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Long-term Trends and Achievements

The most fundamental attribute of modern society is simply this: ours is a high-energy civilization based largely on combustion of fossil fuels. Ever since the onset of sedentary farming and the domestication of draft animals all traditional societies secured their requisite mechanical energy by deploying human and animal muscles, and their thermal energy needed for comfort and cooking (and also light) by burning biomass fuels. Even the simplest water- and wind-driven mechanical prime movers (waterwheels and windmills) were completely or nearly absent in some traditional preindustrial societies, but they eventually came to play major roles in a few early modern economies. Wind-driven, and peat-fueled, Dutch Golden Age of the seventeenth century is perhaps the foremost example of such a society (DeZeeuw 1978).

In any case, average per capita availability of all forms of energy in preindustrial societies remained low and also stagnant for long periods of time. This situation was only marginally different in a few regions (most notably in England, today's Belgium, and parts of North China) where coal had been used in limited amounts for centuries both for heating and in local manufacturing plants. And although the nineteenth century saw widespread industrialization in parts of Europe and North America, most of today's affluent countries (including the United States and Japan) remained more dependent on wood than on coal until its closing decades. In addition, in wood-rich countries the absolute gain in total per capita energy use that accompanied the transition from wood to coal was hardly stunning. For example, the U.S. consumption of fossil fuels surpassed that of wood only in the early 1880s; and during the second half of the nineteenth century the average per capita supply of all energy increased by only about 25% as coal consumption rose tenfold but previously extensive wood burning was cut by four-fifths (Schurr and Netschert 1960).

In contrast, human advances during the twentieth century were closely bound with an unprecedented rise of total energy consumption (Smil 2000a). This growth was accompanied by a worldwide change of the dominant energy base as hydrocarbons have relegated coal almost everywhere to only two essential applications, production of metallurgical coke and, above all, generation of electricity. This latter use of coal is a part of another key transformation that took place during the twentieth century, namely the rising share of fossil fuels used indirectly as electricity. Other sources of electricity—hydro and nuclear generation—further expanded the supply of this most convenient kind of commercial energy.

Substantial improvements of all key nineteenth-century energy techniques and introduction of new, and more efficient, prime movers and better extraction and transportation processes resulted in widespread diffusion of labor-saving and comfort-providing conversions available at impressively lower prices. Technical advances also ushered in an unprecedented mobility of people and goods. As a result, widespread ownership of private cars and mass air travel are among the most important social transformations of the second half of the twentieth century. Emergence of extensive global trade in energy commodities opened the paths to affluence even to countries lacking adequate fuel or hydro resources.

The most recent trend characterizing high-energy civilization has been the rising amount and faster delivery of information. Availability of inexpensive and precisely controlled flows of electricity allowed for exponential growth of information storage and diffusion, first by analog devices and after 1945 by harnessing the immense digital potential. For nearly four decades these innovations were increasingly exploited only for military, research, and business applications; a rapid diffusion among general population began in the early 1980s with the marketing of affordable personal computers, and its pace was speeded up with the mass adoption of the Internet during the latter half of the 1990s.

Although modern societies could not exist without large and incessant flows of energy, there are no simple linear relationships between the inputs of fossil fuels and electricity and a nation's economic performance, social accomplishments, and individual quality of life (for many details on these linkages see chapter 2). Predictably, international comparisons show a variety of consumption patterns and a continuing large disparity between affluent and modernizing nations. At the same time, they also show similar socioeconomic achievements energized by substantially different primary energy inputs. Many of the key twentieth-century trends—including higher reliance on natural gas, slow diffusion of renewable energy techniques, efficiency gains in all kinds of energy conversions, and rising per capita use of energy in low-income countries—will continue during the coming generations, but there will have to be also some fundamental changes.

The key reason for these adjustments is the necessity to minimize environmental impacts of energy use in general, and potentially very worrisome consequences of anthropogenic generation of greenhouse gases in particular. Extraction, transportation, and conversion of fossil fuels and generation and transmission of electricity have always had many local and regional environmental impacts ranging from destruction of terrestrial ecosystems to water pollution, and from acidifying emissions to photochemical smog. Carbon dioxide from the combustion of fossil fuels poses a different challenge: it remains the most important anthropogenic greenhouse gas, and its rising emissions will be the main cause of higher tropospheric temperatures.

Consequently, the future use of energy may not be determined just by the availability of resources or by techniques used to extract and convert them and by prices charged for them—but also by the need to ensure that the global energy consumption will not change many other key biospheric parameters beyond the limits compatible with the long-term maintenance of global civilization. Prevention, or at least moderation, of rapid global warming is the foremost, although not the sole, concern in this category, and it may turn out to be one of the most difficult challenges of the twenty-first century. Loss of biodiversity, human interference in the biogeochemical nitrogen cycle, and the health of the world ocean are other leading environmental concerns associated with the rising use of energy.

A Unique Century

Only infrequently is the human history marked by truly decisive departures from long-lasting patterns. That is why the twentieth century was so remarkable as it offered a greater number of such examples, all of them closely connected with the dramatically higher use of energy, than the entire preceding millennium. They range from veritable revolutions in food production (now irrevocably dependent on synthetic nitrogenous fertilizers, pesticides, and mechanization of field tasks) and transportation (private cars, flying) to even more rapid advances in communication (radio, television, satellites, the Internet). Most of the post-1900 advances in basic scientific understanding—from the new Einsteinian physics whose origins date to the century's first years (Einstein 1905) to the deciphering of complete genomes of about twenty microbial species by the late 1990s (TIGR 2000)—would have been also impossible without abundant, inexpensive, and precisely controlled flows of energy.

As far as the evolution of human use of energy is concerned, practically all pre–twentieth-century technical and managerial advances were gradual processes rather than sudden breaks. Any short list of such events would have to include domestication of large draft animals (cattle, horses) whose power greatly surpasses that of humans, construction and slow diffusion of first mechanical prime movers converting indirect flows of solar energy (waterwheels, windmills), and, naturally, the invention of the steam engine, the first machine powered by combustion of a fossil fuel. The epochal transition from renewable to fossil energies proceeded first fairly slowly. Fossil fuels became the dominant source of human energy needs only about two centuries after Newcomen introduced his first inefficient machines during the first decade of the eighteenth century, and more than a century after James Watt patented (1769, renewal in 1775) and mass-produced his greatly improved steam engine (Dickinson 1967; fig. 1.1).

As there are no reliable data on the worldwide use of biomass energies, whose combustion sustained all civilizations preceding ours, we cannot pinpoint the date but we can conclude with a fair degree of certainty that fossil fuels began supplying more than half of the world's total primary energy needs only sometime during the 1890s (UNO 1956; Smil 1994a). The subsequent substitution of biomass energies proceeded rapidly: by the late 1920s wood and crop residues contained no more than one-third of all fuel energy used worldwide. The share sank below 25% by 1950 and during the late 1990s it was most likely no more than 10% (fig. 1.2; for more on biomass energy use see chapter 5). This global mean hides national extremes that range from more than 80% in the poorest African countries to just a few percent in affluent Western nations.

My personal experience spans this entire energy transition in 30 years and it includes all of the four great sources of heat. During the mid-1950s we, as most of our neighbors, still heated our house in the Bohemian Forest on the Czech-German border with wood. My summer duty was to chop small mountains of precut trunks into ready-to-stoke pieces of wood and stack them in sheltered spaces to air-dry, then getting up early in dark winter mornings and using often recalcitrant kindling to start a day's fire. During my studies in Prague and afterward, when living in the North Bohemian Brown Coal Basin, virtually all of my energy services—space heating, cooking, and all electric lights and gadgets—depended on the combustion of

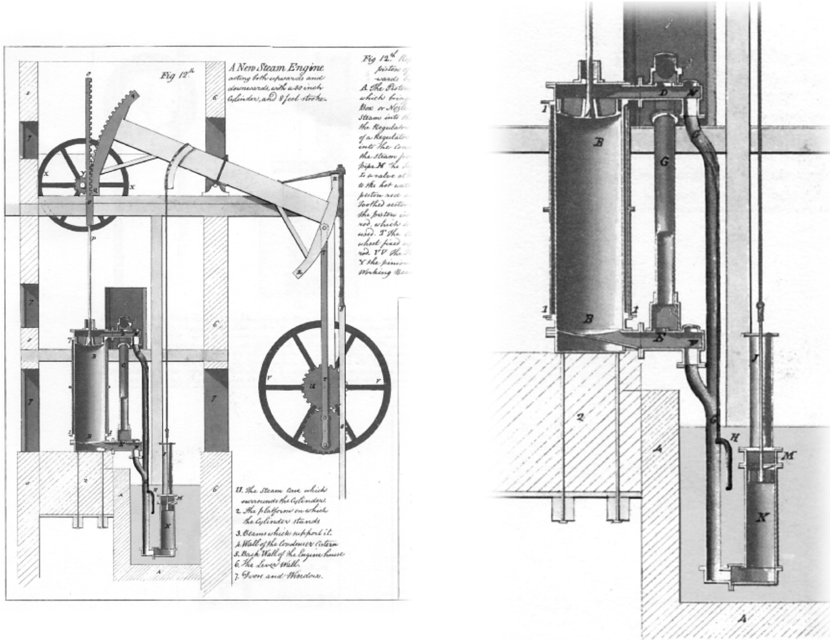


Figure 1.1
Complete drawing of James Watt's improved steam engine built in 1788 and a detail of his key innovation, the separate condenser connected to an air pump. Reproduced from Farey (1827).

lignite. After we moved to the United States the house whose second floor we rented was, as virtually all of its neighbors in that quiet and leafy Pennsylvanian neighborhood, heated by fuel oil. In our first Canadian house, bought in 1973, I had to reset a thermostat to restart a standard natural gas furnace (rated at 60% efficiency), but even that effort has not been necessary for many years. In our new superinsulated passive solar house a programmable thermostat will regulate my superefficient natural gas-fired furnace (rated at 94%) according to a weekly sequence of preset temperatures.

The completed transition means that for the Western nations the entire twentieth century, and for an increasing number of modernizing countries its second half, was the first era energized overwhelmingly by nonrenewable fuels. During the 1990s biomass fuels, burned mostly by households and industries in low-income countries, contained at least 35 EJ/year, roughly 2.5 times as much as during the crossover

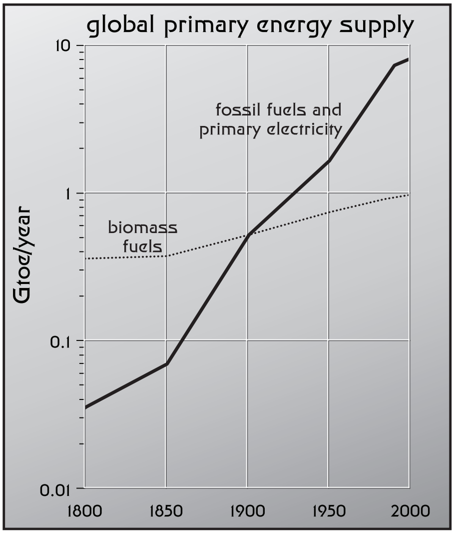


Figure 1.2
Global consumption of biomass and fossil fuels, 1800–2000. Based on Smil (1994a) and on additional data from BP (2001) and UNO (2001).

decade of the 1890s. In contrast, between 1900 and 2000 consumption of fossil fuels rose almost fifteenfold, from about 22 EJ to 320 EJ/year, and primary electricity added about 35 EJ/year (UNO 1956; BP 2001; fig. 1.2). This large expansion of fossil fuel combustion meant that in spite of the near quadrupling of global population—from 1.6 billion in 1900 to 6.1 billion in 2000—average annual per capita supply of commercial energy more than quadrupled from just 14 GJ to roughly 60 GJ, or to about 1.4 toe (Smil 1994a; UNO 2001; BP 2001; fig. 1.3).

But as the global mean hides enormous regional and national inequalities it is more revealing to quote the consumption means for the world's three largest economies (fig. 1.3). Between 1900 and 2000 annual per capita energy supply in the United States, starting from an already relatively high base, more than tripled to about 340 GJ/capita (Schurr and Netschert 1960; EIA 2001a). During the same time the Japanese consumption of commercial energies more than quadrupled to just over 170 GJ/capita (IEE 2000). In 1900 China's per capita fossil fuel use, limited to small quantities of coal in a few provinces, was negligible but between 1950, just after the establishment of the Communist rule, and 2000 it rose thirteenfold from just over 2 to about 30 GJ/capita (Smil 1976; Fridley 2001).

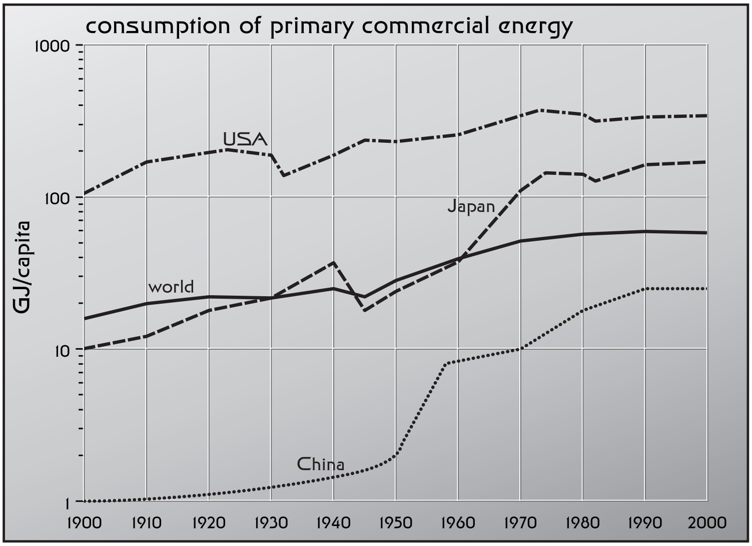


Figure 1.3
Average per capita consumption of primary commercial energy during the twentieth century is shown as the global mean and as national rates for the world's three largest economies, the United States, Japan, and China. Based on Smil (1994a) and on additional data from BP (2001), UNO (2001), and Fridley (2001).

