Energy and Civilization

A History

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7 Energy in World History

All natural processes and all human actions are, in the most fundamental physical sense, transformations of energy. Civilization's advances can be seen as a quest for higher energy use required to produce increased food harvests, to mobilize a greater output and variety of materials, to produce more, and more diverse, goods, to enable higher mobility, and to create access to a virtually unlimited amount of information. These accomplishments have resulted in larger populations organized with greater social complexity into nation-states and supranational collectives, and enjoying a higher quality of life. Outlining the milestones of this history in terms of dominant energy sources and leading prime movers is, as I hope this book demonstrates, fairly straightforward. Nor is it difficult to recount the most important socioeconomic consequences of these technical changes.

What is much more challenging is to find a sensible balance between seeing history through the prism of energy imperatives and paying proper attention to the multitude of nonenergy factors that have always initiated, controlled, shaped, and transformed human use of energy. Even more fundamentally, it is also necessary to note the basic paradox of energy's role in life's evolution in general, and in human history in particular. All living systems are sustained by incessant imports of energy, and this dependence necessarily introduces a number of fundamental constraints. But these life-sustaining energy flows cannot explain either the very existence of organisms or the particular complexities of their organization.

Grand Patterns of Energy Use

The long-term relationship between human accomplishments and dominant energy sources and changing prime movers is perhaps best revealed when viewed in terms of energy eras and transitions. This approach must eschew rigid periodization (as some transitions unfolded very slowly) and it must recognize that generalizations regarding specific periods must take into account differences in the onset and pace of key underlying processes: perhaps the best recent example is China's exceptionally rapid post-1990 development, accomplishing in a single generation what took many nations during the earlier stages of industrialization three generations. There are also many national and regional particularities driving and shaping such complex changes.

The most obvious uniformities dictated by specific energy eras could be seen in activities pertaining to the extraction, conversion, and distribution of energies. Human muscles and harnessed oxen put very similar limits on the extent of land that could be planted or harvested in a day, be it in Punjab or in Picardy; the charcoal yield from traditional piles in Tohoku (northern Honshu) differed little from that in Yorkshire (northern England). In modern global civilization these commonalities have become absolute identities: the same energy sources and the same prime movers are now managed, extracted, and converted worldwide with the same processes and machines, and most of them are often produced or deployed by a small number of globally dominant companies.

Examples of such global companies include Schlumberger, Halliburton, Saipem, Transocean, and Baker for oil field services; Caterpillar, Komatsu, Volvo, Hitachi, and Liebherr for heavy construction machinery; General Electric, Siemens, Alstom, Weir Allen, and Elliott for large steam turbines; and Boeing and Airbus for large jet airliners. As the reach of services and products offered by these firms became truly global, former international differences in performance and reliability have been greatly reduced or even entirely eliminated, and in some cases the late starters now have higher shares of advanced techniques than do the pioneering industrializers. And despite large differences in cultural and political settings there is also a surprisingly wide scope for generalizing about the socioeconomic consequences of these fundamental energetic changes.

Because the most rewarding exploitation of identical energy sources and prime movers requires the same techniques, this uniformity also imposes many identical, or very similar, imprints not only on crop cultivation (leading to the dominance of a few commercial crops and the mass production of animal foods), industrial activities (entailing specialization, concentration, and automation), the organization of cities (leading to the rise of downtown business districts, suburbanization, and subsequently the desirability of green spaces), and transportation arrangements (in large cities manifesting as the need for subways, suburban trains, commuting by car, and taxi fleets) but also on consumption patterns, leisure activities, and intangible aspirations.

In every mature high-energy society, and in the urban areas of many still relatively fast-growing economies, TVs, refrigerators, and washing machines are owned by more than 90% of households, and other items with high rates of ownership range from personal electronic devices to air conditioning units and passenger vehicles. Globally shared food consumption trends include internationalization of tastes (tikka masala being the most popular food item in England, kare raisu in Japan), the popularization of fast food, and the year-round availability of seasonal fruit and vegetables, a convenience bought at a significant energy cost of intercontinental shipments in refrigerated containers and airborne deliveries. Among the now universal leisure activities are flights to warm beaches, visits to theme parks (American Disneylands are now in France, China, Hong Kong, and Japan), and traveling on cruise ships (cruising, formerly a European and American pastime, is now experiencing its fastest growth in Asia). And, taking this a step further, shared energy foundations eventually affect many intangible aspirations, especially for advanced (and elite) education.

But what recurs again and again is the enormous gap between the low-income societies (whose energetic foundations are an amalgam of traditional biomass fuels and animate prime movers and increasing shares of fossil fuels and electricity) and high-energy (industrialized or postindustrial) countries whose per capita consumption of fossil fuels and electricity has reached, or closely approached, saturation levels. This gap can be seen at every level, when looking at the overall economic output or at the average standard of living, at labor productivities or access to education. And this gap is becoming less a matter of international disparities and more a divide based on privilege (access, education, opportunity), the reality best illustrated by the affluent class in China and India. In 2013 one branch of China's Sports Car Club required its members to own a car better than the $440,000 Porsche Carrera GT (Taylor 2013), while Asia's most expensive private residential building, Mukesh Ambani's 27-story $2 billion skyscraper in downtown Mumbai, has an unimpeded view of sprawling slums.

Energy Eras and Transitions

Any realistic periodization of human energy use must take into account both the dominant fuels and the leading prime movers. This need disqualifies the two conceptually appealing divisions of history into just two distinct energy eras. Animate versus inanimate contrasts the traditional societies, in which human and animal muscles were the dominant prime movers, with modern civilization, dependent on fuel- and electricity-powered machines. But this division misleads both about the past and the present. In a number of old high cultures two classes of inanimate prime movers, waterwheels and windmills, were making critical differences centuries before the advent of modern machines.

And the rise of the West owes a great deal to a powerful combination of two inanimate prime movers: to effective harnessing of wind and to the adoption of gunpowder, embodied by oceangoing sail ships equipped with heavy guns (McNeill 1989). Moreover, the cleavage between animate and inanimate prime movers has been fully accomplished only among the richest fifth of the humanity. Substantial reliance on heavy human and animal labor is still the norm in the poorest rural areas of Africa and Asia, and exhaustive (and often risky) manual tasks are performed daily by hundreds of millions of workers in many extractive, processing, and manufacturing industries of low-income countries (ranging from crushing stones to make gravel to dismantling old oil tankers).

The second simplification, the use of renewable versus nonrenewable energy sources, captures the basic dichotomy between the millennia dominated by animate prime movers and biomass fuels and the more recent past, heavily dependent on fossil fuels and electricity. Once again, actual developments have been more complex. Biomass supply in wooden-era societies was not a matter of assured renewability: excessive tree cutting followed by destructive soil erosion on vulnerable slope lands destroyed the conditions for sustainable forest growth over large areas of the Old World, especially around the Mediterranean Sea and in North China. And, in today's fossil fuel–dominated world, water power, a renewable resource, generates roughly one-sixth of all electricity, while (as just noted) most farmers in poor countries still rely on human and animal labor for field work and for the maintenance of irrigation systems.

Clear divisions into specific energy eras are unrealistic not only because of obvious national and regional differences at the time of innovation and the widespread adoption of new fuels and prime movers but also because of the evolutionary nature of energy transitions (Melosi 1982; Smil 2010a). Established sources and prime movers can be surprisingly persistent, and new supplies or techniques may become dominant only after long periods of gradual diffusion. A combination of functionality, accessibility, and cost explains most of this inertia. As long as the established sources or prime movers work well within established settings, are readily available, and are profitable, their substitutes, even those with some clearly superior attributes, will advance only slowly. Economists might see these realities as examples of lock-in or path dependence as conceptualized by David (1985), who based his argument on a takedown of the QWERTY keyboard (as opposed to a supposedly superior Dvorak layout).

But we do not need any new questionable labels to describe what is a very common process of slow, evolutionary progression noticeable in organismic evolution and personal decision making, as well as in technical advances and economic management. Examples from energy history abound. Roman water mills were first used during the first century BCE, but they became really widespread only about 500 years later. Even then their use was almost completely limited to grain grinding. As Finley (1965) noted, freeing slaves and animals from their drudgery was not a powerful enough incentive for the rapid introduction of water mills. By the end of the sixteenth century circumnavigation of the Earth by sail ships had become almost commonplace—but in 1571 in the battle of Lepanto each side used more than 200 galleys, in 1588 the Spanish Armada set to invade England still had four large galleys and four galleasses manned by more than 2,000 convicted oarsmen, and heavily gunned Swedish galleys were used to destroy most of the Russian fleet at Svensksund in 1790 (Martin and Parker 1988; Parker 1996).

Draft animals, water power, and steam engines coexisted in industrializing Europe and North America for more than a century. In the wood-rich United States, coal surpassed fuelwood combustion, and coke became more important than charcoal, only during the 1880s (Smil 2010a). Mechanical power in farming topped horse and mule power only during the late 1920s, there were still millions of mules in the U.S. South in the early 1950s, and the U.S. Department of Agriculture stopped counting working animals only in 1963. And during World War II the mass-produced Liberty (EC2) class ships, the dominant U.S. cargo carriers, were not powered by new, efficient diesel engines but by well-proven three-cylinder steam engines supplied by oil-fired boilers (Elphick 2001).

