are currently working on new models that will run on hydrogen fuel cells. The experimental Daimler-Benz NECAR 3 (New Electric Car, version 3), for example, generates hydrogen onboard from methanol — thus dispensing with the problematic extra weight of batteries and hydrogen tanks. Another solution to the weight problem is to redesign the entire automobile for maximum weight reduction and aerodynamics; this is the approach taken by the "Hypercar," a project of Hypercar Inc.[31]

Hydrogen production is also being proposed as a means to store electrical energy from solar panels or wind turbines in homes or commercial buildings, replacing bulky and inefficient batteries. Hydrogen-powered fuel cells could thus enable a transition to decentralized energy production, reducing costs for the construction and maintenance of centralized generating plants and transmission lines.

Amory Lovins of the Rocky Mountain Institute has published "A Strategy for the Hydrogen Transition," illustrating how "the careful coordination of fuel-cell commercialization in stationary and transportation applications, the use of small-scale, distributed fueling appliances, and Hypercars combine to offer leapfrog opportunities for climate protection and the transition to hydrogen."[32] Implicit in the plan is a reliance on natural gas as the primary source for hydrogen for at least two decades, until renewable energy souces can be scaled up.

That's the good news about hydrogen. Unfortunately, there is bad news as well.

A hydrogen energy infrastructure would be quite different from our present energy infrastructure, and so the transition would require time and the investment of large amounts of money and energy. That transition would be aided tremendously if we were to switch present government subsidies from nuclear power, oil, and coal to renewables, fuel cells, and hydrogen. But, given the political influence of car and oil companies and the general corruption and inertia of the political process, the likelihood of such a subsidy transfer is slim for the moment. Yet if we simply wait for price signals from the market to trigger the transition, it will come far too late.

An even greater problem is the current and continuing reliance on natural gas for hydrogen production. Hydrogen proponents assume the continued, abundant availability of natural gas as a "transition fuel." Without some transitional hydrocarbon source, there is simply no way to get to a hydrogen economy: there is not enough net energy available from renewable sources to "bootstrap" the process while supporting other essential economic activity. As we have seen, prospects for maintaining — much less increasing — the natural gas supply in North America appear disturbingly uncertain. Within only a few years, decision makers will be confronting the problem of prioritizing dwindling natural gas supplies — should they fund the transition to a hydrogen economy or heat people's homes during the winter? Faced with a crisis, they would find it difficult to justify diverting natural gas supplies away from immediate survival needs.

In terms of energy efficiency (setting aside for the moment the problem of emissions and the need for energy storage), we would be better off burning natural gas or using PV or wind electricity directly, rather than going through the extra step of making hydrogen. The Second Law of Thermodynamics insures that hydrogen will be a net-energy loser every time since some usable energy is lost whenever it is transformed (e.g., from sunlight to photovoltaic electricity, from electricity to hydrogen, or from hydrogen back to electricity).

Given the already low net energy from renewables as well as the net energy losses from both the conversion of electricity to hydrogen and the subsequent conversion of hydrogen back to electricity, it is difficult to avoid the conclusion that the "hydrogen economy" touted by well-meaning visionaries will by necessity be a much lower-energy economy than we are accustomed to.

The future may well hold hydrogen fuel cell-powered cars — but not in numbers approaching the current global fleet of 775 million vehicles. In the low-energy social environment toward which we are inevitably headed, it will be possible for only a tiny wealthy minority to navigate over disintegrating streets and highways in sophisticated, highly efficient Hypercars. For the rest of us, a good pair of shoes and a sturdy bicycle will be the best affordable transport tools.

I recently toured the Schatz Energy Research Center (SERC) at Arcata, California, one of the nation's foremost research centers for hydrogen, fuel cells, and renewable energy. The mission of the center is to promote the use of clean and renewable energy. The Schatz lab, housed in a small, converted 1920s hospital building, specializes in generating hydrogen fuel from solar photovoltaics. The lab designed and built a 9kW fuel cell powered car based on a small European electric vehicle — the first street-ready fuel-cell car in the US. SERC has also made a fuel cell that powers a microwave relay station providing telephone service for the Yurok Tribe of Northern California.

Peter Lehman, the SERC Director, showed me several bench-top, state-of-the-art fuel cells — each handmade and expensive to build. Lehman said that for most small-scale applications (including homes and personal automobiles), batteries are still a more efficient storage medium for energy than hydrogen. In most cases, according to Lehman, it just doesn't make sense to take high-quality energy in the form of electricity, turn it into hydrogen, and then turn it back into electricity, since there are losses at each stage along the way — if there are ways of using the electricity directly. However, in larger-scale generation situations — say, a wind farm — at times when there is no immediate use for the electricity being generated, hydrogen production could provide a way to store energy while also producing a transportation fuel for fuel cell vehicles such as trucks or buses. But in commuting situations, when mileage requirements are low, Lehman feels that battery electric vehicles are more efficient and the right choice for private cars. In the foreseeable future, gasoline or diesel hybrid cars also make more sense than do fuel cell vehicles.