These gains appear even more impressive when they are expressed not by comparing the initial energy content of commercial fuels or energies embodied in generation of primary electricity but in more appropriate terms as actually available energy services. Higher conversion efficiencies will deliver more useful energy and industrialized countries have made these gains by a combination of gradual improvements of such traditional energy converters as household coal stoves, by boosting the performance of three devices introduced during the late nineteenth century—electric lights, internal combustion engines (ICEs), and electric motors—and by introducing new techniques, ranging from natural gas furnaces to gas turbines. As a result, affluent nations now derive twice, or even three times, as much useful energy per unit of primary supply than they did a century ago.

When this is combined with higher energy use they have experienced eightfold to twelvefold increases in per capita supply of energy services as well as welcome improvements in comfort, safety, and reliability, gains that are much harder to quantify. And efficiency gains have taken place much faster and have been even more impressive in some of the most successful industrializing countries. Households replaced their traditional stoves (often no more than 10% efficient) by kerosene heaters and, more recently in cities, by natural gas-fueled appliances (now at least 60% efficient). Returning to my personal experience of exchanging a wood stove for a coal stove, coal stove for an oil-fired furnace, and oil-fired furnace for a standard and later a superefficient natural gas furnace, I am now receiving perhaps as much as six times more useful heat from one Joule of natural gas as I did from a Joule of wood.

Many households in industrializing countries have also exchanged incandescent light bulbs for fluorescent tubes, thus effecting an order of magnitude gain in average efficiency. Industrial gains in efficiency came after importing and diffusing state-of-the-art versions of basic smelting (iron, aluminum), synthesis (ammonia, plastics), and manufacturing (car, appliance assemblies) processes. Consequently, in those modernizing economies when such large efficiency gains have been accompanied by rapid increases in overall energy consumption per capita availabilities of useful energy have risen 20, or even 30 times in just 30–50 years.

Post-1980 China has been perhaps the best example of this rapid modernization as millions of urban families have switched from wasteful and dirty coal stoves to efficient and clean natural gas heating, and as industries abandoned outdated industrial processes with an unmistakably Stalinist pedigree (that is, ultimately, derivations of American designs of the 1930s) and imported the world's most advanced processes from Japan, Europe, and North America. Consequently, per capita supplies of useful energy rose by an order of magnitude in a single generation! And although any global mean can be only approximate and subsumes huge national differences, my conservative calculations indicate that in the year 2000 the world had at its disposal about 25 times more useful commercial energy than it did in 1900. Still, at just short of 40% during the late 1990s, the overall conversion efficiency of the world's primary fuel and electricity consumption to useful energy services remains far below the technical potential.

An even more stunning illustration of the twentieth century advances in energy use is provided by the contrasts between energy flows controlled directly by individuals in the course of their daily activities, and between the circumstances experienced by the users. At the beginning of the twentieth century America's affluent Great Plains farmers, with plentiful land and abundance of good feed, could afford to maintain more draft animals than did any other traditional cultivators in human history. And yet a Nebraska farmer holding the reins of six large horses while plowing his wheat field controlled delivery of no more than 5 kW of steady animate power (Smil 1994a).

This rate of work could be sustained for no more than a few hours before the ploughman and his animals had to take a break from a task that required strenuous exertion by horses and at least a great deal of uncomfortable endurance (as he was perched on a steel seat and often enveloped in dust) by the farmer. Only when the horses had to be prodded to pull as hard as they could, for example when a plow was stuck in a clayey soil, they could deliver briefly as much as 10 kW of power. A century later a great-grandson of that Nebraska farmer plows his fields while sitting in an upholstered seat of air-conditioned and stereo-enlivened comfort of his tractor's insulated and elevated cabin. His physical exertion is equal merely to the task of typing while the machine develops power of more than 300 kW and, when in good repair, can sustain it until running out of fuel.

I cannot resist giving at least two more examples of this centennial contrast. In 1900 an engineer operating a powerful locomotive pulling a transcontinental train at a speed close to 100 km/h commanded about 1 MW of steam power. This was the maximum rating of main-line machines permitted by manual stoking of coal that exposed the engineer and his stoker, sharing a confined space on a small, rattling metal platform, to alternating blast of heat and cold air (Bruce 1952). A century later a pilot of Boeing 747-400 controls four jet engines whose total cruise power is about 45 MW, and retraces the same route 11 km above the Earth's surface at an average speed of 900 km/h (Smil 2000b). He and his copilot can actually resort to the indirect way of human supervision by letting the computer fly the plane: human control is one step removed, exercised electronically through a software code.

Finally, in 1900 a chief engineer of one of hundreds of Europe's or North America's small utility companies supervising a coal-fired, electricity-generating plant that was supplying just a section of a large city controlled the flow of no more than 100,000 W. A century later a duty dispatcher in the main control room of a large interconnected electrical network that binds a number of the U.S. states or allows large-scale transmission among many European countries, can reroute 1,000,000,000 W, or four orders of magnitude more power, to cope with surges in demand or with emergencies. Other quantitative and qualitative jumps are noted throughout this chapter as I describe first the diversification of fuel use and technical innovations that made such advances possible and as I outline consumption trends and their socioeconomic correlates.

Changing Resource Base

In 1900 less than 800 Mt of hard coals and lignites accounted for about 95% of the world's *t*otal *p*rimary *e*nergy *s*upply (UNO 1956; using the acronym TPES, favored by the International Energy Agency). That total was doubled by 1949, to nearly 1.3 Gt of hard coals, and about 350 Mt of lignites, overwhelmingly because of the expansion of traditional manual mining of underground seams (fig. 1.4). Some of these exploited seams were as thin as 25–30 cm, and some thicker seams of high-quality hard coal and anthracite were worked hundreds of meters below the surface. Yet another doubling of the total coal tonnage (in terms of hard coal equivalent) took place by 1988 and the global extraction peaked the next year at nearly 4.9 Gt, with about 3.6 Gt contributed by hard coals and 1.3 Gt by lignites. About 40% of that year's lignite production was coming from the now defunct Communist states of East Germany and the Soviet Union, whose lignites were of particularly low quality averaging, respectively, just 8.8 and 14.7 GJ/t (UNO 2001).

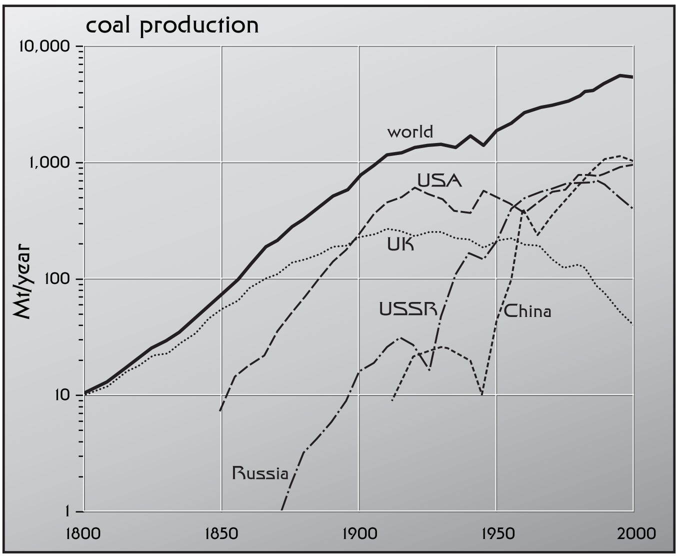


Figure 1.4
Coal production during the nineteenth and twentieth centuries: the ascending global total hides substantial changes in the output of major coal-producing countries, most notably the decline and collapse of the U.K. extraction (see also fig. 1.8) and the rise of China's coal industry. Based on Smil (1994a) and on additional data from BP (2001) and UNO (2001).

Changing makeup of coal extraction was not the only thing that had become different during the second half of the twentieth century. In contrast to the pre-WWII years nearly all of the additional underground production came from highly mechanized workfaces. For example, in 1920 all of the U.S. coal mined underground was manually loaded into mine cars, but by the 1960s nearly 90% was machine-loaded (Gold et al. 1984). Mechanization of underground mining lead to the abandonment of traditional room-and-pillar technique that has left at least half of all coal behind. Where the thickness and layout of seams allowed it, the longwall extraction became the technique of choice. This advancing face of coal cutting protected by moveable steel supports can recover over 90% of coal in place (Barczak 1992; fig. 1.5).

Similar or even higher recoveries are achieved in surface (opencast) mines that have accounted for more than half of America's new coal-producing capacities after 1950. These mines are fundamentally giant earth-moving (more precisely overburden-moving) enterprises aimed at uncovering one or more thick seams from which the

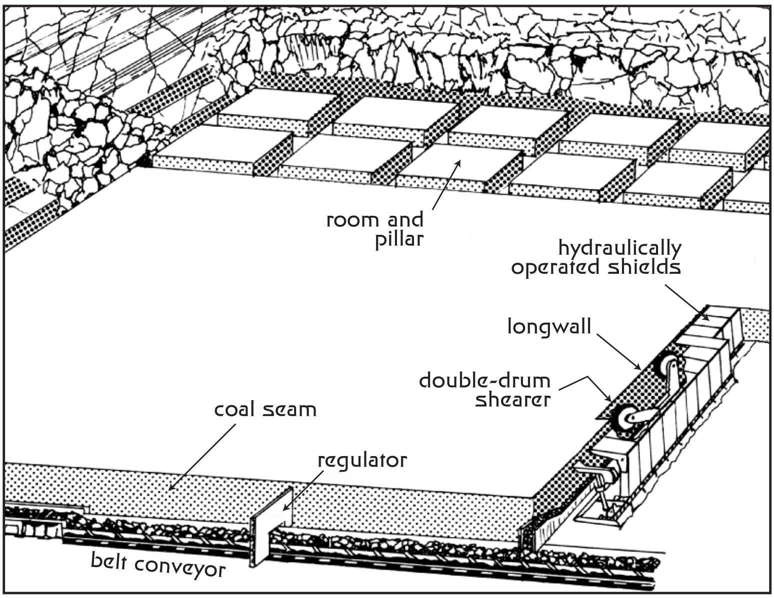


Figure 1.5
Longwall mining—in contrast to the traditional room-and-pillar extraction that leaves at least 50% of coal in place—can recover virtually all coal from level, or slightly inclined, seams. Based on a figure in Smil (1999a).

coal can be mined by not quite as large, but still distinctly oversized, machines. Growth of earth-moving machinery, exemplified by electric shovels and dragline excavators with dippers over 100 m^3, made it possible to exploit seams under as much as 200 m of overburden and to operate mines with annual production in excess of 10 Mt.

Two of the three coal-mining superpowers, the United States and the former Soviet Union, pursued aggressively this method of mining characterized by superior productivity and higher safety. In 1950 only 25% of the U.S. coal originated in surface mines but by the year 2000 the share rose to 65% (Darmstadter 1997; OSM 2001a). About 40% of the Russian coal output now originates in opencast mines, and only the third coal-mining superpower still relies mostly on underground mining. China has always had many small rural surface mines (unmechanized and inefficient operations producing low-quality fuel) but the country's large-scale mining remained an almost exclusively underground affair until the early 1980s, and even now less than 10% of the country's coal originates in modern opencast operations.

Besides impressive gains in fuel recovery these innovations have raised labor productivity and improved occupational safety. Productivity of underground mining rose from less than 1 t/man-shift at the century's beginning to more than 3 t/man-hour in highly mechanized modern pits using longwall or continuous mining systems, while productivities in the largest surface mines in Australia and the United States exceeds 20 t/worker hour (Darmstadter 1997). Fatalities in modern mining have followed the opposite trend. The U.S. statistics show more than a 90% decline of accidental deaths since the early 1930s, and 29 fatalities in 1998 prorated to 0.03 deaths per million tonnes of extracted coal (MSHA 2000). In contrast, death rates in China's coal mines remain extremely high, surpassing five fatalities per million tonnes of extracted coal during the late 1990s (Fridley 2001), and the recent Ukrainian death toll has been higher still.

Completely mechanized surface mining of thick seams raised the annual output of the largest mines to levels approaching, or even matching, annual coal output of smaller coal-producing countries. A number of countries, including the United States, Russia, Germany, and Australia, opened up mines with annual capacities of 15–50 Mt/year. Inevitably, the lower quality subbituminous coals and lignites extracted from shallow seams depressed the average energy content of the fuel. In 1900 a tonne of mined coal was equivalent to about 0.93 tonne of standard fuel (hard coal containing 29 GJ/t); by 1950 the ratio fell to about 0.83, and by the century's end it slipped to just below 0.7 (UNO 1956; UNO 2001).

Energy content of extracted coals thus increased less than 4.5 times between 1900 and 2000 while the world's total fossil fuel consumption rose fifteenfold during the same period. Moreover, the second half of the century saw a notable increase in the generation of primary (hydro and nuclear) electricity. As a result, coal's share in the global supply of primary energy declined during every year of the twentieth century, falling to below 75% just before the beginning of the WWII and to less than 50% by 1962. OPEC's oil price rises of the 1970s engendered widespread hopes of coal's comeback, mainly in the form of gases and liquids derived from the fuel by advanced conversion methods (Wilson 1980), but such hopes were as unrealistic as they were ephemeral (for more on this see chapter 3). Coal's share slipped to just below 30% of the global TPES by 1990 and in 2000 the fuel supplied no more than 23% of all primary commercial energy.

As so many other global means, this one is rather misleading. By the year 2000 only 16 countries extracted annually more than 25 Mt of hard coals and lignites, and six largest producers (in the order of energy content they are the United States, China, Australia, India, Russia, and South Africa) accounted for slightly more than 20% of the world's total coal output in the year 2000. Most notably, in the year 2000 the United Kingdom, the world's second largest coal producer in 1900, extracted less than 20 Mt/year from seventeen remaining private pits, and its peak labor force of 1.25 million miners in the year 1920 was reduced to fewer than 10,000 men (Hicks and Allen 1999; fig. 1.6). Many African and Asian countries use no coal at all, or the fuel supplies only a tiny fraction of their energy consumption, while it still provides nearly 80% of South Africa's, two-thirds of China's, and nearly three-fifths of India's energy demand, but only 25% of the United States and less than 20% of Russia's TPES. In China coal also dominates the household heating and cooking market, as it does in parts of India.