Only suggestive approximations are possible in charting long-term patterns of prime mover deployment in the Old World's preindustrial societies. Their most remarkable feature is the long dominance of human labor (fig. 7.1). Human muscles were the only source of mechanical energy from the beginning of hominin evolution until the domestication of draft animals, which started only about 10,000 years ago. Human power was increased by using a growing number of better tools, while animal work throughout the Old World remained limited for millennia by poor harnessing and inadequate feeding, and draft beasts were absent in the Americas and Oceania. Human muscles thus remained indispensable prime movers in all preindustrial societies.

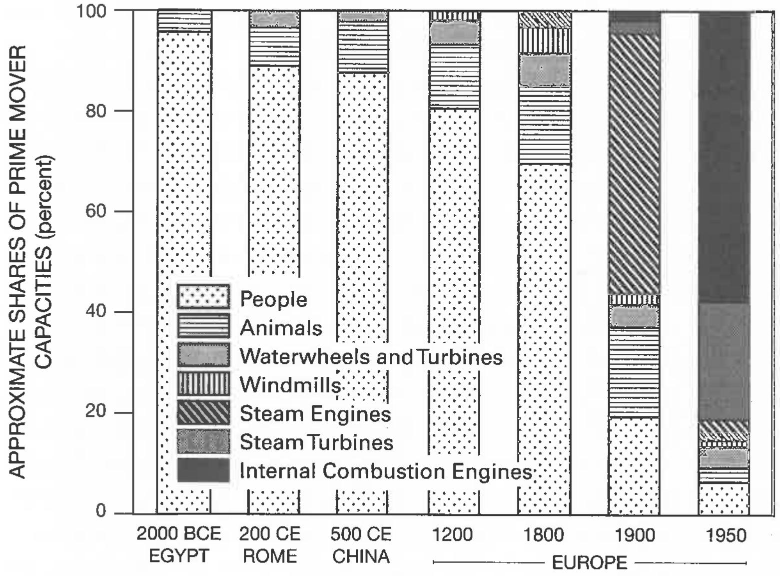

Figure 7.1
The prolonged dominance of human labor, the slow diffusion of water- and wind-driven machines, and the rapid post-1800 adoption of engines and turbines are the three most remarkable features in the history of prime movers. Approximate ratios are estimated and calculated from a wide variety of sources cited in this book.

A remarkable dichotomy characterized the use of human labor in all ancient civilizations. In contrast to its massed deployment to accomplish remarkable feats of heavy construction, old high cultures, whether based on slave, corvée, or mostly free labor, never took the steps to the really large-scale manufacture of goods. The atomization of production remained the norm (Christ 1984). Han Chinese mastered some potentially large-scale production methods. Perhaps most notably, they perfected the casting of iron suitable for mass-producing virtually identical multiple pieces of small metal articles from a single pouring (Hua 1983). But the largest discovered Han kiln was just 3 m wide and less than 8 m long. Outside Europe and North America, relatively small-scale, artisanal manufactures remained the norm until the twentieth century. The lack of inexpensive land transportation was obviously a major factor militating against mass production.

The costs of distribution beyond a relatively small radius would have surpassed any economies of scale gained by centralized manufacturing. And many ancient construction projects did not really require extraordinarily massive labor inputs either. Several hundred to a few thousands corvée laborers working for only two to five months every year could erect enormous religious structures or defensive walls, dig long irrigation and transportation canals, and build extensive dikes over a period of just 20–50 years. But many stupendous projects were under construction for much longer periods. Ceylon's Kalawewa irrigation system took about 1,400 years to build (Leach 1959). Piecemeal construction and repairs of China's Great Wall extended over an even longer period of time (Waldron 1990). And a century or two was not an exceptionally long time to finish a cathedral.

The first inanimate prime movers begun to make notable differences in some parts of Europe and Asia only after 200 CE (water mills) and 900 CE (windmills). Gradual improvements of these devices replaced and sped up many tiresome, repetitive tasks, but the substitution for animate labor was slow and uneven (fig. 7.2). In any case, except for water pumping, waterwheels and windmills could do little to ease field tasks. That is why Fouquet's (2008) approximate calculations for England show human

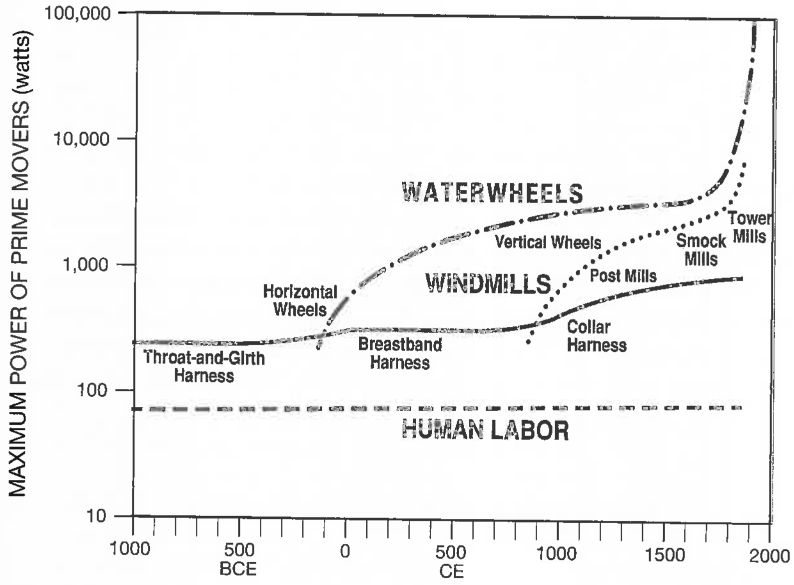

Figure 7.2
The average unit power of traditional prime movers remained limited even after the adoption of larger waterwheels at the beginning of the early modern era. The change came only with steam engines of the nineteenth century. Maximum capacities are plotted from prime mover–specific sources cited in this book.

and animal exertion accounting for 85% of all power in 1500 and still 87% in 1800 (when water and wind delivered about 12%)—but only 27% by 1900: by that time steam had taken over in industries. But even during the steam engine era animate labor remained indispensable for extracting and distributing fossil fuels and in countless manufacturing tasks; and in farming it dominated field work throughout the nineteenth century (box 7.1).

But long before the maximum power of working animals was itself tripled (by strong horses with collar harnesses), waterwheels had become the most powerful prime movers. Their subsequent development was slow: the first tenfold increase in highest capacities took about 1,000 years, the second one about 800. Their peak unit power was finally surpassed by steam engines of the late eighteenth century, but their dominance ended only with the introduction and growth of internal combustion engines and steam turbines, both of which entered use during the 1880s, became dominant by the 1920s, and remain the leading mobile and stationary prime movers, respectively, of the early twenty-first century.

Box 7.1
Persistence of animate power

In the Americas, horse, mule, and ox teams also converted most of the currently cultivated land by plowing up the extensive grasslands of the U.S. Great Plains, the Canadian prairies, the Brazilian cerrado, and the Argentinian pampas during the closing decades of the nineteenth century and at the very beginning of the twentieth century. Only by 1963, when America's tractor power was nearly 12 times the record draft animal capacity of 1920, did the U.S. Department of Agriculture stop counting draft animals. In late dynastic and early republican China, the contribution of windmills, water mills, and steam remained marginal in comparison with that of human labor, whose aggregate power also greatly surpassed that of draft animals. My best estimate was that even by 1970, China's human labor contributed about 200 PJ of useful energy, compared to just over 90 PJ for the country's draft animals (Smil 1976).

The dominance of human muscles limited the most commonly deployed single labor units to 60–100 W of sustained (daylong) useful labor. This means that in all but a few exceptional circumstances, the highest power concentrations of human labor under a single command (hundreds to thousands of laborers at construction sites) reached no more than 10,000–100,000 W during sustained effort, although brief peaks were multiples of those rates. A traditional master architect or a canal builder thus controlled energy flows equivalent to no more than those produced by a single engine powering today's small earth-moving machines.

Despite some important continental and regional differences, typical levels of fuel consumption and the prevailing modes of prime mover use in old high cultures were fairly similar. If there is an ancient society to be singled out for its notable advances in fuel use and prime mover development, it must be Han China (207 BCE–220 CE). Its innovations were adopted elsewhere only centuries, or even more than a millennium, later. The most notable contributions of the Han Chinese were the use of coal in iron making, drilling for natural gas, the making of steel from cast iron, the widespread use of curved moldboard iron plows, the beginning use of collar harness, and use of the multitube seed drill. There was no similar cluster of such key advances for more than a millennium.

Early Islam brought innovative designs for water-raising machines and windmills, and the realm's maritime trade benefited from an effective use of triangular sails. But the Islamic world did not introduce any radical innovations in fuel use, metallurgy, or animal harnessing. Only medieval Europe, borrowing eclectically from earlier Chinese, Indian, and Muslim accomplishments, began to innovate in a number of critical ways. What really set European medieval societies apart in terms of energy use was their rising reliance on the kinetic energies of water and wind. These flows were harnessed by increasingly more complex machines, providing unprecedented concentrations of power for scores of applications. By the time of the first great Gothic cathedrals the largest waterwheels rated close to 5 kW, an equivalent of more than three score men. Long before the Renaissance some European regions became critically dependent on water and wind, first for their grain milling, then for cloth fulling and iron metallurgy; and this dependence also contributed to the sharpening and diffusion of many mechanical skills.