The two biggest problems with fuel cells currently, according to Lehman, are that they don't last long enough, and they're expensive. Schatz's cells are now able to perform for about 2,000 hours (that's three months of continuous operation). The upside is that fuel cells can be remanufactured, so that a user could rotate two cells, with one on the job while the other is being refurbished. But this would, of course, increase the already daunting cost. The Schatz lab is working to overcome both these limitations, but Lehman admits that there is a long way to go, and advances appear to be incremental and slow. There is currently no off-the-shelf, production-model fuel cell available anywhere that could reliably power a home.

Lehman noted that the fuel-cell industry is growing quickly, but that it is rife with secrecy and inflated claims.

Like wind and photovoltaics, hydrogen fuel cells offer certain important advantages over current energy technologies and will no doubt be central features of the post-petroleum infrastructure. We should be dramatically increasing our investments in these alternatives now, while there is still cheap energy to be had. But even assuming a full-scale effort toward a transition to renewables and hydrogen, industrial societies will suffer wrenching changes as a result of the inevitable drastic reduction in available net energy.

Hydroelectricity

While medieval water mills were used to grind grain, modern hydroelectric turbines transform the gravitational potential of rivers and streams into conveniently usable electric power. Electricity generated from water flowing downhill currently constitutes the world's largest renewable energy source.

Throughout the 20th century, hydroelectric dams were built on most major rivers throughout the world — from the Colorado River in the US to the Nile in Egypt. Currently, about 9 percent of electricity in the US is generated by hydro power, a little less than half that generated by nuclear power plants. However, this represents over three times the electricity generated by all other renewable sources combined. In the world as a whole, hydro power accounts for 19 percent of electricity generation.

One of the advantages of generating electricity via hydro dams is that it is relatively easy to store energy during times of low demand. Water empounded behind dams represents stored energy; in addition, surplus electrical power can be used to pump water uphill so that it can be released to flow back through the generating turbines during times of peak demand.

Hydroelectric generation has an attractive EROEI: Odum gives hydro power a net figure of 10, while Cleveland *et al.* assign it 11. Hydro power is thus one of the better current producers of net energy.

Unfortunately, hydroelectric dams typically pose a range of environmental problems: they often ruin streams, cause waterfalls to dry up, and interfere with marine habitat. Dammed rivers are diverted from their geologic and biological work, such as the support of migratory fisheries. Most environmentalists would prefer to remove existing dams rather than see more of them built. Moreover, many existing hydro plants are jeopardized by siltation and foreseeable changes in rainfall patterns resulting from global climate change.

In any case, in the US the building of more large hydroelectric dams is not much of an option. Hydro resources are largely developed; there is little room to increase them. Not one large dam has been approved in the past decade.

The situation is different in Canada, which has immense potential hydroelectric resources. With hydroelectricity as with natural gas, Canada is becoming a major energy source for the US.

Most new hydro developments are being planned not for already-industrialized countries, but for the less-consuming countries of the world. But hydroelectric dams tend to be capital-intensive projects that require huge loans, trapping poor countries in a vicious cycle of debt.

Microhydro — the production of electricity on a small, localized scale from relatively small rivers or streams — offers the advantages of rural electrification with few of the drawbacks of major dam projects. Countless communities in the less-consuming countries may be able to take advantage of this technology, which requires smaller investments and enables local control of resources. Successful microhydro projects are already operating in Sri Lanka, Zimbabwe, the Netherlands, and many other countries.[33] The main drawbacks of such projects are their inability to supply large urban areas with power as well as their reliance on an endangered resource: fresh water.

In sum, hydro power is already a significant energy resource and will continue to be so throughout the coming century. But in many regions of the world — and especially in the US — it is already thoroughly exploited.

Geothermal Power

Humans have enjoyed natural hot springs for millennia, and technologies have more recently been developed for using geothermal waters for home and commercial heating — as is commonly done, for example, in Klamath Falls, Oregon. Underground steam was first used to generate electricity near Rome, Italy, in 1904. The first commercial geothermal electric power plant was built in 1958 in New Zealand; and in 1960, a field of 28 geothermal power plants was completed in the region of Geyserville in northern California.

Geothermal power — whether used for heating or for electricity generation — is necessarily dependent upon geography: plants must be located close to hot springs, geysers, and fumaroles (holes near volcanoes from which vapor escapes). Most geothermal resources are located around the edges of tectonic plates. The west coasts of the Americas as well as Iceland, India, Kenya, the Philippines, Indonesia, Japan, and Thailand all have exploitable geothermal resources.

The US currently has 44 percent of the world's developed geothermal-electric capacity, but the American geothermal industry is stagnant. Less than one percent of the world's electricity production comes from geothermal sources.

By Odum's calculations, geothermal electricity production may currently have an EROEI even higher than that of petroleum (though still far below oil's net yield through the 1960s). However, many geographic locations do not permit the attainment of this degree of net-energy return for geothermal electricity. Moreover, it is unlikely that the generation of electricity from geothermal sources can be increased sufficiently to offset much of the net-energy decline from petroleum depletion.