But the fuel has only three major markets left in affluent countries: to generate electricity and to produce metallurgical coke and cement. More efficient iron smelting cut the use of coke by more than half during the twentieth century: today's best blast furnaces need an equivalent of less than 0.5 t of coal per tonne of hot metal, compared to 1.3 t/t in 1900 (Smil 1994a; de Beer, Worrell, and Blok 1998). Extensive steel recycling (some 350 Mt of the scrap metal, an equivalent of about 40% of annual global steel output, is now reused annually) and slowly growing direct iron reduction reduced the role of large blast furnaces, and hence of coking coal. The latest reason for the declining use of coke is the injection of pulverized coal directly into a blast furnace, a practice that became widespread during the

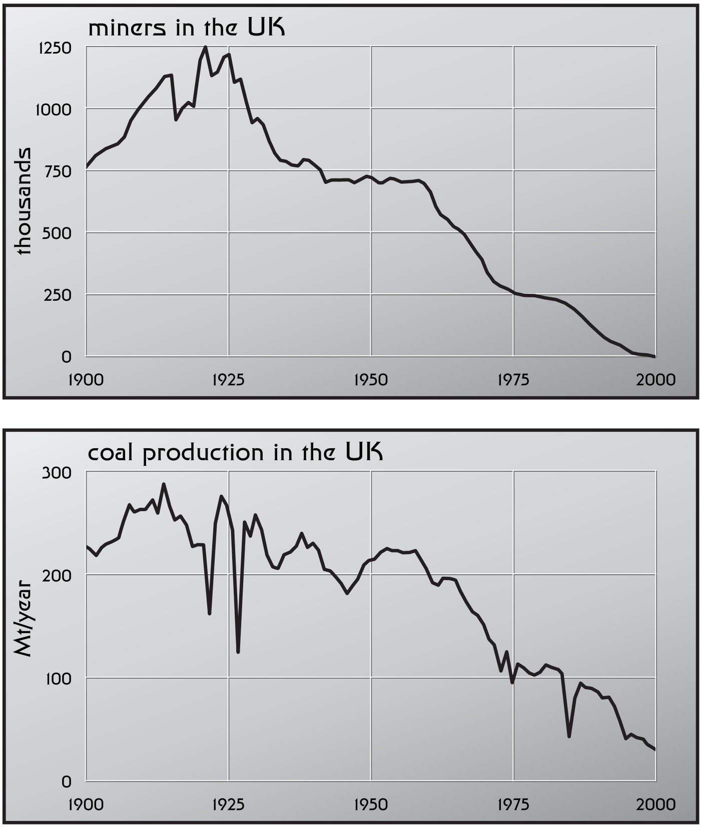


Figure 1.6
The United Kingdom's coal extraction was in decline for most of the twentieth century and the total labor employed in mining peaked during the 1920s. Based on graphs in Hicks and Allen (1999).

1990s: injection of 1 tonne of coal displaces about 1.4 tonnes of coking coal (WCI 2001). Global average of total coal inputs per tonne of crude steel fell from 0.87 in 1980 to 0.73 t by the year 2000 (a 15% decline), and the global demand for metallurgical coke now amounts to only about 17% of extracted hard coal, or just over 600 Mt in the year 2000 (WCI 2001).

Rising demand for electricity has provided the only globally growing market for coal—bituminous and lignite. Almost 40% of the world's electricity is now generated in coal-fired plants (WCI 2001). National shares among major producers are nearly 60% in the United States, close to 70% in India, roughly 80% in China, 85%

in Australia, and 90% in South Africa. Largest coal-fired stations, most of them dating from the 1960s, are either located near huge open-cast or big underground mines, or they are supplied by unit coal trains, permanently coupled assemblies of about 100 wagons with total capacities up to 10,000 t that constantly peddle between a mine and a plant (Glover et al. 1970). But in the long run even the demand for steam coal may weaken substantially, particularly if major coal consumers were to take aggressive steps to reduce the overall level of their carbon emissions (for more on this see the closing section of this chapter; coal's future is assessed in chapter 4).

The only other commercial coal market that has seen a steady growth has been the production of cement. More than 1.5 Gt of cement were produced annually during the late 1990s (MarketPlace Cement 2001) and the processing, requiring mostly between 3–9 GJ/t, has been in many countries increasingly energized by oil or natural gas. Multiplying the global cement output by 0.11, the average conversion factor recommended by the World Coal Institute, results in about 150 Mt of coal used in cement production, mostly in China (now the world's leading producer), with Japan, the United States, and India, each using less than 10 Mt/year (WCI 2001).

Coal was supplying more than 50% of the world's primary commercial energy until 1962, and it remained the single most important commercial fuel until 1966. More importantly, coal that was mined during the twentieth century contained more energy than any other primary resources, about 5,500 EJ. In contrast, the cumulative energy content of all crude oil extracted between 1901 and 2000 was about 5,300 EJ, less than 4% behind the coal aggregate, but during the century's second half, crude oil's total energy surpassed that of coal roughly by one-third. As a whole, the twentieth century can be thus seen as an energetic draw between coal and oil—but coal's rapid post-1960 loss of the global consumption share and its retreat into just the two major markets mark the fuel as a distinct has-been. At the same time, crude oil's recent rise to global prominence (between 1981 and 2000 it supplied nearly 50% more of energy than did coal), its dominance of the transportation market, unpredictable fluctuations of its world price, and concerns about its future supply put it repeatedly into the center of worldwide attention.

The combination of crude oil's high energy density and easy transportability is the fuel's greatest asset. Crude oils vary greatly in terms of their density, pour point, and sulfur content. Differences in density (specific gravity) are due to varying amounts of paraffins and aromatics. Densities are commonly measured by using a reverse °API scale, with heavy Saudi oils rating as low as 28 °API and light Nigerian oils going up to 44 °API (Smil 1991). Pour points extend from −36 °C for the lightest Nigerian crudes to 35 °C for waxy Chinese oil from the Daqing field, and sulfur content ranges between less than 0.5% (sweet oils) to more than 3% (sour crudes). But unlike coals, crude oils have very similar energy content, with nearly all values between 42–44 GJ/t, or about 50% more than the standard hard coal and three to four times as much as poor European lignites (UNO 2001). Unlike the case of coal, the wave of rising demand for crude oil products swept first North America (crude oil has been supplying more than 25% of the country's TPES since 1930), with Europe and Japan converting rapidly to imported liquid fuels only during the 1960s.

Worldwide transition to oil, and particularly its rapid post–World War II phase, was made possible by a combination of rapid technical progress and by discoveries of immensely concentrated resources of the fuel in the Middle East. Every infrastructural element of oil extraction, processing, and transportation had to get bigger, and more efficient, in order to meet the rising demand. Naturally, this growth of ratings and performances captured the often-considerable economies of scale that have made unit costs much lower. The fact that most of these infrastructures had reached size and performance plateaux is not because of the inevitably diminishing returns or insurmountable technical limits but rather because of environmental, social, and political considerations.

Early in the twentieth century, oil extraction began benefiting from the universal adoption of rotary drilling, which was used for the first time at the Spindletop well in Beaumont, Texas in 1901, and from the use of the rolling cutter rock bit introduced by Howard Hughes in 1909 (Brantly 1971). Deepest oil wells surpassed 3,000 m during the 1930s, and production from wells deeper than 5,000 m is now common in several hydrocarbon basins. By far the greatest post-1980 innovation has been a routine use of horizontal and directional drilling (Society of Petroleum Engineers 1991; Cooper 1994). Because horizontal wells can intersect and drain multiple fractures they are more likely to strike oil and to increase productivity (fig. 1.7).

Many horizontal wells can produce 2 to 5 times as much oil as vertical and deviated wells in the same reservoir (Valenti 1991; Al Muhairy and Farid 1993). Progress of horizontal drilling has been remarkable. Initially the drilling and completion costs of horizontal wells were 5–10 times the cost of a vertical bore, but by the late 1980s they declined to as little as 2 times its cost. Horizontal wells are now routinely used for extraction of thin formations and they are particularly rewarding in offshore drilling where a single platform can be used to exploit hydrocarbon-bearing layers

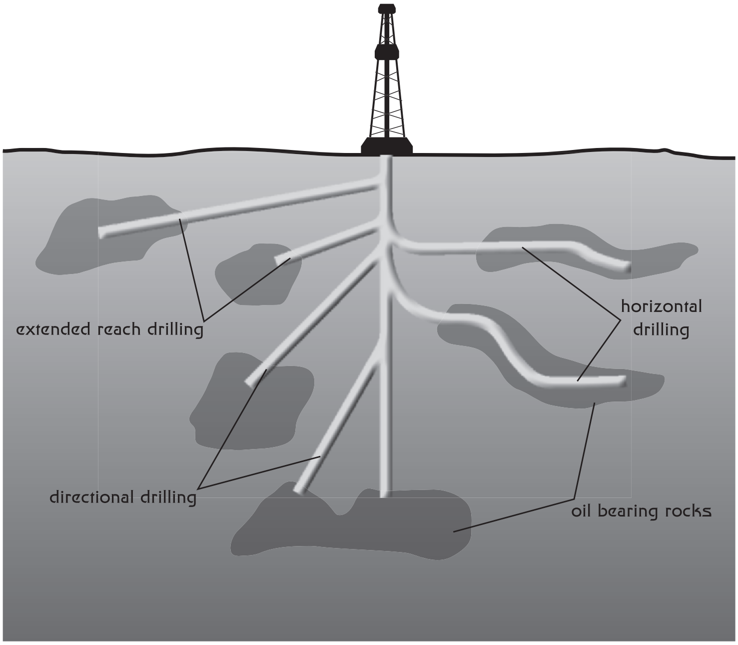


Figure 1.7
Directional drilling (with progressively greater deviation off the vertical), extended-reach drilling (up to 80° off the vertical) and horizontal drilling have made it possible to exploit better several hydrocarbon-bearing structures from a single site and to increase the rate of recovery of oil and gas deposits.

far from the primary hole. The longest horizontal wells are now around 4,000 m, nearly as long as the deepest vertical wells 50 years ago.

In 1947 the first well was completed out of land sight off Louisiana (Brantly 1971). Half a century later offshore extraction was producing about 30% of the global oil output (Alexander's Gas & Oil Connections 1998). This has been made possible by using submersible, semisubmersible, and floating drilling rigs and production platforms that have kept moving to deeper, and also stormier, waters. In 2000 there were 636 mobile offshore drilling units in private and state-owned fleets, about 60% of them being jack-ups and 25% semisubmersibles (World Oil 2000). Some of these rigs are now working in waters up to 2,000 m deep and in 2001 an ultradeepwater drillship, *Discoverer Spirit,* set the record by drilling in 2,900 m of water in the Gulf of Mexico (Transocean Sedco Forex 2001). Offshore production platforms are among the most massive structures ever built. The record-holder in 2000 was the *Ursa* tension leg platform, a joint project of a group of companies lead by the Shell Exploration and Production Company (Shell Exploration and Production Company 1999). The platform has a total displacement of about 88,000 t (more than a Nimitz-class nuclear aircraft carrier), rises 145 m above water and it is anchored 1,140 m below water with 16 steel tendons.

Refining of crude oils—yielding a range of liquid fuels perfectly suited to a variety of specific applications ranging from the supersonic flight to the powering of massive diesel locomotives—was transformed by the introduction of high-pressure cracking after 1913 and of catalytic cracking in 1936. Without these processes it would be impossible to produce inexpensively large volumes of lighter distillates from intermediate and heavy compounds that dominate most of the crude oils. Unlike coals, crude oils are readily pumped on board of large ships and the size of modern crude oil tankers and the cheap diesel fuel they use means that the location of oilfields is virtually of no consequence as far the exports of the fuel are concerned. And crude oil can be sent across countries and continents through the safest, most reliable, and environmentally most benign means of energy transportation, a buried pipeline (for more on tankers and pipelines see the trade section later in this chapter).

Discoveries of the world's largest oilfields (supergiants in oil geology parlance) began during the 1930s and continued for more than two decades. Kuwaiti al-Burgan, now the world's second largest supergiant, was found in 1938. Saudi al-Ghawar, the world's largest oilfield holding almost 7% of the world's oil reserves in the year 2000, was discovered a decade later (Nehring 1978; EIA 2001b). By the time OPEC began increasing its crude oil price in the early 1970s the Middle East was known to contain 70% of all oil reserves, and the region (excluding North Africa) had 50% of the world's oil-producing capacity (fig. 1.8). Global crude oil extraction in 1900 was only about 20 Mt, the mass that is now produced in only about two days. This means that the worldwide crude oil output rose more than 160-fold since 1900 and nearly eightfold since 1950 when the world consumed just over 500 Mt of refined products that provided 25% of all primary commercial energy.