Late medieval and early modern Europe was thus a place of broadening innovation, but, as attested by reports of contemporary European travelers admiring the riches of the Heavenly Empire, the overall technical prowess of contemporary China was certainly more impressive. Those travelers could not know how soon the reverse would be true. By the end of the fifteenth century Europe was on a road of accelerating innovation and expansion while the elaborate Chinese civilization was about to start its long and deep technical and social involution. Western technical superiority did not take very long to transform European societies and extend their reach to other continents.

By 1700 the Chinese and European levels of typical energy use, and hence of average material affluence, were still broadly similar. By the mid-eighteenth century the real incomes of building workers in China were similar to those in less developed parts of Europe but lagged behind the continent's leading economies (Allen et al. 2011). Then the Western advances gathered speed. In the energy realm they were demonstrated by the combination of rising crop yields, new coke-based iron metallurgy, better navigation, new weapon designs, a keenness for trade, and the pursuit of experimentation. Pomeranz (2002) argued that this takeoff had less to do with institutions, attitudes, or demography in the core economic regions of Europe and China than with the fortuitous location of coal, and with the very different relationships between these cores and their respective peripheries, as well as with the process of invention itself.

Others saw the foundations of this success going back to the Middle Ages. Christianity's favorable effect on technical advances in general (including a critical concept of the dignity of manual labor), and medieval monasticism's quest for self-sufficiency in particular, were important ingredients of this process (White 1978; Basalla 1988). Even Ovitt (1987), who questions the importance of these links, acknowledges that the monastic tradition, by upholding the fundamental dignity and spiritual usefulness of labor, was a positive factor. In any case, by 1850 the most economically advanced parts of China and Europe belonged to two different worlds, and by 1900 they were separated by an enormous performance gap: Western European energy use was at least four times the Chinese mean.

The period of very rapid advances after 1700 was ushered in by ingenious practical innovators. But its greatest successes during the nineteenth century were driven by close feedbacks between the growth of scientific knowledge and the design and commercialization of new inventions (Rosenberg and Birdzell 1986; Mokyr 2002; Smil 2005). The energy foundations of nineteenth-century advances included the development of steam engines and their widespread adoption as both stationary and mobile prime movers, iron smelting with coke, the large-scale production of steel, and the introduction of internal combustion engines and of electricity generation. The extent and rapidity of these changes came from a novel combination of these energy innovations with new chemical syntheses and with better modes of organizing factory production. Aggressive development of new ways of transport and telecommunication was also essential, both for boosting production and for promoting national and international trade.

By 1900, the accumulation of technical and organizational innovations gave the West, now including the new power of the United States, command over an unprecedented share of global energy. With only 30% of the world's population the Western nations consumed about 95% of fossil fuels. During the twentieth century the Western world increased its total energy use nearly 15 times. Inevitably, its share of global energy use declined, but by the end of the twentieth century the West (the EU and North America), with less than 15% of the global population, consumed nearly 50% of all primary commercial energy. Europe and North America remain the dominant consumers of fuels and electricity in per capita terms and have retained technical leadership. China's rapid economic growth changed the absolute ranking: the country became the world's largest energy consumer in 2010, by 2015 it was about 32% ahead of the United States, but its per capita energy use was only a third of the U.S. mean (BP 2016).

Only rough approximations are possible in presenting long-term patterns of the Old World's primary energy consumption (fig. 7.3). In the UK, coal had displaced wood already during the seventeenth century; in France and Germany wood receded rapidly in importance only after 1850; and in Russia, Italy, and Spain biomass energies remained dominant into the twentieth century (Gales et al. 2007; Smil 2010a). Once the basic energy statistics become available, it is possible to quantify the transitions and to discern long substitution waves (Smil 2010a; Kander, Malanima, and Warde 2013). In global terms this can be done with fair accuracy since the middle of the nineteenth century (fig. 7.3). Substitution rates have been slow, but, considering the variety of intervening factors, they have been surprisingly similar.

My reconstruction of global energy transitions shows coal (replacing wood) reaching 5% of the global market around 1840, 10% by 1855, 15% by 1865, 20% by 1870, 25% by 1875, 33% by 1885, 40% by 1895, and 50% by 1900 (Smil 2010a). The sequence of years needed to reach these milestones was 15–25–30–35–45–55–60. The intervals for oil replacing coal, with 5% of the global supply reached in 1915, were virtually identical: 15–20–35–40–50–60 (oil will never reach 50%, and its share has been declining). Natural gas reached 5% of the global primary supply by 1930 and 25% of it after 55 years, taking significantly longer to reach that share than coal or oil.

The similar progress of three global transitions—it takes two or three generations, or 50–75, years for a new resource to capture a large share of the global energy market—is remarkable because the three fuels require

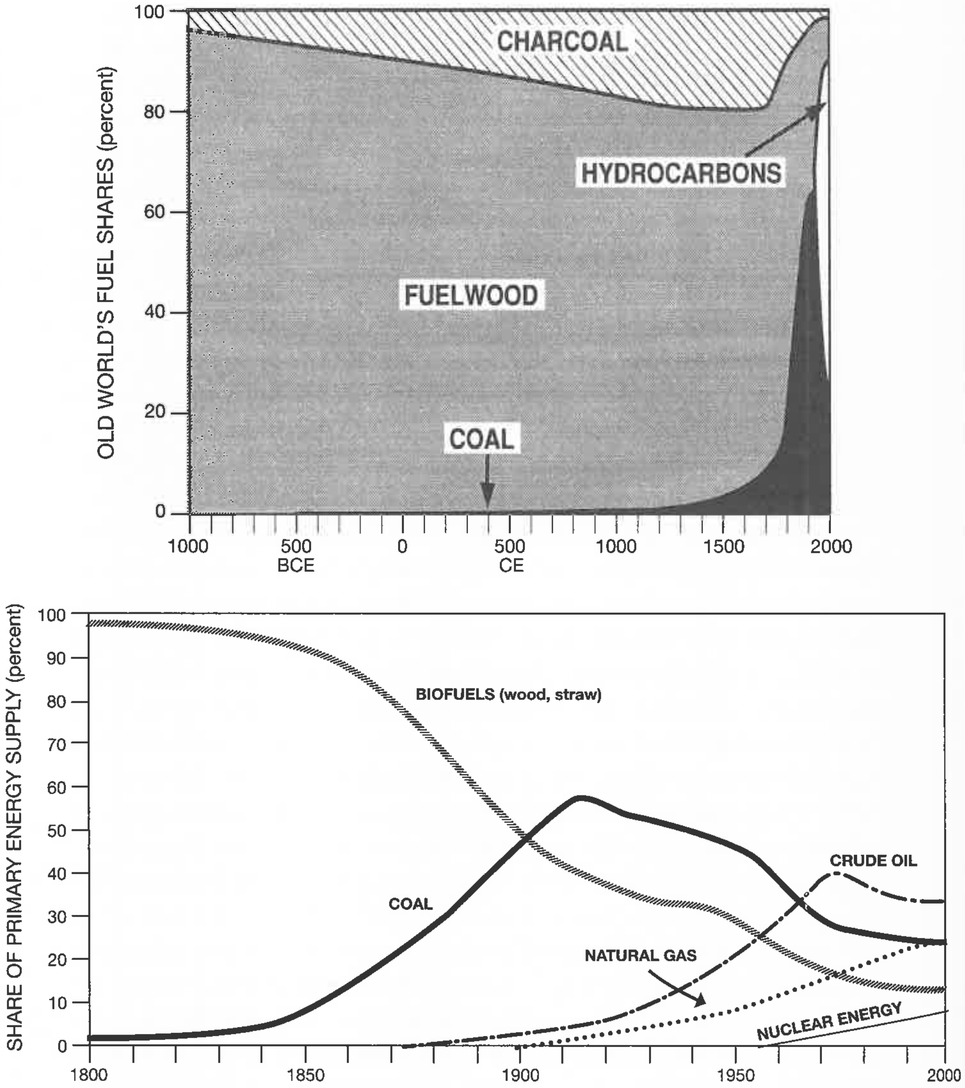

Figure 7.3

Approximate estimates chart the shares contributed by major fuels to the Old World's primary energy supply during the past 3,000 years (top). Reasonably accurate (except for the consumption of traditional biomass fuels) post-1850 statistics reveal successive waves of slow energy transitions (bottom): by 2010 crude oil was the leading fossil fuel, but coal and natural gas were not far behind. Plotted from data in UNO (1956) and Smil (2010a).

different production, distribution, and conversion techniques and because the scales of substitutions have been so different: going from 10% to 20% for coal required increasing the fuel's annual output by less than 4 EJ, whereas going from 10% to 20% of natural gas needed roughly an additional 55 EJ/year (Smil 2010a). The two most important factors explaining the similarities in the pace of transitions are the prerequisites for enormous infrastructural investment and the inertia of massively embedded energy systems.

Although the sequence of three substitutions does not mean that the fourth transition, now in its earliest stage (with fossil fuels being replaced by new conversions of renewable energy flows), will proceed at a similar pace, the odds are highly in favor of another protracted process. In 2015 the two new renewable ways of electricity generation, solar (at 0.4%) and wind (at 1.4%), were still below 2% of the world's primary energy supply (BP 2016). Two early breakthroughs would accelerate the shift: swift construction of new nuclear plants based on the best available designs, and the availability of new, inexpensive ways to store wind and solar electricity on massive scales. And even then we would still face the challenges of replacing billions of tonnes of high energy-density liquid fuels in transportation, and producing pig iron, cement, plastics, and ammonia without any fossil carbon.