There is some debate as to whether geothermal electricity production actually constitutes a renewable energy source. As underground steam or hot water is used to turn turbines, it is gradually depleted. The period in which depletion reaches the point where the resource is no longer commercially useful is estimated to be in the range of 40 to 100 years for most geothermal fields. While fields may naturally recharge themselves over a period of centuries or millennia, that will be of little benefit to the next few generations. At The Geysers fields in northern California, efforts are being made to recharge underground reservoirs with treated waste water pumped from the city of Santa Rosa; however, it is too early to tell what the results will be. If successful, the scheme could make geothermal energy production renewable, though the infrastructure and operating costs of the recharging process would drastically reduce the EROEI for energy production from this source.

If recharging efforts fail, the long-term prospects for geothermal electricity look dim. While nations such as Indonesia and Russia have only begun to develop their large potential geothermal resources, without artificial recharging those resources will be useful for only a few decades.

Geothermal energy production has potential for increased local development, but when viewed against the backdrop of the world's total energy needs, its contribution — even if that potential is fully realized — pales in significance.

Tides and Waves

On the shores of oceans, tides rise and fall predictably day by day. This rising and falling of the tides is a potential source of energy. In a few places, estuaries have been dammed so that water can be let in as the tide rises, and then let out via electricity-generating turbines as the tide falls. For an area with 25-foot tides, Odum calculated an EROEI of 15 — which is the highest net-energy yield for any source he studied. However, this net benefit is substantially reduced when the loss of estuarine fisheries is taken into account.

Tidal energy is renewable, clean, and efficient. Unfortunately, there are fewer than two dozen optimal sites for tidal power in the world, and most of those are in remote areas like northwest Russia or Nova Scotia.

The only US city that is likely to benefit significantly from tidal power is San Francisco, which is committed to developing a one-megawatt tidal power station within two years. A major proponent of this project is HydroVenturi Ltd, whose new technology, developed at Imperial College, has no underwater moving parts. As the tide ebbs and flows, long fins inside an underwater passageway would funnel the current, creating suction, which in turn would pull air from pipes connected to onshore turbines, causing the turbines to turn and generate electricity.

If the $2 million test project is a success, it might be possible to power the entire city with electricity generated from the daily tides in the Bay. Potential environmental problems still need to be addressed, including the possibilities that salmon and other fish could be caught in the fins by sudden drops in water pressure; that alteration of the tidal flow could have a negative impact on other marine life; or that increased sediment buildup in the Bay could impair water quality.

Meanwhile a Canadian company, Blue Energy, has created and marketed a highly efficient underwater vertical-axis windmill that can be used to generate tidal power for almost any coastal community. Blue Energy's scalable technology (from a few kilowatts to thousands of megawatts) is claimed to generate efficient, renewable, and emission-free electricity at prices competitive with today's conventional sources of energy. The design of the turbine is structurally and mechanically straightforward, and the transmission and electrical systems are similar to existing hydroelectric installations.[34]

There is also tremendous energy inherent in the waves that constantly lap the ocean shores, and it is theoretically possible to harness some of that energy. But doing so is difficult. Waves are extremely variable: they can occasionally reach 60 feet in height, but days or weeks may go by when the ocean is calm. In Japan, Norway, Denmark, Britain, Belgium, and India, a variety of systems have been used to tap wave energy. The results have been mixed: energy has been produced at relatively low cost, but it tends to be intermittently available. A comprehensive survey of wave-energy research by David Ross suggests that this source can provide only limited power for industrial societies for the foreseeable future.[35]

Biomass, Biodiesel, and Ethanol

"Biomass" is a modern term for what is, in fact, our oldest fuel source: plant material. Current and potential forms of biomass include wood, animal waste, seaweed, peat, agricultural waste such as sugar cane or corn stalks, and garbage.

As noted in Chapter 2, wood was the principal energy source in the US until the latter part of the 19th century, and it still is in many parts of the world. Deforestation in places like Bangladesh and Haiti is directly attributable to the overharvesting of trees for fuel. In the US, biomass provides more total energy than hydroelectric power, making it the nation's principal renewable energy source (though hydro is its foremost renewable source for electricity production).

Biomass has an extremely variable EROEI. However, the burning of all forms of biomass creates air pollution, which can sometimes be severe. Burning wood for heat releases not only carbon dioxide but a cocktail of toxic substances including nitrogen oxides, carbon monoxide, organic gases, and particulate matter. In India, 200 million tons of cow dung are burned annually as cooking fuel; the practice deprives the soil of needed nutrients and also blankets cities in a pollutant haze.

There is limited growth potential for total energy from biomass. Many parts of the world already are experiencing severe and growing shortages of firewood — which is so scarce in parts of Colombia, Peru, India, Pakistan, Bangladesh, Nepal, and some countries of Africa that many people are reduced to having only one cooked meal a day.

In addition to directly burning biomass for heat or light, it is also possible to make fuels from it to run machinery and vehicles. When Rudolf Diesel invented the diesel engine in the late 1890s, he envisioned it running on a variety of fuels, including peanut oil. Today's diesel fuel is a refined petroleum product, but diesel engines can still be modified to run on vegetable oils.