Although it is highly unevenly distributed, today's crude oil extraction is less skewed than the global coal production. Nearly 30 countries now produce annually more than 25 Mt of crude oil, and the top six producers account for 45% (vs. coal's 75%) of the total (BP 2001). In the year 2000, 3.2 Gt of crude oil supplied two-fifths of all commercial primary energy, about 10% below the peak share of about 44% that prevailed during the 1970s (UNO 1976; BP 2001). Crude oil's role in

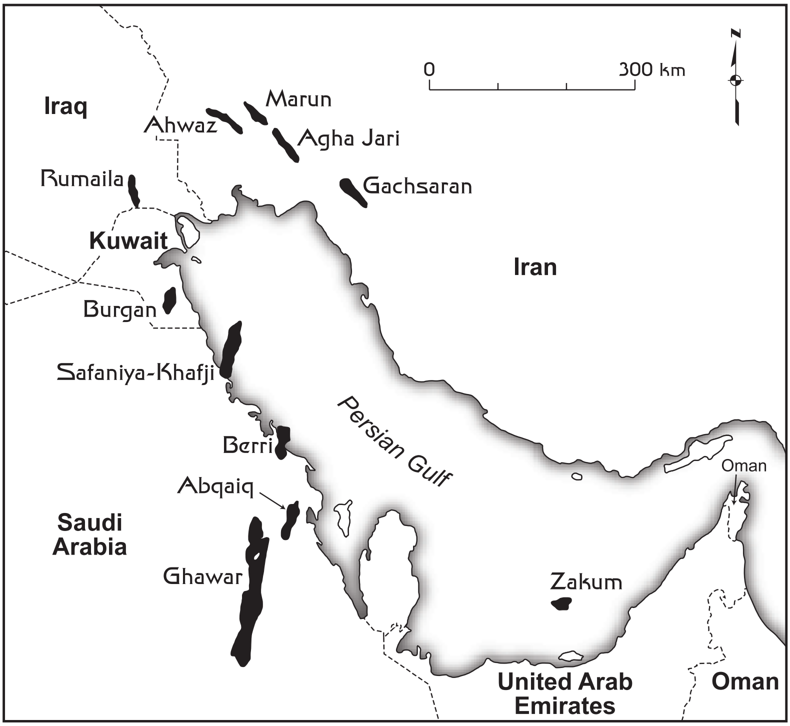


Figure 1.8
Giant Middle Eastern oil fields. Based on oil field maps published in various issues of *Oil & Gas Journal.*

modern societies is even greater than is suggested by its share of the TPES as refined fuels provide more than 90% of energy for the world's transportation. Air transport, one of the twentieth century greatest innovations with enormous economic, military, and social consequences, is unthinkable without refined fuels. So is, of course, the first century of mass public ownership of private cars.

Economic, social, and environmental consequences of automobilization have been even more far-reaching than have been the effects of flying. Land transport was also considerably facilitated by ready availability of inexpensive paving materials derived from crude oil. Crude oil also claims very high shares of the total commercial energy use in many low-income countries that still have only very modest per capita consumption of liquid fuels but rely on them more heavily than most of the affluent world with their more diversified energy supply. Because of these critical supply roles we will go to great lengths in order to secure adequate flows of the fuel that in so many ways defines the modern civilization.

Although crude oil, unlike coal, will never claim more than half of the world's primary commercial energy use I will present, in chapter 4, detailed arguments in order to show that the fuel's future is robust. Spectacular discoveries of supergiant oilfields and expansions that characterized the rise of oil to its global prominence during the twentieth century cannot be replicated in the coming generations, but a strong and globally important oil industry will be with us for generations to come. Its future will be shaped to a large degree by the advances of natural gas industry with which it is either directly commingled or closely associated.

During the first decade of the twentieth century, natural gases contributed only about 1.5% of the world's commercial primary energy consumption, and most of it was due just to the slowly expanding U.S. production. When expressed in energy equivalents the crude oil/natural gas ratio was about 3.1 during the 1910s and the gap between the two hydrocarbon fuels has been narrowing ever since. By the 1950s the ratio was 2.9, by the 1970s, 2.5. Post-1973 slowdown in the growth of oil output contrasted with continuing high increases of natural gas extraction that had doubled during the century's last quarter and lowered the oil/gas ratio to 1.7 during the 1990s. Because of its cleanliness natural gas has been the preferred fuel for space heating, as well as for electricity generation. Unlike many coals and crude oils, its content of sulfur is usually very low, or the gas can be easily stripped of any unwanted pollutants before it is put into a pipeline. Natural gas is now also sought after because it releases the lowest amount of CO_2 per unit of energy (see the last section of this chapter).

Natural gas now supplies 25% of the world's commercial primary energy and all hydrocarbons, ranging from virtually pure CH_4 to heavy crude oils, provide nearly two-thirds of the total. Future growth of the total share of hydrocarbon energies will be almost totally due to the increasing extraction of natural gas (see chapter 4). The two new sources of primary energy supply that could limit the relative share of hydrocarbons—electricity generated by nuclear fission and by converting direct and indirect solar energy flows—are also the ones with very uncertain futures. Coal's dominance of the global commercial primary energy supply lasted about three human generations (70 years), extending from the mid-1890s when it overtook wood to the mid-1960s when it was overtaken by hydrocarbons. Recent years have seen many claims about the imminent peak of global oil output: if true we would be already about halfway through the hydrocarbon era. As I will show in chapter 4 these claims may miss their mark by decades rather than by years. In any case, what is much more difficult to foresee than the timing of the midpoint of global oil extraction is what resource will become dominant after the hydrocarbon extraction begins its inevitable decline.

Technical Innovations

Technical advances that transformed the twentieth-century energy use can be logically divided into three interrelated categories. First are the impressive improvements of several key pre-1900 inventions, most of them originating during the incredibly innovative period between 1880–1895. Second are inventions of new extraction, conversion, and transportation techniques and their subsequent commercialization and refinements. Third are innovations that were introduced for reasons not related to energy production or use but whose later applications to numerous energy-related endeavors have greatly improved their accuracy, reliability, and efficiency. Improved performances of three out of the world's five most important prime movers are the best example in the first category: ICE, electric motor, and steam turbogenerator were all invented during the late nineteenth century. Their inventors would readily recognize the unchanged fundamentals of today's machines but they would marvel at the intervening improvements in performance and at the much higher power ratings of the latest designs.

Two new prime movers, gas turbines and rocket engines, should top a long list of inventions that could be cited in the second category. Both were commercialized only by the middle of the twentieth century but both have subsequently undergone a rapid development. The century's other commercially successful fundamental energy innovations also include two new modes of energy conversion, the now troubled nuclear fission and gradually ascendant photovoltaic generation of electricity. Examples of the last category of technical innovation are hidden everywhere as computerized controls help to operate everything from oil-drilling rigs to power plants, and from room thermostats to car engines. No less fundamentally, new communication, remote sensing, and analytical techniques have greatly transformed operations ranging from the search for deeply buried hydrocarbons to optimized management of interconnected electricity networks.

In spite of this diversity of advances there have been some notable commonalities dictated by the great upheavals of the twentieth century. Diffusion of all kinds of technical advances was set back by World War I, as well as by the economic crisis of the 1930s, but World War II accelerated the introduction of three major innovations: nuclear fission, gas turbines, and rocket propulsion. The two decades following WWII saw a particularly rapid growth of all energy systems, but since the late 1960s most of their individual components—be they coal mines, steam turbines in large thermal stations, transmission voltages, or giant tankers—had reached clear growth plateaux, and in some cases their typical unit sizes or capacities have actually declined.

Mature markets, excessive unit costs, and unacceptable environmental impacts, rather than technical limits to further growth, were the key reasons for this change, as higher efficiency and reliability and a greater environmental compatibility became the dominant design goals of the last two decades of the twentieth century. Next I include only the most important examples in the three principal categories of technical innovations before concentrating in a greater detail on what is perhaps the twentieth century's most far-reaching, long-term energy trend whose course is still far from over, the rising importance of electricity.

Modern life continues to be shaped by several substantially improved late nineteenth-century inventions, above all by electricity generation and transmission systems and by internal combustion engines. Steam engine, the quintessential machine of the early phases of industrialization, continued to be an important prime mover during the first few decades of the twentieth century. By that time its best specimens were nearly ten times more efficient and 100 times more powerful than were the top units at the beginning of the nineteenth century (Smil 1994a). But even these impressive advances could not change the machine's inherently low efficiency and high mass/power ratio. Nascent electricity-generating industry thus rapidly embraced the just-invented steam turbine and once electricity became readily available, electric motors displaced steam engines in countless manufacturing tasks. And, of course, the steam engine could never compete with internal combustion engines as a prime mover in land or airborne transportation.

Every aspect of those two great late nineteenth-century inventions was improved by subsequent innovation, resulting in better performance and reduced environmental impacts. In 1900 efficiencies of thermal electricity generation, with boilers burning lump coal on moving grates, steam pressure at less than 1 MPa and steam temperatures of less than 200 °C, were as low as 5%. Today's best thermal plants, burning pulverized coal and operating at steam pressures in excess of 20 MPa and temperatures above 600 °C, have conversion efficiencies of just over 40% but cogeneration can raise this rate to almost 60% (Weisman 1985; Gorokhov et al. 1999; for more on high-efficiency conversions see chapter 4).

Experiments with milled coal began in England already in 1903 but first large boilers fired with finely pulverized coal were put in operation in 1919 at London's Hamersmith power station. Unit sizes of steam turbines were slow to rise: Parsons' first 1 MW steam turbine was built in 1900 but 100 MW units were widely used only after 1950. But then it took less then two decades to raise the capacity by an order of magnitude as the first 1 GW unit went online in 1967 (fig. 1.9). The largest thermal turbines in coal-fired or nuclear stations now rate about 1.5 GW, but units of 200–800 MW are dominant.

Transmission losses were cut by using better and larger transformers, higher voltages, and direct current links. Peak transformer capacities had grown 500 times during the century. Typical main-line voltages were 23 kV before the WWI, 69 kV during the 1920s, 115 kV during the 1940s, and 345 kV by 1970 (Smil 1994a). Today's top AC links rate 765 kV, with the world's first line of that voltage installed by Hydro-Québec in 1965 to bring electricity 1,100 km south from Churchill Falls in Labrador to Montréal. And the age of long-distance, high-voltage DC transmission began on June 20, 1972 when Manitoba Hydro's 895 km long ±450 kV DC line brought electricity from Kettle Rapids hydro station on the Nelson River to Winnipeg (Smil 1991). Now we have DC links of up to 1,500 kV connecting large plants and major load centers in urban and industrial areas. Creation of regional grids in North America and more extensive international interconnections in Europe (in both latitudinal and longitudinal direction) improved supply security while reducing the requirements for reserve capacities maintained by individual generating systems.

The combination of Daimler's engine, Benz's electrical ignition, and Maybach's float-feed carburetor set a lasting configuration for the expansion of the automobile industry at the very beginning of the automotive era during the mid-1880s, and the subsequent development of Otto-cycle engines has been remarkably conservative (Flink 1988; Newcomb and Spurr 1989; Womack et al. 1991). Still, the industry has seen major technical advances. By far the most important twentieth-century changes included much higher compression ratios (from 4 before WWI to between 8 and 9.5) and declining engine weight. Typical mass/power ratios of ICEs fell from more than 30 g/W during the 1890s to just around 1 g/W a century later (Smil 1994a). Diesel engines have also become both lighter (mass/power ratio is now down to 2 g/W) and much more powerful, particularly in stationary applications.

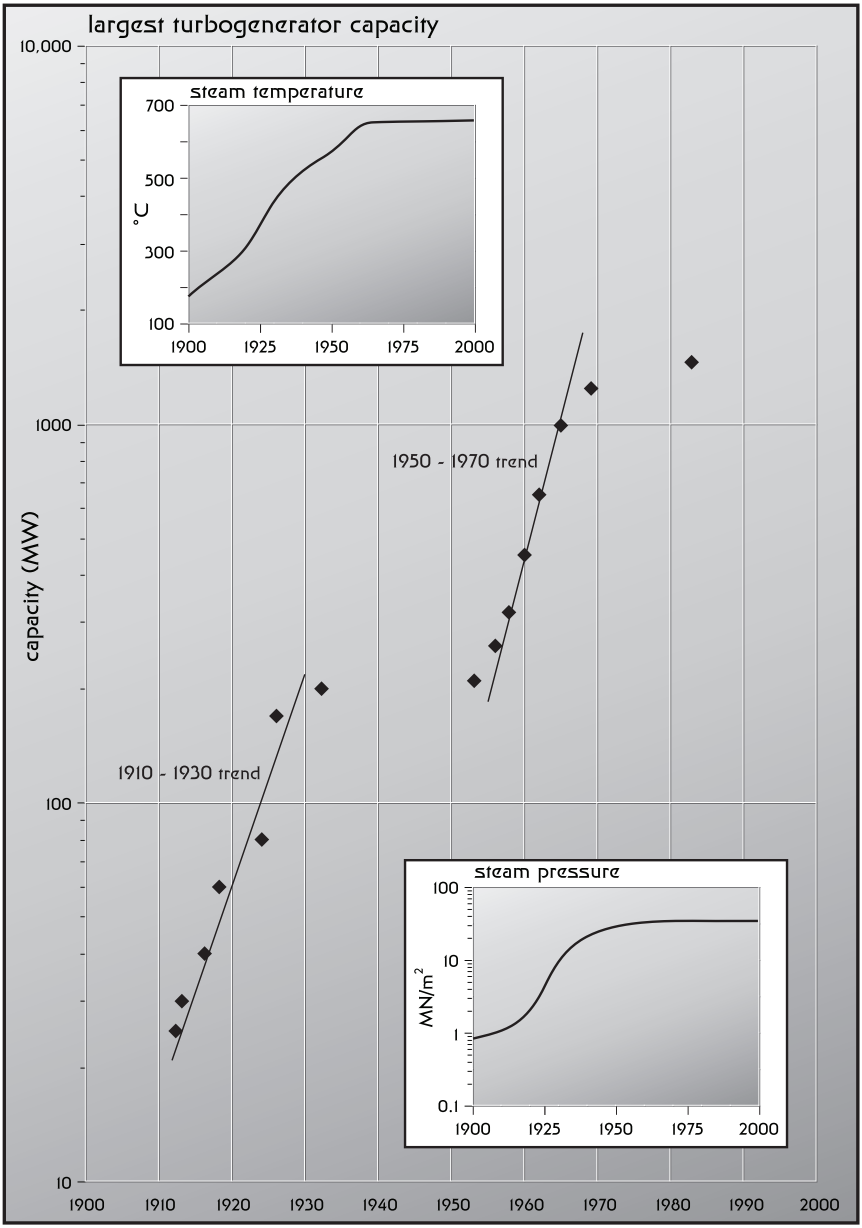


Figure 1.9
Record ratings of the U.S. turbogenerators during the twentieth century. Growth of the highest capacities was interrupted by the economic crisis, WWII, and the postwar recovery; afterward the precrisis growth rate resumed for another two decades. Both the top operating temperatures and the highest pressure used in modern turbogenerators have not increased since the 1960s. Based on data in FPC (1964), various issues of *Power Engineering,* and a figure in Smil (1999a).