Long-Term Trends and Falling Costs

Secular transitions to more powerful prime movers can be traced quite accurately in terms of both typical and maximum capacities (fig. 7.4). The power envelope connecting the peak prime mover capacities moved from roughly 100 W of sustained human labor to about 300–400 W for draft animals sometime during the third millennium BCE; then the line rose to about 5,000 W (5 kW) for horizontal waterwheels by the end of the first millennium of the Common Era. By 1800 it had surpassed 100,000 W (100 kW) in steam engines, and they remained by far the most powerful units until the middle of the nineteenth century, when water turbines gained a short-lived primacy between 1850 and 1910 (reaching 10 MW). Afterward steam turbines have been the most powerful single-unit prime movers, reaching a plateau at more than 1,000,000,000 W (1 GW) in the largest units installed after 1960.

A different perspective is gained by looking at total prime mover capacities. After 1700 the basic global pattern can be reasonably approximated, and accurate historical statistics make the retrospective easy for the United States (fig. 7.5). In 1850 animate labor still accounted for more than 80% of

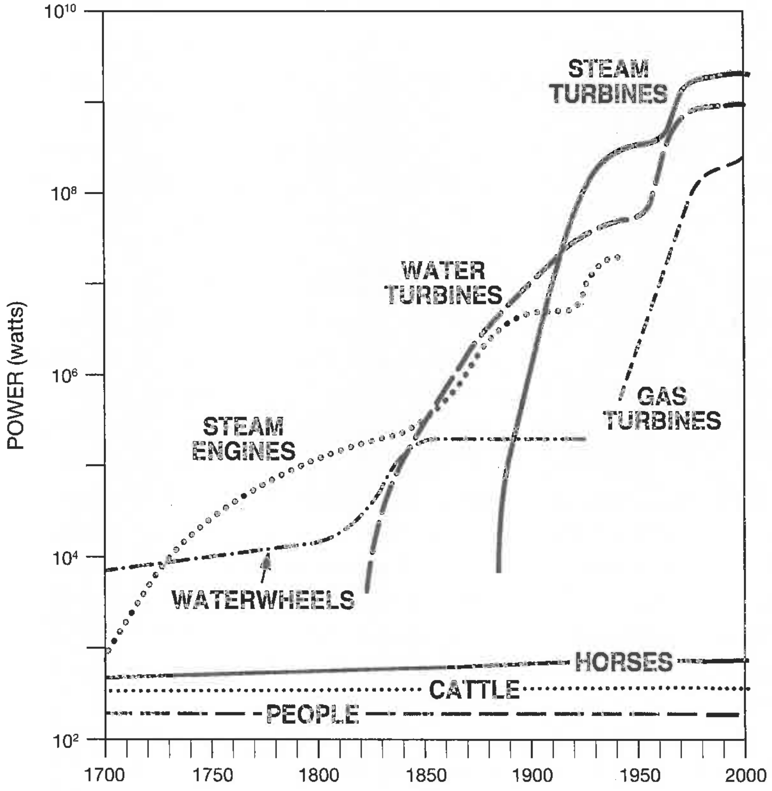

Figure 7.4
Maximum capacities of prime movers predating 1700 and those introduced during the past three centuries. The largest turbogenerators are now six orders of magnitude (nearly two million times) more powerful than heavy draft horses, the most powerful animate prime movers. Waterwheel ratings were surpassed by steam engines before 1750, by 1850 water turbines had become briefly the most powerful prime movers, and steam turbines have been the most powerful prime movers ever since the second decade of the twentieth century. Plotted from data cited in the sections concerning specific prime movers.

the world's prime mover capacity. Half a century later its share was about 60%, with steam engines supplying about one-third. By the year 2000 all but a small fraction of the world's available power was installed in internal combustion engines and electricity generators. U.S. prime mover substitutions predated these global changes. Of course, internal combustion engines (be they in vehicles, tractors, combines, or pumps) are rarely deployed in such a sustained manner as electricity generators. Automobiles and farm machines usually operate less than 500 hours a year, compared to over

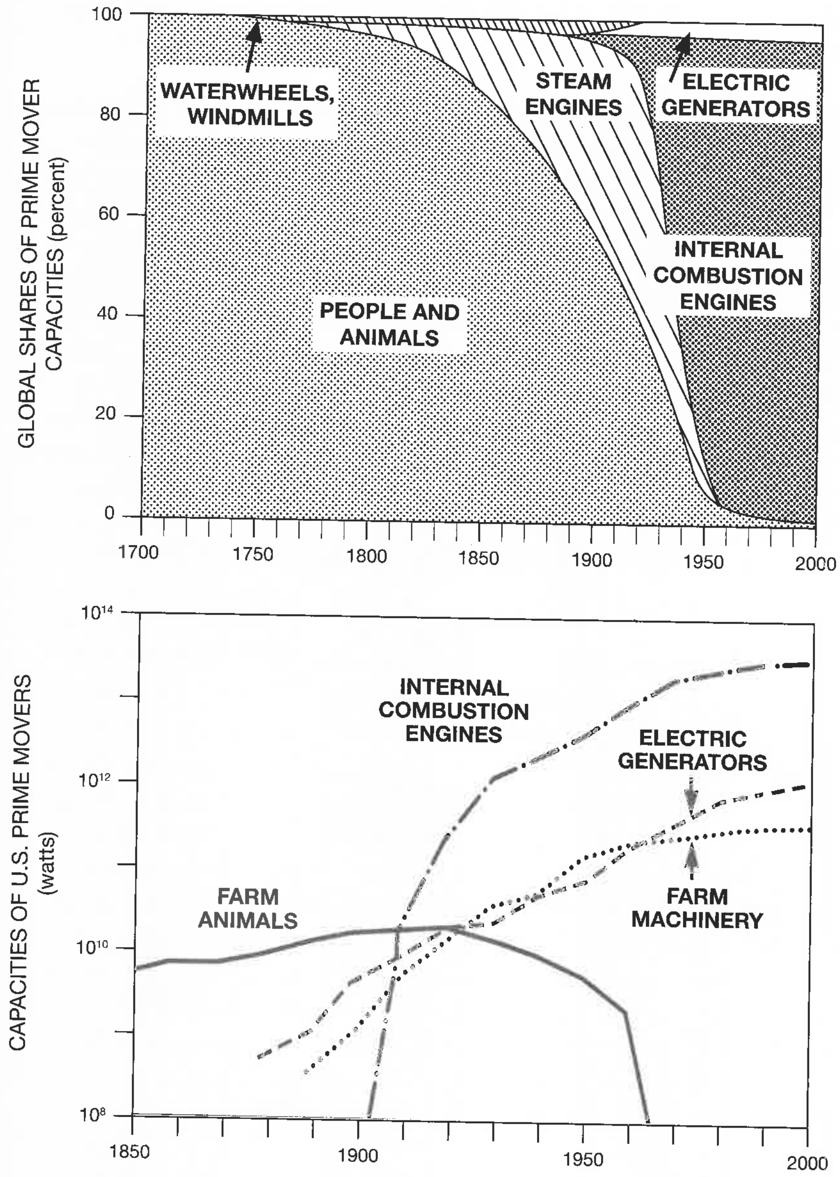

Figure 7.5
Global prime mover shares in 1700 were only marginally different from those of 500 or even 1,000 years ago. In contrast, by 1950 all but a very small fraction of the world's available power was installed in internal combustion engines (mostly in passenger cars) and in steam and water turbines (top). Disaggregated U.S. statistics (bottom) show this rapid transformation with greater detail and accuracy. The global rates were estimated and plotted from data in UNO (1956), Smil (2010a), and Palgrave Macmillan (2013); the bottom graph was plotted from data in USBC (1975) and from subsequent issues of *The Statistical Abstract of the United States*.

5,000 hours for turbogenerators. Consequently, in terms of actual energy production, the global ratio between internal combustion engines and electricity generators is now about 2:1.

Two important general trends have accompanied the growth of unit power of inanimate prime movers and the accumulation of their total capacity: their mass/power ratios have declined (producing more power from smaller units), and their conversion efficiencies have increased (producing more useful work from the same amount of initial energy input). The first trend has brought progressively lighter and hence more versatile fuel converters (fig. 7.6). The earliest steam engines, while much more powerful than horses, were exceedingly heavy because their mass/power ratio was of the same order of magnitude as that of draft animals. More than two centuries of subsequent development lowered the mass/power ratio of steam engines to about one-tenth of initial values, still too high for the engines to serve on roads or to power flight.