Unmodified diesel engines can burn a fuel known as "biodiesel," which is a chemically altered vegetable oil. The production process for the latter is fairly simple: aside from vegetable oil, the two main ingredients are methanol and lye, and with a little practice and some basic equipment it is possible to produce batches of low-cost biodiesel in one's garage using discarded restaurant deep-fry cooking oil.

Personally, I love biodiesel; I run my car on it. Biodiesel has some distinct advantages over petroleum-based diesel fuel. When burned, it produces fewer pollutants — significantly less CO_2, less particulate matter, no aromatics (benzene, toluemene, xylene), and no sulfur, though nitrogen oxide emissions are the same as with conventional diesel fuel. Mileage per gallon is typically slightly less for biodiesel than for conventional diesel fuel, but users of the former report that the exhaust from their cars or trucks tends pleasantly to smell like French fries or donuts (depending on the oil source).

However, for all its advantages, biodiesel may be destined to remain merely a "boutique" fuel: currently, there are fewer than ten biodiesel plants in the US and only 21 retail pumps scattered throughout the country; moreover, commercial biodiesel sells for over $3 per gallon — significantly more than conventional diesel fuel. An even worse problem is that the production of vegetable oil for use as a fuel is usually, depending on the type of oil, a net energy loser. The National Renewable Energy Laboratory has performed experiments with the extraction of oil from algae, showing that this source could be extremely productive — several times more so than palms or coconuts. However, it has not been shown that this procedure can be scaled up to produce significant commercial quantities of oil. Given the petroleum-intensive nature of modern agriculture, it probably takes more energy to produce a gallon of biodiesel than the biodiesel yields when burned; but if further research on algae oil continues to yield promising results, it is possible that a favorable net-energy production could be achieved and a sizeable portion of the diesel fleet could be run on biofuels.

While most enthusiasts use vegetable oil in the form of biodiesel, some modify their diesel car's fuel system to accept ordinary, recycled vegetable oil. Both strategies appeal to a tiny but growing number of environmentally aware motorists who have started fuel-sharing co-ops and who maintain websites devoted to the promotion of vegetable oil-fueled transportation. While there simply aren't enough fast-food restaurants or donut shops to fuel large fleets of cars and trucks, this is a good option for the few mavericks willing to make the effort.

Ethanol — a fuel-grade form of alcohol produced from grain fermentation — suffers from the net-energy constraints similar to those of biodiesel. Promoters tout ethanol as a clean energy alternative since it produces fewer pollutants when burned than do petroleum byproducts, and the US Congress has adopted laws requiring ethanol to be mixed with gasoline for automobile consumption. Essentially, this Federal mandate amounts to a subsidy for agribusiness, since ethanol is produced primarily from corn grown in the American Midwest. Altogether, the ethanol industry receives about $1.4 billion per year in direct or indirect subsidies, most of which end up benefiting giant agribusiness cartels such as Archer Daniels Midland.

Cornell University professor David Pimentel, who has performed two net-energy analyses of ethanol, found in both instances that the fuel cost more energy to produce than it eventually delivered to society. While his recent study was more favorable than the previous one, it nevertheless showed an EROEI of roughly 0.81, meaning a 29 percent net loss of energy.[36]

However, Pimentel's studies have been attacked by ethanol proponents, who cite much more favorable reports — especially several USDA studies led by Hosein Shapouri, the most recent of which comes to the optimistic conclusion that ethanol offers up to a 77 percent energy profit.[37]

But Shapouri's and other ethanol-favorable studies have in turn been devastatingly critiqued by Tad W. Patzek of University of California, Berkeley, in a 114 page paper titled "Thermodynamics of Corn-Ethanol Biofuel Cycle."[38] Patzek argues that Shapouri has disregarded or minimized several important energy inputs to the process of ethanol production; once these figures are corrected, the net energy gain cited in the USDA studies is "insupportable."

Ethanol proponents correctly point out that crops other than corn (such as sugar cane) can yield more alcohol per acre; moreover, engines that burn ethanol may last considerably longer than gasoline-burning engines, thus leading to energy savings elsewhere in the industrial system.

Proponents also point to Brazil's experimental use of ethanol from sugar cane as a vehicle fuel in the 1980s. An impressive 91 percent of Brazilian cars produced in 1985 ran on sugar-cane ethanol. However, as world oil prices plummeted during the latter half of the decade, and as sugar prices rose, demand for alcohol-fueled cars subsided. It could be argued that Brazil was able to afford its ethanol experiment primarily because of its favorable ratio of available cropland to automobiles: even if energy and topsoil were being lost in the exercise, the country was temporarily able to absorb these losses because they were small and temporary; the situation would likely be very different in the US.

Brazil remains the world's largest producer of ethyl alcohol, supplying 38 percent of the worldwide total. Yet many environmentalists have expressed fears that if demand for ethanol accelerates, Brazil could be transformed into one giant sugar cane field. Already Brazilian agriculture is encroaching on the *cerrado,* a vast grassland and savannah region in the southeastern section of the central Brazilian plateau constituting a unique and seriously threatened ecosystem.