But the environmental advantages of better internal engine performance were negated for decades by rising average car power ratings. Ford's celebrated model T, which was sold between 1908 and 1927, rated originally less than 16 kW (21 hp), while even small American cars of the early 1970s had in excess of 50 kW (67 hp). Consequently, the specific fuel consumption of new American passenger cars, which averaged about 14.8 L/100 km (16 mpg) during the early 1930s, kept deteriorating slowly for four decades and it became as high as 17.7 L/100 km (13.4 mpg) by 1973 (EIA 2001a).

This undesirable trend was finally reversed by the OPEC's oil price increases. Between 1973 and 1987 the average fuel demand of new cars on the North American market was cut in half as the Corporate Automobile Fuel Efficiency (CAFE) standard fell to 8.6 L/100 km (27.5 mpg). Unfortunately, the post-1985 slump in crude oil prices first stopped and then actually reversed this legislative and technical progress. Assorted vans, SUVs and light trucks—with power often in excess of 100 kW and, being exempt from the 27.5 mpg CAFE that applies only to cars, with performance that does not often even reach 20 mpg—have gained more than half of new vehicle market by the late 1990s (Ward's Communications 2000).

Both of the century's new prime movers were adopted so rapidly because of the WWII and the subsequent superpower rivalry. In a remarkable case of a concurrent but entirely independent invention, the first designs of gas turbines took place during the late 1930s when Frank Whittle in England and Hans Pabst von Ohain in Germany built their experimental engines for military planes (Constant 1981). Introduced at the war's very end, jet fighters made no difference to the war's outcome, but their rapid postwar development opened the way for commercial applications as nearly all first passenger jets were modifications of successful military designs. Speed of sound was surpassed on October 14, 1947 with the Bell X-1 plane. The British 106 Comet 1 was the first passenger jet to enter scheduled service in 1952 but structural defects of its fuselage led to its failure. The jet age was ushered in successfully in 1958 by the Boeing 707 and by a redesigned 106 Comet 4.

A decade later came the wide-bodied Boeing 747, the plane that revolutionized transoceanic flight. Pan Am ordered it first in 1966, the prototype plane took off on February 9, 1969, and the first scheduled flight was on January 21, 1970 (Smil 2000b). The first 747s had four Pratt & Whitney turbofan engines, famous JT9D each with a peak thrust of 21,297 kg and with mass/power ratio of 0.2 g/W. Three decades later the Boeing 747-300—the holder of speed and distance (20,044.2 km from Seattle to Kuala Lumpur) records for passenger jets (Boeing 2001)—is powered by twin engines from the same company (PW 4098) whose maximum thrust of 44,452 kg is more than twice as high (Pratt & Whitney 2001). Thrust/weight ratio of these engines is now more than 6, and turbines powering the supersonic military aeroplanes are even better, with thrust/weight ratios as high as 8 (fig. 1.10).

The impact of gas turbines goes far beyond transforming the aerial warfare and worldwide long-distance travel. These prime movers have also found very important stationary applications. They are used to power centrifugal compressors in pumping stations of natural gas pipelines, by many chemical and metallurgical industries, and during the past 15 years they have been increasingly chosen to drive electricity generators (Williams and Larson 1988; Islas 1999). Rising demand for peak electricity generation has lead to steadily higher stationary gas turbine ratings (commonly in excess of 100 MW by the late 1990s) and to efficiency matching the performance of the best steam turbines (fig. 1.10).

The only prime mover that can develop even more power per unit of mass than a gas turbine is the rocket engine. Its large-scale development began only during the WWII with ethanol-powered engines for the infamous German V-1 and V-2 used against England. After a decade of slow development the superpower rocket race started in earnest with the launch of the Earth's first artificial satellite, the Soviet *Sputnik* in 1957. Subsequent advances were driven by the quest for more powerful, but also more accurate, land- and submarine-based intercontinental ballistic missiles. No other prime mover comes close to liberated immense power, necessarily only very briefly, by the largest rocket engines. The U.S. Saturn C5 rocket, which on July 16, 1969 sent Apollo spacecraft on its journey to the Moon, developed about 2.6 GW during its 150-second burn (von Braun and Ordway 1975).

Moon flights were an ephemeral endeavor but satellites launched by relatively inexpensive rockets ushered the age of cheap intercontinental telecommunications, more reliable weather forecasting, and real-time monitoring of extreme weather events that made it possible to issue life-saving warnings. Satellites have also given us unprecedented capacities to monitor the Earth's land use changes, ocean dynamics, and photosynthetic productivity from space (Parkinson 1997; Smil 2002)—and to pinpoint our locations through the global positioning system (Hofmann-Wellenhof et al. 1997).

Discovery of nuclear fission introduced an entirely new form of energy conversion but its rapid commercial adaptation uses the heat released by this novel transformation for a well-tested process of generating steam for electricity generation. The sequence of critical developments was extraordinarily rapid. The first proof of fission

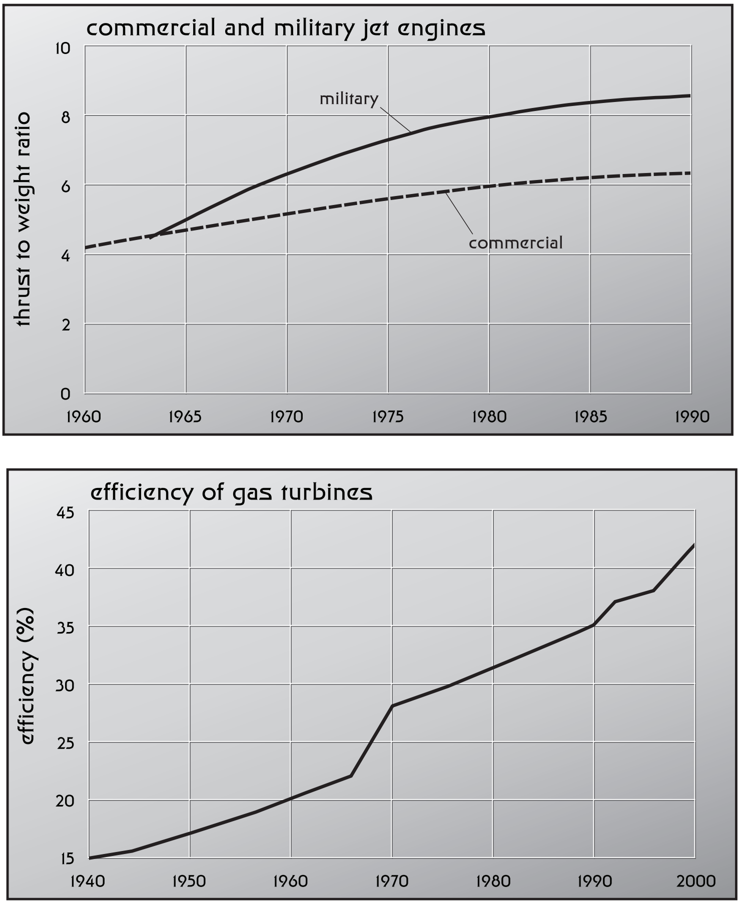


Figure 1.10
Two illustrations of the improving performance of gas turbines. The first graph shows the the increasing thrust ratio of military and commercial jet engines, the other one charts the rising efficiency of stationary gas turbines used for electricity generation. Based on data published in various energy journals.

was published in February 1939 (Meitner and Frisch 1939). The first sustained chain reaction took place at the University of Chicago on December 2, 1942 (Atkins 2000). Hyman Rickover's relentless effort to apply reactor drive to submarines led to the launch of the first nuclear-powered vessel, *Nautilus,* in January 1955 (Rockwell 1991). Rickover was put immediately in charge of, almost literally, beaching the General Electric's pressurized water reactor (PWR) used on submarines and building the first U.S. civilian electricity-generating station in Shippingport, Pennsylvania. The station reached initial criticality on December 2, 1957, more than a year after the world's first large-scale nuclear station, British Calder Hall (4x23 MW), was connected to the grid on October 17, 1956 (Atkins 2000; fig. 1.11).

PWR became the dominant choice as this new electricity-generating technique entered the stage of precipitous adoption. Ten years between 1965 and 1975 saw the greatest number of new nuclear power plant orders, and European countries (including the former Soviet Union) eventually ordered about twice as many power reactors

Figure 1.11
Aerial view of Calder Hall on the Cumberland coast, the world's first commercial nuclear electricity-generating station. Photo, taken in May 1962, courtesy of the U.K. Atomic Energy Authority.

as did the United States. As I will detail in the third chapter, the expert consensus of the early 1970s was that by the century's end the world would be shaped by ubiquitous and inexpensive nuclear energy. In retrospect, it is obvious that the commercial development of nuclear generation was far too rushed and that too little weight was given to the public acceptability of commercial fission (Cowan 1990).

Arguments about the economics of fission-produced electricity were always dubious as calculations of generation costs did not take into account either the enormous subsidies sunk by the governments into nuclear R&D (see chapters 2 and 6) or the unknown costs of decommissioning the plants and storing safely the highly radioactive waste for the future millennia. And looking back Weinberg (1994, p. 21) conceded that "had safety been the primary design criterion [rather than compactness and simplicity that guided the design of submarine PWR], I suspect we might have hit upon what we now call inherently safe reactors at the beginning of the first nuclear era. . . ." More fundamentally, promoters of nuclear energy did not take seriously Enrico Fermi's warning (issued even before the end of the WWII at one of the University of Chicago meetings discussing the future of nuclear reactors) that the public may not accept an energy source that generates large amounts of radioactivity as well as fissile materials that might fall into the hands of terrorists (Weinberg 1994).

By the early 1980s a combination of other unexpected factors—declining demand for electricity (see chapter 3 for details), escalating costs in the era of high inflation and slipping construction schedules, and changing safety regulations that had to be accommodated by new designs—helped to turn the fission's prospects from brilliant to dim. Many U.S. nuclear power plants eventually took twice as long to build as originally scheduled, and cost more than twice as much than the initial estimates. Safety concerns and public perceptions of intolerable risks were strengthened by an accident at the Three Mile Island plant in Pennsylvania in 1979 (Denning 1985). By the mid-1980s the shortlived fission era appeared to be over everywhere in the Western world with the exception of France. Accidental core meltdown and the release of radioactivity during the Chernobyl disaster in Ukraine in May 1986 made matter even worse (Hohenemser 1988). Although the Western PWRs with their containment vessels and much tighter operating procedures could have never experienced such a massive release of radiation as did the unshielded Soviet reactor, that accident only reinforced the erroneous but widely shared public perception of all nuclear power being inherently unsafe.

Still, by the century's end nuclear generation was making a substantial contribution to the world's TPES (Beck 1999; IAEA 2001a). By the end of the year 2000 there were 438 nuclear power plants in operation with a total net installed capacity of 351 GW. Fission reactors accounted for about 11% of all installed electricity-generating capacity but because of their high availability factors (global average of about 80% during the late 1990s) they generated about 16% of all electricity (IAEA 2001a). The highest national contributions were in France, where 76% of electricity was generated by PWRs. Lithuania, with its large Soviet-built station in Ingalina, came second with nearly 74% and Belgium third (57%). Japan's share was 33%, the United States' share 20%, Russia's 15%, India's 3%, and China's just over 1% (IAEA 2001a). I will assess the industry's uncertain future in chapter 4.

I would also put photovoltaics (PV), another remarkable nineteenth-century invention, into the category of important new twentieth-century energy conversions. This placement has a logical justification: unlike other conversion techniques that were invented and began to be commercialized before 1900, PV's first practical use took place during the late 1950s. Discovery of the PV phenomenon can be dated precisely to young Edmund Becquerel's 1839 finding that electricity generation in an electrolytic cell made up of two metal electrodes increased when exposed to light (PV Power Resource Site 2001). Little research was done on the PV effect during the subsequent three decades, but the 1873 discovery of the photoconductivity by selenium made it possible for W. G. Adams and R. E. Day to make the first PV cell just four years later. Selenium wafer design was described by Charles Fritts in 1883 but conversion efficiencies of such cells were a mere 1–2%. Einstein's work on the photoelectric effect (Einstein 1905), and not his more famous studies of relativity, earned him a Nobel Prize 16 years later, but had little practical impact on PV development. Nor did Jan Czochralski's fundamental 1918 discovery of how to grow large silicon crystals needed to produce thin semiconductor wafers.

The breakthrough came only in 1954 when a team of Bell Laboratories researchers produced silicon solar cells that were 4.5% efficient, and raised that performance to 6% just a few months later. By March 1958, when Vanguard-I became the first PV-powered satellite (a mere 0.1 W from about 100 cm^2), Hoffman Electronics had cells that were 9% efficient, and began selling 10%-efficient cells just one year later (PV Power Resource Site 2001). In 1962 Telstar, the first commercial telecommunications satellite, had 14 W of PV power, and just two years later Nimbus rated 470 W. PV cells became an indispensable ingredient of the burgeoning satellite industry but land-based applications remained uncommon even after David Carlson and Christopher Wronski at RCA Laboratories fabricated the first amorphous silicon PV cell in 1976. Worldwide PV production surpassed 20 MW of peak capacity (MW_p) in

1983 and 200 MW_p by the year 2000 as solar electricity became one of the fastest growing energy industries (Markvart 2000). Still, the total installed PV capacity was only about 1 GW in 1999, a negligible fraction of more than 2.1 TW available in fossil-fueled generators (EIA 2001c).

The last category of technical, and management, innovations resulting from the diffusion of computers, ubiquitous telecommunications, and common reliance on automatic controls and optimization algorithms has transformed every aspect of energy business, from the search for hydrocarbons to the design of prime movers, and from the allocation of electricity supplies to monitoring of tanker-borne crude oil. An entire book could be devoted to a survey of these diverse innovations that are largely hidden from public view. Its highlights would have to include, among others, a veritable revolution in searching for hydrocarbons, unprecedented accuracy and intensity of monitoring complex dynamic networks, and dematerialized design of prime movers and machines.