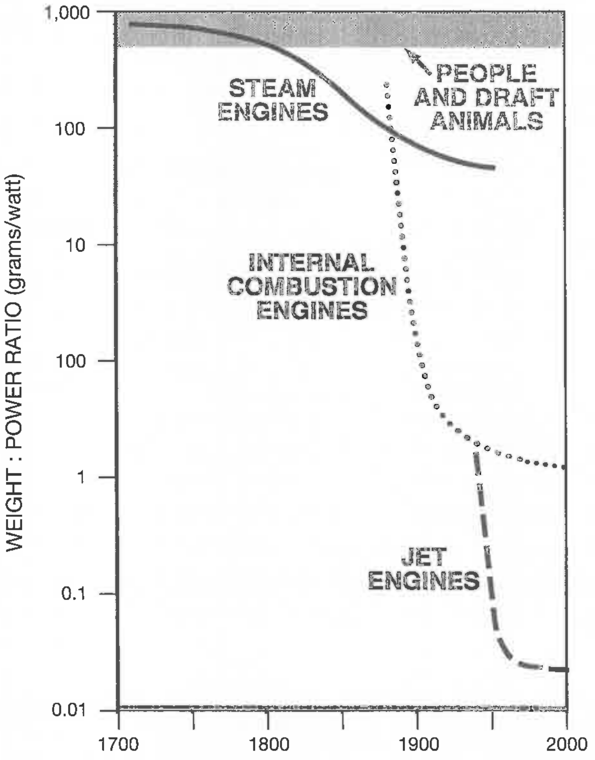

Figure 7.6
Every new inanimate energy converter became eventually much lighter and more efficient. The steady decline in the weight/power ratio of leading prime movers means that the best internal combustion engines now weigh less than 1/1,000 of what the equally powerful draft animals or early steam engines weighed. Plotted from data cited throughout this book.

The mass/power ratio of internal combustion engines (first gasoline engines, then diesels) declined by two orders of magnitude in less than 50 years after the first commercial models, horizontal engines fueled by coal gas, were introduced during the 1860s. That precipitous drop opened the way to the affordable mechanization of road transport (cars, buses, trucks) and made aviation possible. Starting in the 1930s (both for stationary use and in flight), gas turbines carried these improvements by almost another two orders of magnitude, making speedy jet-powered air travel possible, starting in 1958 and on a mass scale after the introduction of wide-body jets, with the Boeing 747 leading the way in 1969. Concurrently, gas turbines have emerged as a leading choice for flexible and clean electricity generation.

The efficiencies of prime movers are limited by fundamental thermodynamic considerations. Technical advances have been narrowing the gaps between best performances and theoretical maxima. The efficiencies of steam-driven machines rose from a fraction of a percent for Savery's primitive engines to just over 40% for large turbogenerators of the early twenty-first century. Only marginal improvements are now possible for turbogenerators, whether steam- or water-driven, but combined-cycle gas turbines can reach efficiencies of 60%. Similarly, the best combustors now perform close to theoretical limits. Both large power plant boilers and household natural gas furnaces may be up to 97% efficient. In contrast, the everyday performances of internal combustion engines, the prime movers with the largest aggregate installed power, are still very low. Poorly maintained car engines often perform at less than a third of their rated maxima. Improvements in lighting efficiency have been even more impressive (box 7.2).

More powerful yet more efficient and lighter mechanical prime movers have increased the typical speeds of long-distance travel by more than tenfold on land and on water, and made flying possible (fig. 7.7). In 1800 horse-drawn coaches usually covered less than 10 km/h, while heavy freight wagons moved at half that speed. In the year 2000 highway traffic could flow at speeds above 100 km/h and high-speed passenger trains ran at speeds approaching, or even surpassing, 300 km/h, while the standard cruising speed for jet planes is 880–920 km/h at about 11 km above the

Box 7.2

Efficiency and efficacy of lighting

Candles convert as little as 0.01% and no more than 0.04% of the chemical energy of the burning wax, tallow, or paraffin into light. Edison's first light bulbs, which used oval loops of carbonized paper secured by platinum clamps to platinum wires sealed through the glass, converted 0.2%, an order of magnitude better than candles but no better than contemporary gas lights (0.15–0.3%). Osmium filaments, introduced in 1898, converted nearly 0.6% of electric energy into light. This rate was more than doubled after 1905 with tungsten filaments in a vacuum, and then doubled again with inert gas in bulbs. In 1939 the first fluorescent light pushed the efficiency above 7%, and the rates rose well above 10% after World War II (Smil 2006).

But the best way to appreciate these gains is in terms of luminous efficacy. This ratio of luminous and radiant flux (expressed in lumens per watt, lm/W) measures the efficiency with which a source of radiant energy produces visible light, and its maximum is 683 lm/W. Here are the ascending luminous efficacies, all in lm/W (Rea 2000): candle, 0.3; gas light, 1–2; early incandescent light bulbs, less than 5; modern incandescent lights, 10–15; fluorescent lights, up to 100. Low-pressure sodium lamps are currently the most efficient commercial source of light (with maxima just above 200 lm/W), but their yellowish light is used only for street lighting. Light-emitting diodes, suitable for any indoor applications, already deliver close to 100 lm/W, and soon they will go above 150 lm/W (USDOE 2013).

ground. Increasing speeds have been accompanied by growing capacities and ranges in transporting both goods and people.

On land, this mechanical evolution has recently peaked with multi-axle trucks, unit trains (carrying up to 10,000 t of bulk materials), and fast electric passenger trains (for up to 1,000 people). Supertankers move up to 500,000 t of crude oil, while the largest passenger planes, the Boeing 747 and the Airbus 380, carry about 500 people and the largest cargo plane, the Antonov 225, can lift 250 t. The range increase has been equally impressive: the greatest distance that can be covered by a passenger car without refueling is now just over 2,600 km—the record made in 2012 with the diesel-powered Volkswagen Passat TDI (Quick 2012)—and the Boeing 777–200LR can fly more than 17,500 km.

The increased speed and range of passenger and goods transportation had its destructive counterpart in the increased speed, range, and effective power of projectiles released by weapons. The killing range of spears was just a few tens of meters; an expertly fielded spear-thrower could increase this distance to more than 60 m. Good composite bows delivered piercing arrows up to 500–700 m. This was also the range for the more powerful crossbows. Various catapults could throw stones of 20–150 kg 200–500 m. The reach rose rapidly when muscles were replaced by gunpowder. Just before 1500 the heaviest cannons could fire 140 kg iron balls about 1,400 m and lighter stone balls twice as far (Egg et al. 1971).

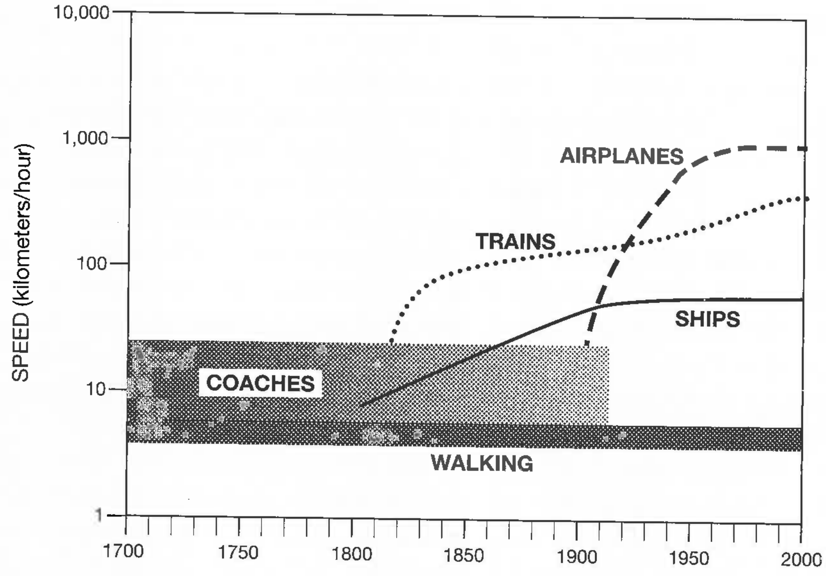

Figure 7.7

Maximum speeds of passenger transportation rose from less than 20 km/h for coaches of the pre-railway era to well over 100 km/h after just a few decades of better locomotive designs. Modern rapid trains commonly travel at 200–300 km/h and jetliners cruise at speeds just above 900 km/h. Plotted from data in numerous references cited in the book's sections dealing with transportation.

By the beginning of the twentieth century, when the ranges of big field pieces had reached several tens of kilometers, guns lost their primacy in the long-range delivery of destruction to bombers. Bomber ranges surpassed 6,000 km, with the delivery of up to 9 t of bombs, by the end of World War II, and bombers in turn were surpassed by ballistic missiles (Spinardi 2008). Since the early 1960s these missiles could deliver more powerful nuclear bombs with greater accuracy either from land-based silos or from submarines to any place on Earth. The increase in range from the ancient Old World's compound bow to a late twentieth-century ballistic missile has been about 30,000-fold, while a missile has a destructive power 16 orders of magnitude greater than an arrow's.

Long-term consumption trends, both in absolute and in relative terms, have been no less impressive. On the global scale, total primary energy flows, including traditional biomass fuels, reached 20 EJ in 1800, nearly 45 EJ in 1900, 100 EJ in 1950, just over 380 EJ in the year 2000, and more than 550 EJ in 2015. This means that the annualized power rose from about 650 GW in 1800 to 12.2 TW in 2000, a nearly 20-fold rise in two centuries, and by 2015 it had increased by more than 40%, to about 17.5 TW. The increase in fossil fuel extraction between 1800 and 2000 was nearly 900-fold, from less than 0.4 EJ to more than 300 EJ. Rising energy use has profoundly changed both the absolute and relative levels of typical per capita consumption.