If the US were to attempt to imitate Brazil's feat, how much farmland would be needed to provide enough ethanol to replace fossil fuels? The United States has about 400 million acres of cropland and about 200 million cars. American farmers produce about 7,110 pounds of corn per acre per year, and an acre of corn yields about 341 gallons of ethanol. The typical American driver would burn 852 gallons of ethanol per year, thus requiring 2.5 acres of cropland. According to this calculation, 500 million acres of farmland would be needed to provide fuel for the American fleet — or 25 percent more farmland than currently exists. (This assumes that no farmland would be used to grow food.) While ethanol advocates point out that land used for ethanol production can simultaneously be used to produce cattle feed (which is how corn is mostly used these days anyway), the above calculation should nevertheless give us pause, especially given the fact that in 2005 the US will become a net food importer (in dollar terms) for the first time in its history as a nation.[39]

Even if we accept the controversial claim that ethanol can be produced in such a way as to yield a net energy profit, it would be foolish to assume that a large percentage of US fleet could be run on the fuel, given the above environmental constraints. If our goal is a sustainable energy regime, it is more realistic merely to envision organic farmers devoting a portion of their land to the production of modest amounts of ethanol with which to run their farm machinery.

Fusion, Cold Fusion, and Free-Energy Devices

Some people maintain that there are energy sources not constrained by the laws of physics as presently understood. It would be simple enough to write off this viewpoint as pseudoscience; however, in the context of the resource depletion discussion, such claims deserve to be addressed. Are free-energy devices possible?

In essence, a free-energy (or "over-unity") device is one that produces more power than it consumes in its operation. The search for free energy (formerly referred to as "perpetual motion") began long ago. In the 14th century, Villand de Honnecourt produced a drawing of a perpetual-motion machine, as did Leonardo da Vinci a couple of centuries later. Johanes Taisnerius, a Jesuit priest, worked on a perpetual-motion machine based on permanent magnets; and Cornelis Drebbel, an alchemist and magician, supposedly made one in 1610. The first English perpetual-motion patent was granted in 1635; by 1903, 600 such patents had been granted. In the 19th century, so many people were working on *perpetual-motion* machines that their goal inspired a musical genre — the perpetuum mobile — which transfixed the audiences of virtuosi like Nicolo Paganini and Carl Maria von Weber.

In the 20th century, the free-energy literature tended to center on the work of Nikola Tesla (whose career is briefly discussed in Chapter 2). Tesla produced most of his useful inventions before 1910; thereafter his work became progressively more obscure — some would say, visionary. According to one often repeated (and likely apocryphal) anecdote, in 1931 the reclusive inventor fitted a new Pierce-Arrow with a mysterious 80-horsepower, alternating-current electric motor that had no batteries and no external power source, and drove it for a week.

Unlike Tesla, most 20th-century claimants to perpetual motion were relatively obscure figures. In the 1920s, a self-taught inventor named Lester Hendershot built a generator comprising twin basket-weave coils, capacitors, transformers, and an input magnet/clapper unit, which reputedly produced useful electrical power at about 300 watts. The device tended to be erratic, as its operation depended on the tuning of the input component; moreover, Hendershot himself was unable to provide a scientific explanation of how the device worked.

Also in the 1920s, Dr. T. Henry Moray of Salt Lake City began experimenting with solid-state circuitry, cold cathode-ray tubes, and a radiant-energy device that produced up to 50 kilowatts of electrical power. Similar radiant-energy devices were developed independently by L. R. Crump, Peter Markovitch, and others. Several patents were granted, and efforts have more recently been made to explain the phenomenon in terms of "neutrino flux" and "tachyon fields."

In the 1980s, an inventor named Joseph Newman introduced a series of machine generators built around a powerful permanent magnet rotating within a coil consisting of a very large number of turns of copper wire. In the course of his promotional efforts, Newman gave a weeklong demonstration in the Super Dome in New Orleans and appeared on the *Tonight* show. He claimed that his machine produced much more energy than it consumed, but critics maintained that the apparent surplus of power (most of which was dissipated in heat) was actually the result of measurement errors.

The above in no way constitutes an exhaustive list of perpetual-motion or free-energy claimants. There are and have been literally scores of others — some deliberate hoaxers, others sincere but naïve backyard tinkerers, and still others serious scientists. Many of their efforts seem transparently quixotic. Their goal is clear enough: If only we can find a new, infinite source of energy, we can free ourselves from all sorts of material constraints. But how do free-energy researchers explain — to themselves or their investors — that such a thing is even possible?

The standard textbook view of energy begins with the First Law of Thermodynamics, which states that the sum of all matter and energy in the universe is constant and that energy can be neither created nor destroyed — only its form changes. There are no exceptions: this is the most fundamental law by which we must live, one that cannot be bent, broken, or repealed. What makes free-energy advocates think they can get around it? Is there a loophole?