Advances in the capabilities of electronic devices used in remote sensing and orders of magnitude higher capacities to store and process field data are behind the revolutionary improvements in the reach and the quality of geophysical prospecting. By the mid-1990s traditional two-dimensional seismic data used in oil exploration were almost completely replaced by three-dimensional images and the latest four-dimensional monitoring (time-lapse three-dimensional) of reservoirs makes it possible to trace and to simulate the actual flow of oil in hydrocarbon-bearing formations and to interpret fluid saturation and pressure changes. This knowledge makes it possible to increase the oil recovery rates from the maxima of 30–35% achievable before 1980 to at least 65% and perhaps even to more than 75% (Morgan 1995; Lamont Doherty Earth Observatory 2001). Global positioning system makes it possible for a company to be instantaneously aware of the exact location of every one of its trucks crisscrossing a continent or every one of its tankers carrying crude oil from the Middle East—and an optimizing algorithm receiving the information about road closures and detours, or about extreme weather events (cyclones, fog) can minimize fuel consumption and time delays by rerouting these carriers.

The Rising Importance of Electricity

There are many reasons to single out electricity for special attention. After millennia of dependence on the three basic energy conversions—burning of fuels, that is fresh or fossilized biomass, use of human and animal muscles, and the capture of indirect solar flows of water and wind—large-scale generation of electricity introduced a new form of energy that has no rival in terms of its convenience and flexibility. No other kind of energy affords such an instant and effortless access. Electricity's advantage, taken utterly for granted by populations that have grown up with its cheap and ubiquitous supply, is evident to anybody who managed a household in the preelectrical era, or who lived in places where expensive electricity was used just for inadequate lighting.

To all those who have never faced daily chores of drawing and hauling water, preparing kindling in morning darkness and cold, washing and wringing clothes by hand, ironing them with heavy wedges of hot metal, grinding feed for animals, milking cows by hand, pitchforking hay up into a loft, or doing scores of other repetitive manual tasks around the house, farmyard, or workshop, it is not easy to convey the liberating power of electricity. I am aware of no better literary attempt to do so than two chapters in an unlikely source, in the first volume of Robert Caro's fascinating biography of Lyndon Johnson (Caro 1982).

Caro's vivid descriptions of the repetitive drudgery, and physical dangers, experienced by a preelectric society are based on recollections of life in the Texas Hill Country during the 1930s. These burdens, falling largely on women, were much greater than the exertions of subsistence farmers in Africa or Latin America because the Hill Country farmers tried to maintain a much higher standard of living and managed much larger farming operations. The word *revolution* is then no exaggeration to describe the day when transmission lines reached the homes of such families.

Electricity's advantages go far beyond instant and effortless access as no other form of energy can rival the flexibility of its final uses. Electricity can be converted to light, heat, motion, and chemical potential and hence it can be used in every principal energy-consuming sector with the exception of commercial flying. Unmanned solar-powered flight is a different matter. AeroVironment's Pathfinder rose to 24 km above the sea level in 1998, and a bigger Helios—a thin, long curved and narrow-flying wing (span of just over 74 m, longer than that of Boeing 747, width of 2.4 m) driven by 14 propellers powered by 1 kW of bifacial solar cells—became the world's highest flying plane in August 2001 as it reached the altitude of almost 29 km (AeroVironment 2001; fig. 1.12).

In addition to its versatility, electricity use is also perfectly clean and silent at the point of consumption and it can be easily adjusted with very high precision to provide desirable speed and accurate control of a particular process (Schurr 1984). And once a requisite wiring is in place it is easy to accommodate higher demand or a

Figure 1.12
The solar-electric *Helios Prototype* flying wing during its record-setting test flight above Hawaiian islands on July 14, 2001. NASA photo ED 01-0209-6 available at <http://www.dfrc.nasa.gov/gallery/photo/HELIOS/HTML/EDO1-0209-6.html>.

greater variety of electricity converters. Finally, electricity can be converted without any losses to useful heat (it can also be used to generate temperatures higher than combustion of any fossil fuel), and it can be turned with very high efficiency (in excess of 90%) into mechanical energy. Among all of its major uses only lighting is still generally less than 20% efficient.

The combination of these desirable attributes brought many profound changes to the twentieth-century use of energy and hence to the functioning of modern economies and the conduct of everyday life. The universal impact of this new form of energy is attested to by the fact that electrification became the embodiment of such disparate political ideals as Lenin's quest for a new state form and Roosevelt's New Deal. Lenin summarized his goal in his famously terse slogan "Communism equals the Soviet power plus electrification." Roosevelt used extensive federal involvement in building dams and electrifying the countryside as a key tool of his New Deal program of economic recovery (Lilienthal 1944).

As with so many other energy-related innovations, the United States pioneered the introduction and mass diffusion of new electric conversions, with Europe and

Japan lagging years to decades behind, and with a large share of today's poor world still undergoing only the earliest stages of these fundamental transformations. The three truly revolutionary shifts—affordable, clean, and flexible lighting, conversion of industrial power from steam to electricity, and the adoption of an increasing variety of household energy converters—proceeded concurrently during the century's early decades, and lighting caused the first large-scale electricity-powered socioeconomic transformation.

Although Edison's incandescent carbon filament lamp, patented in 1879, was about 20 times as efficient as a candle (which converted a mere 0.01% of the burning paraffin into light) it would not have been affordable to mass-produce a device that turned just 0.2% of expensively generated electricity to light. Efficiency comparisons for lighting are done usually in terms of efficacy, the ratio of light (in lumens) and the power used (in W). The earliest light bulbs produced less than 2 lumens/W, and although osmium filaments, introduced in 1898, tripled that rate, they still produced only fairly dim light (no more than a modern 25-W lamp) whose cost was unacceptably high to illuminate properly households or public places. Steady advances during the course of the twentieth century improved the best light efficiencies by an order of magnitude (fig. 1.13; Smithsonian Institution 2001). Light bulb performance was

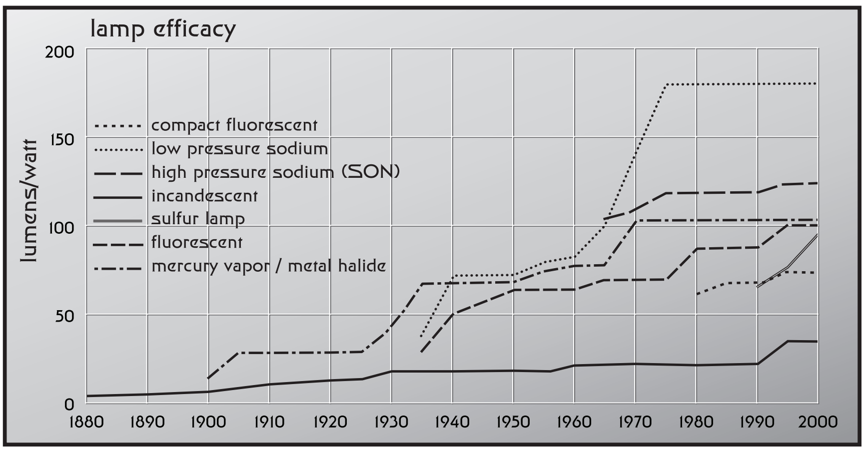


Figure 1.13
Increasing efficacy (lumens/watt) of various kinds of electric lights during the twentieth century. Based on a Smithsonian Institute graph available at <http://americanhistory.si.edu/lighting/chart.htm>.

improved first by squirted tungsten filaments, available after 1905, then by tungsten filaments in vacuum, and by argon-filled lamps with coiled filaments, invented by Irving Langmuir in 1913 (Bowers 1998).

Several breakthroughs came during the 1930s with the introduction of low-pressure sodium lamps (LPS), mercury-vapor lamps (both for the first time in Europe in 1932) and fluorescent lights. LPS, whose stark yellow light dominates street lighting, are the most efficient lights available today. With 1.47 mW/lumen being the mechanical equivalent of light, the efficacy of 175 lumens/W means that LPS lamps convert just over 25% of electric energy into light (fig. 1.13). Mercury-vapor lamps put initially about 40 lumens/W of blue- and green-tinged white light.

Early fluorescent lights had the same efficacy, and as their efficiency more than doubled and as different types were introduced to resemble more the daylight spectrum they eventually became the norm for institutional illumination and made major inroads in the household market. Today's best fluorescent lights have efficiencies in excess of 100 lumens/W, about equal to metal halide lamps (mercury-vapor lamps with halide compounds) that are now the dominant lighting at sporting events and other mass gatherings that are televised live (fig. 1.13). High-pressure sodium lamps, introduced during the 1960s, produce a more agreeable (golden yellow) light than LPS sources but with about 30% lower efficiency.

For consumers the combination of rising lighting efficacies and falling prices of electricity (see chapter 2) means that a lumen of electric light generated in the United States now costs less than 1/1,000 than it did a century ago. In addition there are obvious, but hard-to-quantify, convenience advantages of electric light compared to candles or whale-oil or kerosene lamps. On a public scale the twentieth century also witnessed spectacular use of light for aims ranging from simple delight to political propaganda. First many American industrialists used concentrated lighting to flood downtowns of large cities with "White Ways" (Nye 1990). Later, Nazis used batteries of floodlights to create immaterial walls to awe the participants at their party rallies of the 1930s (Speer 1970). Now outdoor lighting is a part of advertising and business displays around the world—and in the spring of 2002 two pillars of light were used to evoke the destroyed twin towers of the World Trade Center. The total flux of indoor and outdoor lighting has reached such an intensity that night views of the Earth show that all densely inhabited affluent regions now have more light than darkness, and the only extensive unlighted areas are the polar regions, great deserts, Amazon, and Congo basin—and North Korea (fig. 1.14).

Figure 1.14
Composite satellite image of the Earth at night is a dramatic illustration of electricity's impact on a planetary scale. The image and more information on the Earth at night are available at <http://antwrp.gsfc.nasa.gov/apod/ap001127.html>.

An even more profound, although curiously little appreciated, process was underway as people in industrializing countries were illuminating their homes with better light bulbs: electrification revolutionized manufacturing even more than did the steam engines. This shift was so important not because electric motors were more powerful than steam engines they replaced but because of unprecedented gains in the reliability and localized control of power. These critical gains did not accompany the previous prime-mover shift from waterwheels, or windmills, to steam engines. All of these machines used systems of shafts and toothed wheels and belts to transmit mechanical energy to the point of its final use. This was not a problem with simple one-point uses such as grain milling or water pumping, but it entailed often complex transmission arrangements in order to deliver mechanical power to a multitude of workplaces so it could be used in weaving cloth or machining metals.

Space under factory ceilings had to be filled with mainline shafts that were linked to parallel countershafts in order to transfer the motion by belts to individual machines (fig. 1.15). Accidental outage of the prime mover or a failure anywhere along the chain of transmission shut down the entire arrangement, and even when running flawlessly, such transmission systems lost a great deal of energy to friction: overall mechanical efficiency of belt-driven assemblies was less than 10% (Schurr and Netschert 1960). Continuously running belts were also idling much of the time and made it impossible to control power at individual workplaces. Everything changed only when electric motors dedicated to drive individual machines became the industrial norm. Electrification did away with the overhead clutter (and noise) of transmission shafts and belts, opened up that space for better illumination and ventilation, sharply reduced the risk of accidents, and allowed for flexible floor plans that could

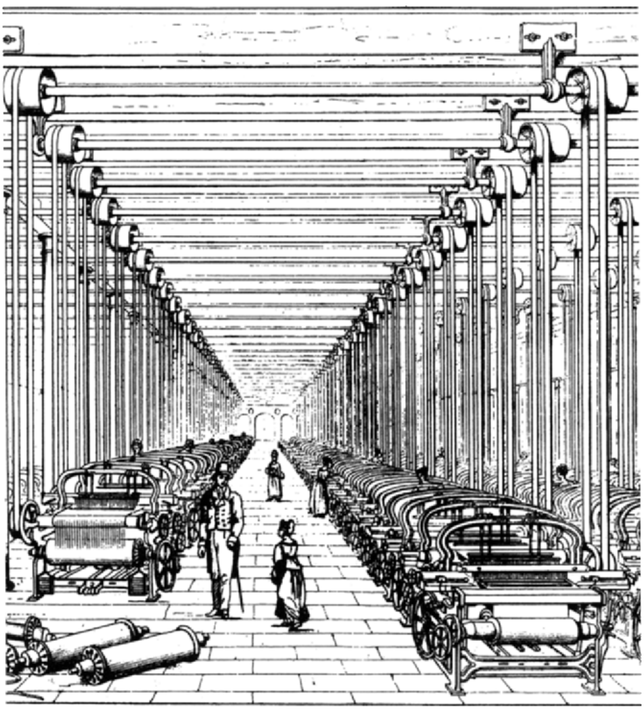


Figure 1.15
Rotating axles and transmission belts were needed to transfer mechanical energy from a central steam engine to individual machines. These cumbersome, dangerous, and inefficient arrangements disappeared with the introduction of electric motors.

easily accommodate new configurations or new machines, and more efficient (at least 70%, often more than 90%) and more reliable power supplies and their accurate control at the unit level raised average labor productivities.

In the United States this great transformation began around 1900 and it took about three decades to complete. At the century's beginning electric motors made up less than 5% of all installed mechanical power in America's industries; by 1929 they added up to over 80% (Devine 1983; Schurr 1984). And the process did not stop with the elimination of steam power as electric motors came to occupy a growing number of new niches to become the most ubiquitous and hence the most indispensable energy converters of modern civilization. In this sense their material analog is steel, an indispensable structural foundation of modern affluence.