The energy needs of foraging societies were dominated by the provision of food, basic clothing, and temporary shelters. Ancient high cultures channeled slowly rising energy use into permanent shelters, a greater variety of cultivated and processed food, better clothing, transportation, and a variety of manufactures (with charcoal the dominant source supplying the heat needed for smelting ores and firing bricks). Early industrial societies—with larger numbers of domestic animals, with the kinetic energy of waterwheels and windmills, and with a rising extraction of coal—easily doubled the per capita energy use that prevailed in the high Middle Ages.

Initially, most of that increase went into new manufactures, construction, and transportation (including extensive infrastructural developments), but the eventual rise of the discretionary private use of energies is not captured by the standard reporting of sectoral energy use: for example, International Energy Agency statistics show that in 2013, only 12% of the U.S. primary energy use was residential, while the U.S. Energy Information Agency put that share (including all electricity and losses in its generation) at about 22%, and the actual share (including large proportions of energy use classed under commercial and transportation categories) is well over 30%.

The U.S. per capita energy supply was already fairly high in 1900 and hence its rate during the first decade of the twenty-first century was "only" 2.5 times higher (330 vs. 132 GJ/capita), while Japan's per capita consumption between 1900 and 2015 rose 15-fold, and the multiple was nearly 10 in China. Owing to the steady rise of average conversion efficiencies, increases in per capita consumption of useful energy have been far higher: depending on the country, they were at least fourfold and up to 50-fold during the twentieth century. With an overall energy efficiency no higher than 20%, the United States consumed no more than about 25 GJ/t of useful energy in 1900, but by the year 2000, with an average efficiency of 40%, the rate was about 150 GJ/capita, a sevenfold rise in a century. My best calculation for China shows the rise from 0.3 GJ/capita of useful energies in 1950 to about 15 GJ in 2000, a 50-fold increase in just two generations.

Fouquet's (2008) British data illustrate these useful gains for major energy consumption categories for 250 years between 1750 and 2000. For all industrial power (in 1750 provided by animate labor, waterwheels, wind mills, and a few steam engines; in 2000 delivered mostly by electric motors and internal combustion engines) the multiple was 13 in 250 years; for space heating it was 14; for all passenger transport (in 1750 horses, carts, coaches, barges, and sail ships; in 2000 vehicles and ships powered by internal combustion engines and mostly jet-powered airplanes) it was nearly 900; and (as already noted) lighting gains take the top place, with the average Briton consuming about 11,000 times more light in 2000 than in 1750.

These multiples tracing the gains of useful energy services are the most revealing energy metric as they explain large gains in productive capacity, quality of life, unprecedented mobility, and (if a sapient extraterrestrial were to take a look) so much light that nighttime satellite images show large regions of Europe, North America, and Asia as continuous patches of brilliance. But higher energy efficiencies have been swamped by the combination of growing demand and larger populations, and although the global economy has become relatively less energy-intensive, its aggregate energy use has been increasing, and only some of the most advanced economies have shown saturation of average per capita energy demand during the recent three decades.

Concurrently, energy used to provide the physical necessities of life has become a steadily smaller part of the rising consumption, and the production of an enormous variety of goods, the provision of countless services, and transportation and leisure activities now consume the bulk of fuels and electricity in all affluent countries; the same pattern applies to increasing numbers of affluent urbanites in all populous modernizing countries, above all in China, India, and Brazil. And long-run efficiency gains have been the most important reason for substantial declines in energy prices (compared in real, inflation-adjusted, terms).

Kander (2013) showed that during the twentieth century, real Western European energy prices declined by 75%, ranging from an 80% decline in the UK to a 33% decline in Italy. Some of the most interesting long-term trends (properly compared in constant monies, or per unit of specific performance or delivered service) were presented by Fouquet (2008), who took advantage of English price data, some going back as far as the Middle Ages. Between the years 1500 and 2000 the cost of domestic heating fell by nearly 90%, the cost of industrial power by 92%, the cost of freight transport on land by 95%, and the cost of ocean freight transport by 98%. But by far the most impressive decline was for lighting.

The falling cost of fuels used to generate light directly or via electricity and the rising efficiency of lighting devices have combined to produce the secular drop in the cost of lighting services (monies/lumens) that is unequaled by any other kind of energy conversion. In the year 2000 a lumen of light in Britain cost merely 0.01% of what it did in 1500 and about 1% of what it did in 1900 (Fouquet 2008). And Nordhaus (1998) calculated that by the end of the twentieth century the cost of illumination in the United States was four orders of magnitude lower (the actual fraction ratio was about 0.0003) than it was in 1800. Real electricity prices declined by 97–98% during the twentieth century both in Europe and in North America (Kander 2013), and when this decline is combined with a concurrent fivefold rise in average per capita disposable income and up to an order of magnitude increase in conversion efficiency, it means that in the year 2000 a unit of electricity service in the United States was at least 200 times, and up to 600 times, more affordable than in 1900 (Smil 2008a). And since the year 2000 total energy expenditures of an average American family have been just 4-5% of its disposable income, an extraordinary bargain considering the typical housing size and the intensity of transportation (USEIA 2014).

All of these secular price declines portray indisputable trends, but at the same time, it must be kept in mind that virtually all of these trajectories would look different if energy prices had fully reflected a variety of externalities, including the environmental and health impacts associated with fuel extraction, transportation, processing, and combustion, and the various ways of electricity generation. That was never the case anywhere. Some externalities, including the capture of particulate matter and flue gas desulfurization, have been largely internalized, while others remain ignored: most notably, no fossil fuel has borne the eventual cost of CO_2-driven global warming. In addition, most energy prices—no matter whether in so called free-market economies or in states with heavy dirigiste economic policies, whether in high- or low-income countries—have been subsidized, often heavily, mostly by ignoring externalities, by setting low tax rates, and by other preferential treatments (box 7.3).

Box 7.3
Energy subsidies

The International Monetary Fund (IMF 2015) more than doubled its original 2011 estimate of $2.0 trillion of global energy subsidies, to $4.2 trillion, and put the 2015 total at $5.3 trillion, or about 6.5% of the world economic product. Most of these subsidies stem from undercharging for domestic environmental and health burdens and other externalities (including traffic congestion and accidents). China, with its massive coal combustion, has been the leading subsidizer in absolute terms (about $2.27 trillion in 2015); Ukraine's subsidies amounted to 60% of the country's GDP; and Qatar's per capita subsidies ranked first, with about $6,000 for every inhabitant. A new wave of energy subsidies has been used to establish and then to expand solar and wind generation, the two leading ways of renewable electricity production, and fermentation of carbohydrate crops to produce automotive ethanol (Charles and Wooders 2011; Alberici et al. 2014; USEIA 2015c).

What Has Not Changed?

Given the fundamental nature of energy-driven developments, this is a fair question to ask—and the obvious simple answer must be that the adoption and diffusion of new energy sources and new prime movers have been the fundamental physical reasons for economic, social, and environmental change and that they have transformed virtually every facet of modern societies: the process has always been with us, but its pace has been accelerating. Prehistoric changes brought about by better tools, the mastery of fire, and better hunting strategies were very slow, unfolding over tens of thousands of years. The subsequent adoption and intensification of permanent farming lasted for millennia. Its most important consequence was a large increase in population densities, leading to social stratification, occupational specialization, and incipient urbanization. High-energy societies created by the rising consumption of fossil fuels became the very epitomes of change, leading to a widespread obsession with the need for constant innovation.

The densities of foraging populations spanned a wide range, but, with the exception of some maritime cultures, they never surpassed one person per square kilometer. Even the least productive shifting farming raised this rate at least ten times. Permanent cropping resulted in yet another tenfold increase. Intensification of traditional farming required higher energy inputs. As long as animate labor remained the sole prime mover of field work, the share of the population engaged in crop cultivation and animal husbandry had to remain very high, more than 80%, commonly over 90%. The net energy returns of intensive farming involving irrigation, terracing, multicropping, crop rotation, and fertilization were generally lower than those in extensive agriculture but allowed unprecedented population densities.

The most intensive traditional farming—most notably Asia's year-round multicropping, sustaining largely vegetarian diets—could commonly support more than five people per hectare of cultivated land. Such densities led to gradual urbanization, but the growth of cities, extensive trade, and the effective integration of expanding empires were restricted above all by the slow speeds and low capacities of land transport. But in maritime societies they were aided by the improving capabilities of sail ships, used both for lucrative intercontinental trade and for the long-distance projection of power.

In contrast to the slow, cumulative transformations of traditional societies, the socioeconomic consequences of fossil fuel-based industrialization were nearly instantaneous. The substitution of fossil fuels for biomass fuels and the later replacement of animate energies by electricity and internal combustion engines created a new world within just a few generations (Smil 2005). The American experience was the extreme example of these compressed changes. More than in any other modern nation, the power and influence of the United States have been created by its extraordinarily high use of energy (Schurr and Netschert 1960; Jones 1971; Jones 2014; Smil 2014b). In 1850 the country was an overwhelmingly rural, wood-fueled society of marginal global import. A century later—after more than tripling its per capita consumption of useful energy and becoming both the world's largest producer and consumer of fossil fuels and the leading technical innovator able to translate these advantage into a complete victory in World War II—it was both an economic and military superpower and the world's leading technical innovator.