The best chance of finding one, some suggest, is by way of quantum physics. Theoretical physicists speculate that empty space may not really be empty after all; it may, in fact, be filled with energy. If so, all we would need to do to harvest that energy would be to assemble the equivalent of a quantum windmill to capture the quantum "wind."

If the details of the process are a bit abstruse, the fact that the well-known science fiction writer Arthur C. Clarke has endorsed the possibility of obtaining energy from vacuum — this is sometimes called "zero-point" energy — is encouraging. Perhaps the search for new energy sources has outgrown the garages of inventors like Hendershot and is ready to move into university physics labs.

Another potential path toward free energy is cold fusion. In 1989, physicists Stanley Pons and Martin Fleishman of Salt Lake City announced that they had produced a nuclear-fusion reaction at room temperature — a feat previously considered impossible. Cold fusion reputedly occurs when ordinary hydrogen and an isotope of hydrogen called deuterium are brought together with metals such as palladium, titanium, and lithium. The reaction (again, reputedly) releases enormous quantities of energy — more than ordinary chemical reactions could possibly yield. Cold fusion, in contrast to hot fusion, happens in a relatively simple apparatus roughly the size of a postage stamp and does not emit neutron radiation. It also gives off very little, if any, of the radiation common to nuclear-fission reactions.

Many American scientists still consider cold fusion a form of crank science, though well over 1,000 peer-reviewed papers on the subject have been published. Cold-fusion researchers have never claimed that the effect produces power from vacuum or that it violates any known laws of physics.[40]

What impact will any of these efforts to develop exotic energy devices have on the energy shortages of the 21st century? In the near term, very little. In all likelihood, most if not all of the ballyhooed free-energy claims of the past were the result of deliberate deception, measurement error, or naïveté on the part of unschooled researchers. Moreover, it is difficult to avoid the impression that many of the current Internet discussions of exotic energy devices are pervaded by paranoia and extravagant claims, such as, "The oil companies are buying up all the patents and suppressing the evidence!" or "A secret, unelected military government is running free-energy 'black' projects with technology stolen from space aliens!" or, "Our only hope is to quickly fund this or that maverick inventor, whose latest device generates a million times more power than it consumes!"

Is the US government really secretly experimenting with free-energy devices? That is entirely possible. It is even possible (in the sense that almost anything is possible) that the technology was acquired from space aliens. The problem with discussing the subject is that most secret government programs are surrounded with disinformation spread by well-paid experts. Given the continual rain of lies and half-truths about military or intelligence "black" projects, it is impossible to know what to believe about them, and under such circumstances most speculation is a waste of time.

Sensationalism aside, it appears that, even if cold-fusion devices or "quantum windmills" could work, harnessing these new power sources would not be easy. Currently, the world derives exactly zero percent of its commercially produced energy from all of these exotic sources combined. It is likely that, even in the best case, decades of further research and development would be required to change that statistic appreciably.

Energy production from conventional or hot nuclear fusion is less controversial from a theoretical point of view than are proposed zero-point or cold-fusion projects. Billions of research dollars have been devoted to fusion research over the past two decades. If made practical, fusion could produce almost limitless energy from seawater. However, the hurdles to actually producing fusion energy are prodigious. Reactor temperatures would have to be in the range of 360 million degrees Fahrenheit (200 million degrees Celsius), and no materials or processes are currently capable of containing such temperatures for more than a tiny fraction of a second. No fusion reactor has yet succeeded in producing more energy than it consumes. Even promoters say that commercially useful power production from fusion is at least 50 years away — but it may not be possible to continue funding expensive and energy-intensive fusion research in the energy-constrained environment of the 21st century.

Conservation: Efficiency and Curtailment

Nearly everyone agrees that the best ways to cushion the impact of an energy shortage are simply to consume less and to get the most out of what we do use. The term *conservation* is often employed to refer to these two parallel but

fundamentally different strategies. The first strategy — perhaps more accurately termed *curtailment* — would, for example, translate into the prosaic action of turning off a light when leaving a room. The second — more accurately termed *efficiency* — would, in terms of the same example, mean replacing an incandescent bulb with a compact fluorescent bulb that produces the same amount of light from a quarter of the electricity. There is plenty of room for energy savings from both strategies.

In the past three decades, American homes and workplaces have become much more energy efficient. In the 1950s, the US economy as a whole used over 20,000 BTU for every inflation-adjusted dollar of gross domestic product; by 2000, it was consuming only about 12,000 BTU per dollar. Much of this improvement in efficiency was due to the redesign of common appliances such as refrigerators, lamps, and washing machines. Today's houses are typically insulated better than houses a few decades ago, and most buildings and factories have been redesigned for energy efficiency.

More such gains are possible. Between 1980 and 1995 the fuel efficiency of US automobiles improved dramatically, but since then that trend has reversed. Cars themselves did not become less efficient; instead, many drivers — encouraged by low gas prices — began buying light trucks or sport utility vehicles, which typically use much more fuel than smaller cars. Toyota and Honda have begun marketing hybrid gasoline-electric cars that achieve over 50 miles per gallon, and American automakers are beginning to roll out their own hybrid versions of existing cars — including SUVs. In the future, an 80 mpg full-size car is probably feasible. Many homes can still benefit greatly from extra insulation, low-e windows, the planting of shade trees to reduce the need for air conditioning, and the replacement of incandescent bulbs with compact fluorescents.