The alloy sustains our standard of living in countless ways. A choice list could start with such spectacular applications as supertanker hulls, tension cables suspending graceful bridges, and pressure vessels containing the cores of nuclear reactors. The list could continue with such now mundane machines as semisubmersible oil drilling rigs, electricity-generating turbines or giant metal-stamping presses; and it could close with such hidden uses as large-diameter transcontinental gas pipelines and reinforcing bars in concrete. Steel is indispensable even for traditional materials or for their latest substitutes. All wood and stone are cut and shaped by machines and tools made of steel, all crude oils yielding feedstocks for plastics are extracted, transported, and refined by machines and assemblies made of steel, as are the injection machines and presses moulding countless plastic parts. Not surprisingly, steel output (almost 850 Mt in 2000) is almost 20 times as large as the combined total of five other leading metals, aluminum, copper, zinc, lead, and nickel (IISI 2001).

Ubiquity and indispensability of electric motors is similarly unnoticed. Everything we eat, wear, and use has been made with their help: they mill grain, weave textiles, saw wood, and mould plastics. They are hidden in thousands of different laboratory and medical devices and are being installed every hour by thousands aboard cars, planes, and ships. They turn the fans that distribute the heat from hydrocarbons burned by household furnaces, they lift the increasingly urbanized humanity to high-rise destinations, they move parts and products along assembly lines of factories, whether producing Hondas or Hewlett Packards. And they make it possible to micromachine millions of accurate components for machines ranging from giant turbofan jet engines to endoscopic medical diagnostic devices.

Modern civilization could retain all of its fuels and even have all of its electricity but it could not function without electric motors, new alphas (in baby incubators) and omegas (powering compressors in morgue coolers) of high-tech society. Consequently, it is hardly surprising that electric motors consume just over two-thirds of all electricity produced in the United States, and it is encouraging that they are doing so with increasing efficiencies (Hoshide 1994). In general, their conversion efficiencies increase with rated power; for example, for six-pole open motors full-load efficiencies are 84% at 1.5 hp, 90.2% at 15 hp, and 94.5% at 150 hp. At the same time, it is wasteful to install more powerful motors to perform tasks where they will operate at a fraction of their maximum load. Unfortunately, this has been a common occurrence, with about one-quarter of all U.S. electric motors operating at less than 30% of maximum loads, and only one-quarter working at more than 60% of rated maxima (Hoshide 1994).

The third great electricity-driven transformation, the proliferation of household appliances, has been due, for the most part, to the use of small electric motors but its origins were in simpler heat-producing devices. General Electric began selling its first domestic electrical appliances during the late 1880s but during the 1890s their choice was limited to irons and immersion water heaters and it also included a rather inefficient "rapid cooking apparatus" that took 12 minutes to boil half a liter of water. In 1900 came the first public supply of three-phase current and new electric motor-driven appliances were then introduced in a fairly quick succession. Electric fans were patented in 1902, washing machines went on sale in 1907, vacuum cleaners ("electric suction sweepers") a year later, and first refrigerators in 1912.

Ownership of refrigerators and washing machines is now practically universal throughout the affluent world. A detailed 1997 survey showed that in the United States 99.9% of households had at least one refrigerator and 92% households in single-family houses had a washing machine (EIA 1999a). Ownership of color TVs was also very high: 98.7% of households had at least one set, and 67% had more than two, and the portable vacuum cleaner has metamorphosed in many homes to a central vacuum. Electrical appliances have been also diffusing rapidly in many modernizing countries. In 1999 China's urban households averaged 1.1 color TV sets, 91% of them had a washing machine, and 78% owned a refrigerator (fig. 1.16; NBS 2000).

And there are also many indispensable conversions of electricity where motors are not dominant. Without inexpensive electricity it would be impossible to smelt aluminum, as well as to produce steel in electric arc furnaces. And, of course, there would be neither the ubiquitous feedback controls (from simple thermostats to fly-by-wire wide-bodied jets) nor the omnipresent telecommunications, computers, and

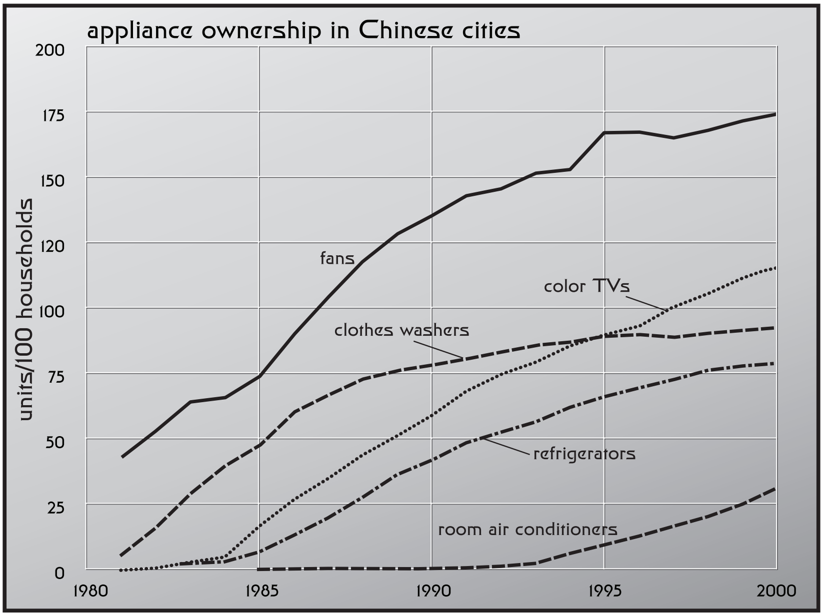


Figure 1.16
Rising ownership of electric appliances in China, 1980–2000. Based on a graph in Fridley (2001) and on data published annually in *China Statistical Yearbook*.

the Internet. Electricity use by the Internet and by a multitude of PC-related devices has been a matter of considerable controversy that began with publications by Mills (1999) and Huber and Mills (1999). They estimated that the Internet-related electricity demand was as much as 8% of the U.S. consumption in 1999. In contrast, Romm (2000) argued that a partial dematerialization of the economy effected by the Internet actually brings net energy savings (Romm 2000), and other analysts found that electricity consumed by computers, their peripheral devices, and the infrastructure of the Internet (servers, routers, repeaters, amplifiers) adds up to a still small but rising share of national demand (Hayes 2001).

A detailed study of the U.S. electricity consumption in computing and other office uses (copiers, faxes, etc.) put the total annual demand at 71 TWh, or about 2% of the nation's total (Koomey et al. 1999). In spite of their large unit capacity (10–20 kW) some 100,000 mainframes used just over 6 TWh compared to more than 14 TWh/year for some 130 million desktop and portable computers whose unit power rates usually only in 100 W. The entire controversy about electricity demand and the Internet—more on this controversy can be found at RMI (1999)—is an excellent example of difficulties in analyzing complex and dynamic systems, yet regardless of what exactly the specific demand may be, the new e-economy will almost certainly increase, rather than reduce, the demand for electricity. I will return to these matters of more efficient energy use in chapter 6.

Inherently high losses of energy during the thermal generation of electricity are the key drawback of the rising dependence of the most flexible form of energy. In 1900 they were astonishingly high: the average U.S. heating rate was 91.25 MJ/kWh, which means that just short of 4% of the available chemical energy in coal got converted to electricity. That efficiency more than tripled by 1925 (13.6%) and then almost doubled by 1950 to 23.9% (Schurr and Netschert 1960). Nationwide means surpassed 30% by 1960 but it has stagnated during the past 40 years, never exceeding 33% (EIA 2001a; fig. 1.17). Only a few best individual stations have efficiencies of 40–42%. Similar averages and peaks prevail elsewhere in the Western world.

The good news is that the average performance of thermal power plants had risen an order of magnitude during the twentieth century. The unwelcome reality is that a typical installation will still lose two-thirds of all chemical energy initially present

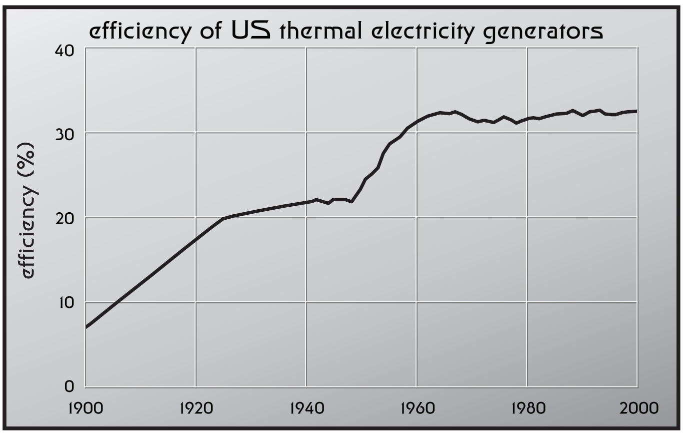


Figure 1.17
By 1960 the average efficiency of the U.S. thermal generation of electricity surpassed 30% and while the best power plants now operate with efficiencies just above 40% the nationwide mean has stagnated for 49 years, clearly an unacceptable waste of resources. Plotted from data in USBC (1975) and EIA (2001a).

in a fossil fuel, or of nuclear energy charged into a reactor in fissile isotopes. This decades-long stagnation of average power plant efficiency is clearly one of the most important performance failures of the modern energy system. For comparison, during the late 1990s, energy wasted annually in U.S. electricity generation surpassed Japan's total energy consumption and it was nearly one-quarter larger than Latin America's total supply of all fossil fuels and primary electricity. I will return to this intolerable inefficiency problem in chapter 4 where I will outline various technical options—some of them already available, others to become commercial soon—to raise this poor average not just above 40% but well over 50%.

But numerous advantages of electricity override the inherent inefficiency of its thermal generation, and the twentieth century saw a relentless rise of the share of the total fossil fuel consumption used to generate electricity. The U.S. share rose from less than 2% in 1900 to just over 10% by 1950 and to 34% in the year 2000 (EIA 2001a). The universal nature of this process is best illustrated by a rapid rate with which China has been catching up. The country converted only about 10% of its coal (at that time virtually the only fossil fuel it used) to electricity in 1950, but by 1980 the share surpassed 20% and by the year 2000 it was about 30%, not far behind the U.S. share (Smil 1976; Fridley 2001). Because of this strong worldwide trend even the global share of fossil fuels converted to electricity is now above 30%, compared to 10% in 1950, and just over 1% in 1900. And, of course, the global supply of electricity has been substantially expanded by hydro generation, whose contribution was negligible in 1900, and by nuclear fission, commercially available since 1956.

Harnessing of hydro energy by larger and more efficient water wheels and, beginning in 1832 with Benoit Fourneyron's invention, by water turbines, was a leading source of mechanical power in early stages of industrialization (Smil 1994a). Two new turbine designs (by Pelton in 1889, and by Kaplan in 1920) and advances in construction of large steel-reinforced concrete dams (pioneered in the Alps, Scandinavia, and the United States before 1900) ensured that water power remained a major source of electricity in the fossil-fueled world. Hydro generation was pushed to a new level before World War II by state-supported projects in the United States and the Soviet Union. Two U.S. projects of that period, Hoover Dam on the Colorado (generating since 1936), and Bonneville on the Columbia, surpassed 1 GW of installed capacity. Giant Grand Coulee on the Columbia (currently 6.18 GW) began generating in 1941 (fig. 1.18), and since 1945 about 150 hydro stations with capacities in excess of 1 GW were put onstream in more than 30 countries (ICOLD 1998).

Figure 1.18
Photograph of the nearly completed Grand Coulee dam taken on June 15, 1941. The station remains the largest U.S. hydro-generating project. U.S. Bureau of Reclamation photograph available at <http://users.owt.com/chubbard/gcdam/highres/build10.jpg>.

Top technical achievements in large dam construction include the height of 335 m of the Rogun dam on the Vakhsh in Tajikistan, reservoir capacity of almost 170 Gm^3 held by the Bratsk dam on the Yenisey, and more than 65 km of embankment dams of the Yacyretâ 3.2 GW project on the Paraná between Paraguay and Argentina (ICOLD 1998). Paraná waters also power the largest hydro project in the Western hemisphere, 12.6 GW Itaipu between Brazil and Paraguay. The world's largest hydro station—the highly controversial Sanxia (Three Gorges) rated at 17.68 GW—is currently under construction across the Chang Jiang in Hubei (Dai 1994). In total about 150 GW of new hydro-generating capacity is scheduled to come online before 2010 (IHA 2000).

Almost every country, with the natural exception of arid subtropics and tiny island nations, generates hydroelectricity. In thirteen countries hydro generation produces virtually all electricity, and its shares in the total national supply are more than 80%

in 32 countries, and more than 50% in 65 countries (IHA 2000). But the six largest producers (Canada, the United States, Brazil, China, Russia, and Norway) account for almost 55% of the global aggregate that, in turn, makes up about 18% of all electricity generation. Combined hydro and nuclear generation, together with minor contributions by wind, geothermal energy, and photovoltaics, now amounts to about 37% of the world's electricity.

Electricity's critical role in modern economies is perhaps best illustrated by comparing the recent differences in intensity trends. As I will explain in some detail in the next chapter, many forecasters were badly mistaken by assuming that a close link between the total primary energy use and GDP growth evident in the U.S. economy after World War II can be used to predict future energy demand. But the two variables became uncoupled after 1970: during the subsequent 30 years the U.S. inflation-adjusted GDP grew by 260% while the primary energy consumption per dollar of GDP (energy intensity of the economy) declined by about 44%. In contrast, the electricity intensity of the U.S. economy rose about 2.4 times between 1950 and 1980, but it has since declined also by about 10%, leaving the late 1990s' intensity almost exactly where it was three decades ago.

Consequently, there has been no decisive uncoupling of economic growth from electricity use in the U.S. case. Is this gentle and modest decline of the electricity intensity of the U.S. economy during the past generation a harbinger of continuing decoupling or just a temporary downturn before a renewed rise of the ratio? Future trends are much clearer for populous countries engaged in rapid economic modernization because during those stages of economic development electricity intensity of an economy tends to rise rapidly.

Trading Energy

Modern mobility of people has been more than matched by the mobility of goods: expanding international trade now accounts for about 15% of the gross world economic product, twice the share in 1900 (Maddison 1995; WTO 2001). Rising trade in higher value-added manufactures (it accounted for 77% of all foreign trade in 1999) makes the multiple much larger in terms of total sales. Total merchandise sales have topped $6 trillion, more than 80 times the 1950 value when expressed in current monies (WTO 2001). Even after adjusting for inflation this would still be about a twelvefold increase.