The most obvious physical transformations of the new fossil-fueled world have been created by the intertwined processes of industrialization and urbanization. On the most fundamental level, they released hundreds of millions of people from hard physical labor and brought a growing supply and greater variety of food and better housing conditions. The combination of more productive farming and new labor opportunities in expanding industries led to mass migration from villages and sustained rapid urbanization on all continents. In turn, this change has had an enormous positive feedback on the global use of energy. The infrastructural requirements of urban life increase the average per capita energy consumption much above rural means even if the cities are not highly industrialized. These relatively high-energy-density needs could not be supported without cheap means of long-distance transportation of food and fuel, and later without the transmission of electricity.

The mechanization of mass factory production energized by fossil fuels and electricity has enabled the mass production of common goods, bringing their greater variety and improved quality at affordable prices. It introduced new materials (metals, plastics, composites) and greatly intensified trade, transport, and telecommunication, all now at truly global levels and accessible to all individuals with reasonable disposable incomes (with crowding and commodification of experiences as inevitable consequences, evident as armies of tourists besiege every notable architectural or scenic site for a perfunctory look and a bunch of selfies on a stick).

These developments have also accelerated every facet of social change. They broke the traditional circle of limited social and economic horizons, in the first instance (leaving aside the inevitable inverse relationship between the quantity of communication and its quality) all the way to billions of "social media" users, in the second instance to often counterproductive offshoring and subcontracting of industrial activities (owing to inherently higher transportation costs and the loss of proper quality control). They have improved health and prolonged lives, nearly universal benefits (whose obverse is the burden of dealing with aging populations). They spread both basic literacy and higher education (although the mass granting of all university degrees has diminished their worth) and allowed a modicum of affluence for a rising share of the world's population. They have made more space for democracy and human rights (but they certainly did not make the world truly more democratic).

Electricity must be singled out for its many unique roles. Reliance on this most flexible and most convenient form of energy has rapidly developed into an all-encompassing dependence. Without electricity, modern societies could not farm or eat the way they do: electricity powers compressors in both ammonia plants and domestic refrigerators. They could not prevent disease (now controlled with refrigerated vaccines) and take care of the sick (with diagnoses dependent on electricity-powered machines, from venerable x-ray machines to the latest MRI, and with extensive monitoring in intensive care units), control their transportation networks, or handle their enormous volume of information (with data centers becoming some of the largest point consumers of electricity) or urban sewage.

And, of course, without electricity modern societies could not operate and manage their industries to mass-produce a growing range of higher-quality yet more affordable goods. This production has erased most of the ancient division between an admirable variety of refined luxury goods produced in small numbers for the richest few and the limited assortment of generally available crude manufactures. A rising share of this advancing output has found its way onto the world market. In 2015 foreign trade accounted for about 25% of the gross world economic product, compared to less than 5% in 1900 (World Bank 2015c). This trend has accelerated with faster and more reliable methods of transportation and with instant electronic telecommunication. Fossil fuels and electricity have moved the world from a mosaic of economic autarchies and limited cultural horizons to an increasingly interdependent whole.

No less profound transformations of the fossil-fuel era have included new structures of social relations. Perhaps the most important one has been a new system of distributing wealth. The change from status to contract has led to greater personal and political independence. This transformation has brought into existence new work regimens (typically, fixed working hours and multilayered organizational hierarchies) and new social groupings with special interests (labor unions, management, investors). Almost from its beginning it also introduced new national challenges, above all the need to cope with the extremes of rapid regional industrial growth and chronic economic decline. This disparity continues to plague even the richest nations. New tensions in international relations have been caused by trade barriers, subsidies, tariffs, and foreign ownership.

The introduction of new sources of primary energy and new prime movers has also had a profound impact on economic growth and technical innovation cycles. Substantial investment is needed to develop the extensive infrastructure needed to extract (or to harness) new energy sources, to transport (or transmit) fuels and electricity, to process fuels, and to mass-manufacture new prime movers. In turn, the introduction of these new sources and prime movers elicits clusters of gradual improvements and fundamental technical innovations. Schumpeter's (1939) classic account of business cycles in industrializing Western countries showed the unmistakable correlation between new energy sources and prime movers, on the one hand, and accelerated investment on the other (box 7.4, fig. 7.8).

Subsequent extensions of these long cycles work quite well. The postwar economic upswing was associated with the global substitution of hydrocarbons for coal, with the worldwide rise in electricity generation (including by nuclear fission), and with mass car ownership and extensive energy subsidies in agriculture. This expansion was arrested by OPEC's quintupling of oil prices in 1973. The latest wave of innovations has included a variety of highly efficient industrial and household energy converters and progress in photovoltaics. The rapid diffusion of microchips, advances in computing, a greater use of optical fibers, the introduction of new materials and new ways of industrial production, and ubiquitous automation and robotization will have even greater energy implications.

Box 7.4
Business cycles and energy

The first well-documented upswing (1787–1814) coincides with the spreading extraction of coal and with the initial introduction of stationary steam engines. The second expansion wave (1843–1869) was clearly driven by the diffusion of mobile steam engines (railroads and steamships) and by advances in iron metallurgy. The third upswing (1898–1924) was influenced by the rise of commercial electricity generation and by the rapid replacement of mechanical drives by electric motors in factory production. The center points of these upswings are about 55 years apart. Fascinating post-1945 research brought a great deal of confirmation about the existence of approximately 50-year pulsations in human affairs (Marchetti 1986), and about the recurrence of such long waves in economic life and in technical inventions in particular (van Duijn 1983; Vasko, Ayers, and Fontvieille 1990; Allianz 2010; Bernard et al. 2013).

These studies indicate that the initial stages of adopting new primary energies correlate significantly with the starts of major innovation waves. The history of energy innovations also strongly confirms a still contentious proposition that economic depressions act as triggers of innovative activity. The center points of the three temporal innovation clusters identified by Mensch (1979) fall almost perfectly into the midpoints of Schumpeterian downswings. The first cluster, peaking in 1828, is clearly associated with the deployment of stationary and mobile steam engines, the substitution of coke for charcoal, and the generation of coal-derived gas. The second one, peaking in 1880, includes the revolutionary innovations of electricity generation, electric light, telephone, steam turbine, the electrolytic production of aluminum, and the internal combustion engine. The third one, clustered around 1937, includes the gas turbine, jet engine, fluorescent lights, radar, and nuclear energy.

The economic consequences of the world's prodigious energy use are also reflected in the roster of the world's largest companies (Forbes 2015). In 2015, five of the top 20 nonfinancial multinational corporations were oil

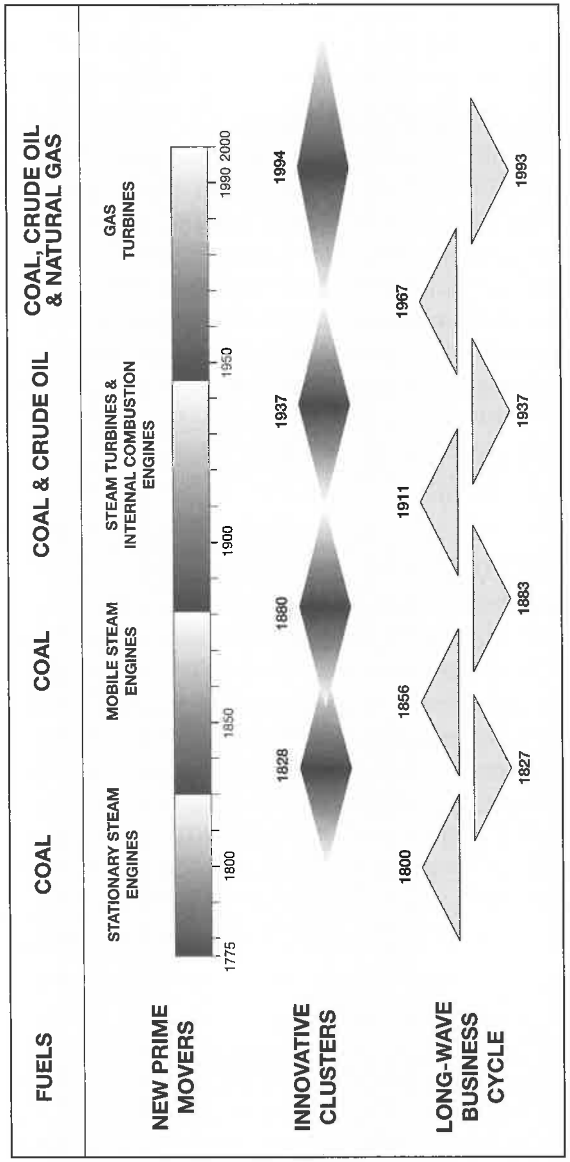

Figure 7.8
Comparison of the onsets of major energy eras (identified by principal fuels and prime movers) with innovation clusters according to Mensch (1979) and with Schumpeter's (1939) long waves of Western business cycles. I have extended both waves to the year 2000.

companies—EXXON, PetroChina, Royal Dutch Shell, Chevron, and Sinopec—and three were car and truck makers, Toyota, Volkswagen, and Daimler. The intensification of production has been enabled by a reliable supply of affordable energies and has promoted the economies of scale evident in industrial concentration. Virtually every sector offers good examples of this process. In 1900 the United States had about 200 car manufacturing companies and France had more than 600 (Byrn 1900). By the year 2000 there were only three American firms, GM, Ford, and Chrysler, and two French firms, Renault and Citroen-Peugeot. The number of British beer breweries fell from more than 6,000 in 1900 to just 142 by 1980 (Mark 1985). But in a number of industries (including beer microbreweries) a reverse movement has been under way since the 1970s. This change is largely attributable to a combination of better communication, faster deliveries, and opportunities to supply specialized demands.