Substantially increased energy savings from efficiency are also possible in industry. Philips, a large European manufacturing firm, is a typical success story in this regard. After deciding in the early 1990s to target energy efficiency, the company hired consultants and began making changes in its operations. Between 1994 and 1999, Philips improved energy efficiency by 31 percent, while reducing its waste stream by 56 percent.

The efficiency of US electricity generation plants peaked in 1958 at about 35 percent. However, newer plant designs are able to achieve efficiencies of 57 percent or more. In 1998, two-thirds of electric generating plants were more than 25 years old; replacing half of these with new, more efficient plants could increase available electricity by about 25 percent with no increase in fossil fuel consumption. Moreover, waste heat from generating plants could be employed to heat homes and factories, or to raise the efficiency of hydrogen production.

Many of these potential improvements could be speeded up through offering subsidies or tax incentives, and energy markets could benefit greatly from intelligent regulations that promote efficient energy provision and consumption. Such an intelligent redesign of regulations in the UK in the 1990s led to a significant increase in energy efficiency, a decrease in the use of nuclear power, and a 39-percent reduction in CO_2/kWh.

However, there are limits to the benefits from efficiency, since increasing investments in energy efficiency typically yield diminishing returns. Initial improvements tend to be easy and cheap; later ones are more costly. Also, the energy costs of retooling or replacing equipment and infrastructure can sometimes wipe out gains. A simple example: Suppose you are currently driving a two-year-old car that travels 25 miles on a gallon of gasoline. You see a similar new car advertised that gets 30 mpg It would appear that, by trading cars, you would be conserving energy. However, the situation is not that simple, since a little over ten percent of all the energy consumption attributable to each vehicle on the road occurs in the manufacturing process — before that vehicle has traveled its first mile. Thus, by putting off trading cars you might be conserving more net energy than you would be by buying the new, more fuel-efficient replacement.

In the late 1980s, Gever *et al.* studied the relationship between energy efficiency and national economies, as expressed in the ratio between gross domestic product (GDP) and total energy consumed (a rising ratio of GDP to energy consumption means that the economy is becoming more energy-efficient). Not surprisingly, they found that nations like Sweden, Switzerland, and Denmark were much more energy-efficient than the US, and that US energy efficiency had improved significantly during the 1980s. But what were the factors driving increased efficiency? Their analysis showed that energy efficiency increases with the use of more energy-dense sources — this is by far the most important factor — as well as with the reduction of household use of energy and with increased energy prices. As industrial nations made the transition from burning coal to using higher net-yield sources — oil, gas, hydro, and nuclear power — energy efficiency improved dramatically. Household energy consumption (which goes mostly to heating homes and fueling cars) does not add as much to the GDP as does industrial use of energy, which goes toward the production of goods and services, and so efficiency improved as households used proportionately less. And higher energy prices encouraged the switch to more energy-stingy technologies. But the authors pointed out that:

> our analysis indicates that the ability of technical change to increase the goods and services produced from the same amount and mix of fuels is much smaller than most economists claim .... There are several reasons to believe that previous assessments of technology's ability to save energy were overly optimistic. For one, many analyses ignored important changes in the kinds of fuels used in the economy and in the division of fuel supplies between household and intermediate sectors. As a result, changes in efficiency due to these factors were mistakenly attributed to technological advances and/or fuel prices ....[41]

The authors also noted that:

> [i]n agriculture, for example, the amount of fuel used directly on a cornfield to grow a kilogram of corn fell 14.6 percent between 1959 and 1970. However, when the calculation includes the fuel used elsewhere in the economy to build the tractors, make the fertilizers and pesticides, and so on, it turns out that the total energy cost of a kilogram of corn actually rose by 3 percent during that period.[42]

The inescapable implications of these findings are first, that many efforts toward energy efficiency actually constitute a kind of shell game in which direct fuel uses are replaced by indirect ones, usually in the forms of labor and capital, which exact energy costs elsewhere; and second, that the principal factor that enabled industrial countries to increase their energy efficiency in the past few decades — the switch to energy sources of higher net yield — does not constitute a strategy that can be applied indefinitely in the future.

Thus the curtailment of energy usage offers clearer benefits than improved efficiency. By simply driving fewer miles one unequivocally saves energy — regardless of whether one's car is old or new and whether it is more or less efficient.

Some curtailment is painless — as is the case with turning off the lights when one leaves a room or turning down the thermostat at night. But the economy as a whole is inextricably tied to energy usage, and so significant degrees of curtailment throughout society are likely to have noticeable economic consequences.

We have historical data in this regard. In the 1970s and early 1980s, the US curtailed some of its energy usage due to the oil-price shocks of 1973 and

1979. People drove fewer miles in smaller cars and drove more slowly due to lowered speed limits. As a result, the national GDP/energy ratio improved — but at some cost in terms of the standard of living. That cost was relatively easily borne, but that it was indeed a cost is shown by the fact that when fuel prices drifted back downward, people again began driving more and faster, and choosing larger cars.

Given that, from a historical and cross-cultural perspective, Americans' average standard of living is lavish, it would seem that some curtailment of consumption may not be such a bad thing. After all, people currently have to be coaxed and cajoled from cradle to grave by expensive advertising to consume as much as they do. If the message of this incessant propaganda stream were simply reversed, people could probably be persuaded to happily make do with less. Many social scientists claim that our consumptive lifestyle damages communities, families, and individual self-esteem; a national or global ethic of conservation could thus be socially therapeutic.[43]

However, eventually curtailment means reducing economic activity — it means fewer jobs, goods, and services. It means fundamental changes not only in the *pattern* of life but also in the *quality* of life that we have become accustomed to. Mild degrees of curtailment in national energy usage might just involve sacrifices of speed and convenience. Intermediate degrees might imply tradeoffs in health care, transportation, housing space, and entertainment options. But severe curtailment — unless undertaken systematically over a period of decades — would likely lead to rampant unemployment and shortages of basic necessities.

Energy conservation — both increased efficiency and curtailment of energy usage — will be crucial in cushioning impacts from the depletion of oil. But it is not a panacea.

* * *

With such a broad array of alternatives to choose from, many people assume it must be possible to cobble together a complex strategy to enable a relatively painless transition away from fossil fuels. Surely, for example, by building more wind turbines and fuel cells, by exploiting advances in photovoltaic technologies, and by redoubling our national conservation efforts, we could effortlessly weather the downside of the Hubbert curve.

A recurring subtext of this chapter has been the importance of net-energy analysis. To date, very few such analyses have been performed by impartial and competent parties. It is essential to the welfare of current and future generations that a standardized and well-defined net-energy methodology be adopted by national and international planning agencies. Reliance on market price as a basis for energy policy is shortsighted, because hidden subsidies so often distort the picture. Any standardized EROEI evaluation methodology will inevitably be imperfect, but it will nevertheless provide the public and decision makers alike with much sounder insights into the costs of various energy options before precious resources are committed to them. As we have seen, the net-energy returns for some renewables (particularly wind) already exceed the dwindling returns for nonrenewable coal and domestic petroleum. Other options (such as hydrogen) may lose their luster when looked at closely.

Clearly, we would see the best outcome if all of the nations of the world were to undertake a full-scale effort toward conservation and the transition to renewables, beginning immediately. And undoubtedly some sort of complex strategy will eventually be adopted. But we should not delude ourselves. Any strategy of transition will be costly — in terms of dollars, energy, and/or our standard of living. Odum and Odum summarize the situation succinctly: "Although many energy substitutions and conservation measures are possible, none in sight now have the quantity and quality to substitute for the rich fossil fuels to support the high levels of structure and process of our current civilization."[44]

This is somewhat of a double message. Renewable alternatives are capable of providing net-energy benefit to industrial societies. We *should* be investing in them and converting our infrastructure to use them. If there is any solution to industrial societies' approaching energy crises, renewables plus conservation will provide it. Yet in order to achieve a transition from nonrenewables to renewables, decades will be required — and we do not have decades before the peaks in the extraction rates of oil and natural gas occur. Moreover, even in the best case, the transition will require shifting investment from other sectors of the economy (such as the military) toward energy research, conservation, and the implementation of renewable alternatives. Those alternatives will be unable to support the *kinds* of transportation, food, and dwelling infrastructure we now have; thus the transition will necessarily be comprehensive: it will entail an almost complete redesign of industrial societies. The result — an energy-conserving society that is less mobile, more localized, and more materially modest — may bring highly desirable lifestyle benefits for our descendants. Yet it is misleading to think that we can achieve that result easily or painlessly.

If indeed none of the energy alternatives now available has the near-term potential to "support the high levels of structure and process of our current civilization," then profound changes are virtually inevitable in every sphere of human concern as oil begins to run out. Just what sorts of changes can we expect to see within the next 50 years?

5

A Banquet of Consequences

Anyone who believes exponential growth can go on forever in a finite world is either a madman or an economist.

— Kenneth Boulding (ca. 1980)

If we continue ... to consume the world until there's no more to consume, then there's going to come a day, sure as hell, when our children or their children or their children's children are going to look back on us — on you and me — and say to themselves, "My God, what kind of monsters were these people?"

— Daniel Quinn (2000)

Current debates over where and how to drill for oil in this country soon may be rendered irrelevant by a nation desperate to maintain its quality of life and economic productivity. War over access to the diminishing supply of oil may be inevitable unless the United States and other countries act now to develop alternatives to their dependence on oil.

— Senator Mark Hatfield (1990)

We need an energy bill that encourages consumption.

— George W. Bush (2002)

Sooner or later, we sit down to a banquet of consequences.

— Robert Louis Stevenson (ca. 1885)

When the global peak in oil production is reached, there will still plenty of petroleum in the ground — as much that will be u mately recoverable as has been extracted from 1859 to the prese