In personal terms, by far the most important consequence of the high-energy era has been the unprecedented degree of affluence and the improving quality of life. Most fundamentally, this achievement is based on an abundant and varied supply of food. People in rich countries have average per capita availabilities much above any realistic needs. Persisting malnutrition, even hunger, in the midst of this surplus (in 2015 about 45 million Americans were receiving food stamps) is a matter of distributional inequalities. In physical terms the rising affluence has manifested most convincingly in drastically lower infant mortalities and longer life expectancies. Intellectually, it has been reflected in higher literacy rates, longer years of schooling, and easier access to a greater variety of information.

Another important ingredient of this affluence has been the use of energy to save time. These uses include much more than a widespread preference for more energy-intensive but faster private cars as opposed to the use of public transportation. Refrigeration (obviating daily food shopping), electric and gas ranges, microwave ovens and food processors (simplifying and accelerating the cooking or reheating of food), and central heating (eliminating the need for repeated kindling of fires and stocking up on fuels) have all been excellent time-saving techniques now universally adopted throughout the affluent world. In turn, the time gained by these energy investments is increasingly used for leisure trips and pastimes often requiring further considerable energy inputs.

But one fundamental reality has not changed: all of these clear and impressive historical trends tracing the rise of new sources, new superior performances, and efficiency gains do not mean that humanity has been using energy in a progressively more rational manner. Urban car driving, preferred by many because of its supposedly faster speed, is a perfect example of an irrational energy use. After taking into account the time needed to earn monies for buying (or leasing) the car and to fuel it, maintain it, and insure it, the average speed of U.S. car travel amounted to less than 8 km/h in the early 1970s (Illich 1974)—and, with more congestion, by the early 2000s the speed was no higher than 5 km/h, comparable to speeds achieved before 1900 with horse-drawn omnibuses or by simply walking. In addition, with well-to-wheel efficiencies well below 10%, cars remain a leading source of environmental pollution; as already noted, they also exact a considerable death and injury toll (WHO 2015b).

Fuels, electricity, and lighter, more reliable, more flexible, and more efficient converters are too often deployed in a wasteful manner, causing environmental problems while producing ephemeral personal satisfaction (or at least a claim of it) as their only positive payoff. As Rose (1974, 359) concluded, "So far, increasingly large amounts of energy have been used to turn resources into junk, from which activity we derive ephemeral benefit and pleasure; the track record is not too good." But there is nothing new about unproductive energy uses, and they could be seen as wasteful only if human societies were driven strictly by one overarching goal, to minimize the use of energy devoted only to tasks or processes directly relevant to species survival.

But as soon as our mastery of the physical world began to yield modest energy surpluses, human ingenuity used them to create a man-made world of diversity and (for some) leisure, even though more energy could be used to secure basic physical needs. A weight-bearing column could be just a simple smooth stone cylinder or an elongated prism; there was never any structural or functional need for the three orders of ancient Greek architecture (the Doric, Ionic, and Corinthian). A rich dinner was not enough: Roman feasts had to go on for days. This quest for distinction, novelty, variety, and diversity reached a new (relative) ubiquity during the Renaissance and early modern (1500–1800) eras, but even at that time its most captivating displays were still few and overwhelmingly designed for public consumption and for posterity.

Moreover, it is easy to conclude that the monumental structures of premodern societies were not simply wasted repositories of scarce resources. Norenzayan (2013) has argued that the belief in judgmental deities ("big gods") was critical to foster the cooperation needed to build and sustain complex societies and monumental structures. As material expressions of such beliefs they thus contributed to social cohesion and encouraged awe, respect, humility, contemplation, and charity. In any case, the posterity intent has often worked to perfection, as attested by the numbers of visitors who each year travel to admire Rome's Saint Peter's Basilica or Agra's Taj Mahal (fig. 7.9). In comparison, does not the label of wasteful energy diversions apply much more readily to the extravagant, and mostly uninspiring, structures we build to manage monies or to watch modern gladiators kicking, throwing, or hitting assorted balls?

More important, modern societies have carried this quest for variety, leisure pastimes, ostentatious consumption, and differentiation through ownership and variety to ludicrous levels and have done so on an unprecedented scale. There are now hundreds of millions of people whose annual discretionary spending on nonessential items (including a rising share of luxury products) far surpasses the average income of a Western family a century ago. Examples of these extravaganzas abound. Family size in affluent countries keeps shrinking, but the average size of U.S. custom-built houses has passed 500 m^2; shipbuilders have waiting lists for yachts with helicopter pads; many cars on the market have so much excess power that they can be never fully tested on any public road: the Koenigsegg Regera

Figure 7.9
Saint Peter's Basilica completed in 1626 (Corbis).

engine rates 1.316 MW, while the Lamborghini and the top Mercedes-Benzes come with "only" 1.176 MW, the latter value being equal to nearly 1,600 hp, or 11 times the power of the small car, a Honda Civic, that I drive.

On a more mundane level, tens of millions of people annually take intercontinental flights to generic beaches in order to acquire skin cancer faster; the shrinking cohort of classical music aficionados has more than 100 recordings of Vivaldi's *Quattro Stagioni* to choose from; there are more than 500 varieties of breakfast cereals and more than 700 models of passenger cars. Such excessive diversity results in a considerable misallocation of energies, but there appears to be no end to it: electronic access to the global selection of consumer goods has already multiplied the choice available for Internet orders, and the customized production of many consumer items (using individualized adjustments of computer designs and additive manufacturing) would raise it to yet another level of excess. The same is true of speed: do we really need a piece of ephemeral junk made in China delivered within a few hours after an order was placed on a computer? And (coming soon) by a drone, no less!

But regardless of the indicators used, those kinds of wasteful, unproductive, and excessive final energy use are still in the global minority. When looking at average per capita energy supply, then only about one-fifth of the world's 200 countries have accomplished the transition to mature, affluent industrial societies supported by the high consumption of energy (>120 GJ/capita), and the share is even lower in population terms, about 18% (1.3 billion among 7.3 billion in 2015). Adding rich households in such low- and middle-income countries as China, India, Indonesia, and Brazil would raise the population share only marginally, to about 20%. For example, China now has the world's fourth-largest number of affluent families (following the United States, Japan, and the UK), but that still worked out to fewer than five million of such families in 2015 (Atsmon and Dixit 2009; Xie and Jin 2015).

Consequently, the global diffusion of the Western miracle of rapid technical innovation has resulted in a worrisome global split, in an unprecedented level of economic inequality among nations. By 2015 the richest 10% of humanity (living in 25 nations) claimed about 35% of the world's energy. In personal terms, this meant that a week's worth of per capita energy use in the United States is equivalent to the total annual primary energy consumption of an average Nigerian and two years of the annual energy supply for an average Ugandan. Conversely, the poorest 5% of humanity (living in 15 African countries) consumes no more than 0.2% of the world's primary commercial energy supply.

These disparities have no easy remedies, and narrowing the gap takes time, even with an extraordinarily rapid economic growth: during 35 years of rapid modernization, from 1980 to 2015, China nearly quintupled its average per capita energy consumption to reach just over 90 GJ/capita. In the process it paid major environmental and health costs and strained the global energy trade, but it is still 20–25% below the comfortable supply rate. Most fundamentally, even if the requisite resources were readily available, the environmental consequences of raising the rest of the world to the West's level of primary energy consumption would be unacceptable. Already concerns about biospheric integrity have become major considerations in contemplating the future of high-energy civilization. They range from preservation of biodiversity to rapid anthropogenic climate change.

Between Determinism and Choice

Many historical developments are the result of a limited array of outcomes that follow using particular energies in certain ways. A reliance on different primary energies leaves distinct imprints on everyday work and leisure. Life spent breaking clods with heavy hoes, transplanting dripping seedlings, grasping handfuls of stems and cutting them with a sickle, husbanding the straw for cooking, and hand-pounding the grain (all still quite common in the late nineteenth-century Chinese countryside) creates a different world from one in which teams of strong horses pull curved moldboard plows, mechanical seeders, and harvesters, in which a fuelwood grove yields plenty of wood for large stoves and flour is ground by steam-powered mills (all common in the late nineteenth-century United States).

Similarly, a reliance on different prime movers determines a different scope and tempo of everyday affairs. The laborious harnessing of horses with bits, nosebands, head crowns, hames, collars, backbands, and traces, the clatter of horseshoes, the jolting of poorly sprung coaches, the muzzles of resting animals stuck in feedbags, the sweeping of horse manure from city streets and carting it away to nourish suburban gardens—these images evoke a pace of life profoundly unlike that dominated by turns of the ignition key, the swishing of radial tires, the smooth and swift ride of sedans and SUVs, networks of filling stations, and the easy availability of vegetables and fruits carried by processions of heavy trucks from California or Spain—or in refrigerated containers and in cargo holds of jetliners from other continents.

Using energy as a principal analytical concept of human history is thus an obvious, profitable, and desirable choice. But we should not look at it as the principal explanatory factor. The explanatory power of an energy