Global fuel exports were worth almost exactly \$400 billion in 1999, equal to just over 7% of the world's merchandise trade. This was nearly 2.6 times the value of all other mining products (about \$155 billion) but about 10% behind the international food sales, which added up to \$437 billion. Only in the Middle East does the value of exported fuels dominate the total foreign sales, with Saudi Arabia accounting for about 11% of the world's fuel sales. A relatively dispersed pattern of the global fuel trade is illustrated by the fact that the top five fuel exporters (the other four in terms of annual value are Canada, Norway, United Arab Emirates, and Russia) account for less than 30% of total value (WTO 2001).

But the total of annually traded fuels greatly surpasses the aggregate tonnages of the other two extensively traded groups of commodities, metal ores and finished metals, and of food and feed. World iron ore trade totaled about 450 Mt (more than one-third coming from Latin America) and exports of steel reached 280 Mt in 2000, with Japan and Russia each shipping about one-tenth of the total (IISI 2001). Global agricultural trade is dominated by exports of food and feed grains that have grown to about 280 Mt/year by the late 1990s (FAO 2001). In contrast, the tonnage of fuels traded in 2000—just over 500 Mt of coal, about 2 Gt of crude oil and refined products, and only about 95 Mt of natural gas (converting 125 Gm^3 by using average density 0.76 kg/m^3) added up to roughly 2.6 Gt.

Although only about 15% of the global coal production are traded, with some two-thirds of the total sold for steam generation and one-third to produce metallurgical coke, the fuel has surpassed iron ore to become the world's most important seaborne dry-bulk commodity and hence its exports set the freight market trends (WCI 2001). Australia, with more than 150 Mt of coal shipped annually during the late 1990s (roughly split between steam and coking fuel), has become the world's largest exporter, followed by South Africa, the United States, Indonesia, China, and Canada. Japan has been the largest importer of both steam and coking coal (total of over 130 Mt during the late 1990s), followed now by the South Korea, Taiwan, and, in a shift unforeseeable a generation ago, by two former coal-mining superpowers, Germany and the United Kingdom, which import cheaper foreign coal mainly for electricity generation.

Crude oil leads the global commodity trade both in terms of mass (close to 1.6 Gt/year during the late 1990s) and value (just over \$200 billion in 1999). Almost 60% of the world's crude oil extraction is now exported from about 45 producing countries and more than 130 countries import crude oil and refined oil products.

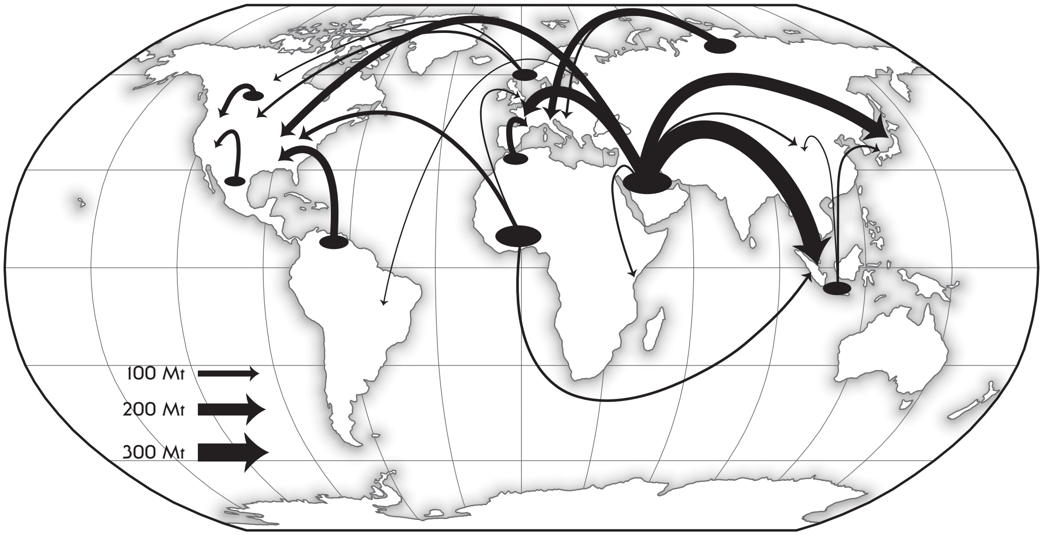


Figure 1.19
Crude oil exports are dominated by flows from the Middle East. Venezuela, Western Siberia, Nigeria, Indonesia, Canada, Mexico, and the North Sea are the other major sources of exports. Based on a figure in BP (2001).

Global dominance of the Middle Eastern exports is obvious (fig. 1.19). The six largest exporters (Saudi Arabia, Iran, Russia, Norway, Kuwait, and the UAE) sell just over 50% of the traded total, and six largest importers (the United States, Japan, Germany, South Korea, Italy, and France) buy 70% of all shipments (BP 2001; UNO 2001). Rapidly rising post-WWII demand for crude oil in Europe and Japan stimulated the development of larger oil tankers. After going up from just over 2,000 dead-weight tons (dwt) to over 20,000 dwt between the early 1880s and the early 1920s, capacities of largest tankers stagnated for over a generation. They took off again only after WWII when the size of largest tankers began doubling in less than 10 years and it reached a plateau in excess of 500,000 dwt by the early 1980s (Ratcliffe 1985; Smil 1994a).

As already noted earlier in this chapter, pipelines are superior to any other form of land transportation. Their compactness (1-m-diameter line can carry 50 Mt of crude oil a year), reliability and safety (and hence the minimal environmental impact) also translate into relatively low cost of operation: only large riverboats and ocean tankers are cheaper carriers of energy. The United States had long-distance pipelines for domestic distribution of crude oil since the 1870s but the construction of pipelines for the export of oil and gas began only after WWII. Large American lines from the Gulf to the East Coast were eclipsed by the world's longest crude oil pipelines laid during the 1970s to move the Western Siberian crude oil to Europe. The Ust′–Balik–Kurgan–Almetievsk line, 2,120 km long and with a diameter of 120 cm, can carry annually up to 90 Mt of crude oil from a supergiant Samotlor oilfield to European Russia and then almost 2,500 km of branching large-diameter lines are needed to move this oil to Western European markets.

Natural gas is not as easily transported as crude oil (Poten and Partners 1993; OECD 1994). Pumping gas through a pipeline takes about three times as much energy as pumping crude oil and undersea links are practical only where the distance is relatively short and the sea is not too deep. Both conditions apply in the case of the North Sea gas (distributed to Scotland and to the European continent) and Algerian gas brought across the Sicilian Channel and the Messina Strait to Italy. Transoceanic movements would be utterly uneconomical without resorting first to expensive liquefaction. This process, introduced commercially during the 1960s, entails cooling the gas to −162 °C and then volatilizing the liquefied natural gas (LNG) at the destination.

Just over 20% of the world's natural gas production was exported during the late 1990s, about three-quarters of it through pipelines, the rest of it as LNG. Russia, Canada, Norway, the Netherlands, and Algeria are the largest exporters of piped gas, accounting for just over 90% of the world total. Shipments from Indonesia, Algeria, and Malaysia dominate the LNG trade. The longest (6,500 km), and widest (up to 142 cm in diameter) natural gas pipelines carry the fuel from the supergiant fields of Medvezh'ye, Urengoy, Yamburg, and Zapolyarnyi in the Nadym–Pur–Taz gas production complex in the northernmost Western Siberia (fig. 1.20) to European Russia and then all the way to Western Europe, with the southern branch going to northern Italy and the northern link to Germany and France.

The largest importers of piped gas are the United States (from Canadian fields in Alberta and British Columbia), Germany (from Siberian Russia, the Netherlands, and Norway), and Italy (mostly from Algeria and Russia). Japan buys more than half of the world's LNG, mainly from Indonesia and Malaysia. Other major LNG importers are South Korea and Taiwan (both from Indonesia and Malaysia), France and Spain (from Algeria). The U.S. imports used to come mostly from Algeria and Trinidad but recent spot sales bring them in from other suppliers.

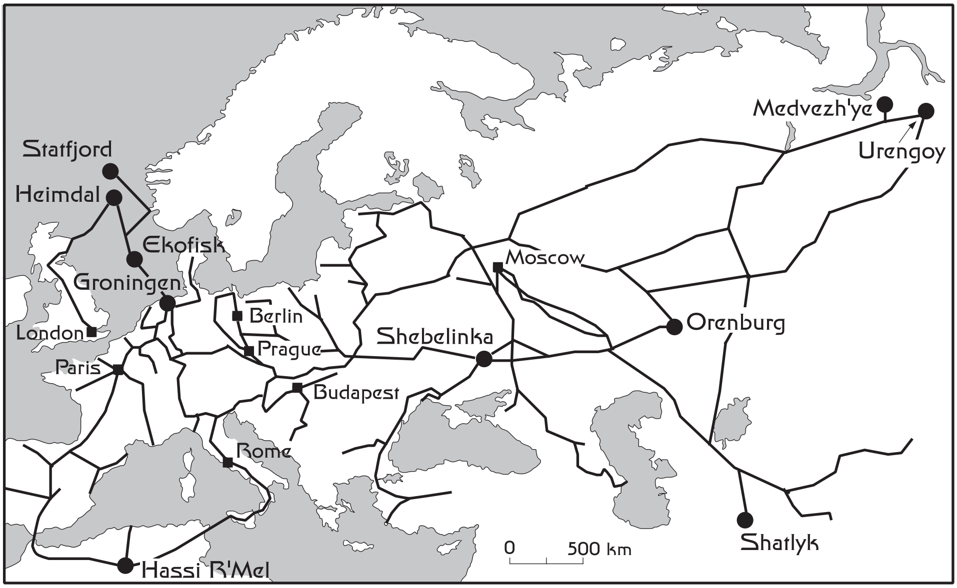


Figure 1.20
The world's longest natural gas pipelines carry the fuel from giant fields in Western Siberia all the way to Western Europe over the distance of more than 4,000 km. Reproduced from Smil (1999a).

In comparison to large-scale flows of fossil fuels the international trade in electricity is significant in only a limited number of one-way sales or multinational exchanges. The most notable one-way transmission schemes are those connecting large hydrogenerating stations with distant load centers. Canada is the world's leader in these exports: during the late 1990s it transmitted annually about 12% of its hydroelectricity from the British Columbia to the Pacific Northwest, from Manitoba to Minnesota, the Dakotas, and Nebraska, and from Québec to New York and the New England states. Other notable international sales of hydroelectricity take place between Venezuela and Brazil, Paraguay, and Brazil, and Mozambique and South Africa. Most of the European countries participate in complex trade in electricity that takes advantage of seasonally high hydro-generating capacities in Scandinavian and Alpine nations as well as of the different timing of daily peak demands.

Combination of continuing abandonment of expensive coal extraction in many old mining regions, stagnation and decline of crude oil and natural gas production in many long-exploited hydrocarbon reservoirs, and the rising demand for cleaner fuels to energize growing cities and industries means that the large-scale trade in fossil fuels and electricity that has contributed so significantly to the transformation of energy use in the twentieth century is yet another trend in the evolution of global energy system that is bound to continue during the twenty-first century.

Consumption Trends

As noted at the beginning of this chapter, the twentieth century saw large increases of not only of aggregate but also of average per capita energy consumption, and these gains look even more impressive when the comparison is done, as it should be, in terms of actual useful energy services. Although the proverbial rising tide (in this case of total energy consumption) did indeed lift all boats (every country now has a higher average per capita TPES than it did a century ago), the most important fact resulting from long-term comparisons of national energy use is the persistence of a large energy gap between the affluent nations and industrializing countries.

High-energy civilization exemplified by jet travel and the Internet is now truly global but individual and group access to its benefits remains highly uneven. Although the huge international disparities in the use of commercial energy had narrowed considerably since the 1960s, an order-of-magnitude difference in per capita consumption of fuels still separates most poor countries from affluent nations, and the gap in the use of electricity remains even wider. There are also large disparities among different socioeconomic groups within both affluent and low-income nations.

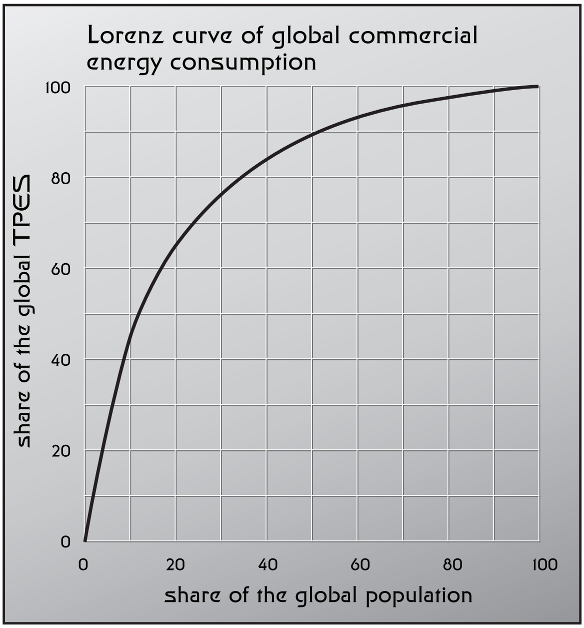
At the beginning of the twentieth century, industrializing countries of Europe and North America consumed about 98% of the world's commercial energy. At that time most of the world's inhabitants were subsistence farmers in Asia, Africa, and Latin America and they did not use directly any modern energies. In contrast, the United States per capita consumption of fossil fuels and hydro electricity was already in excess of 100 GJ/year (Schurr and Netschert 1960). This was actually higher than were most of the national European means two or three generations later, but because of much lower conversions efficiencies delivered energy services were a fraction of today's supply. Very little had changed during the first half of the twentieth century: by 1950 industrialized countries still consumed about 93% of the world's commercial energy (UNO 1976). Subsequent economic development in Asia and Latin America finally began reducing this share, but by the century's end affluent countries, containing just one-fifth of the global population, claimed no less than about 70% of all primary energy.

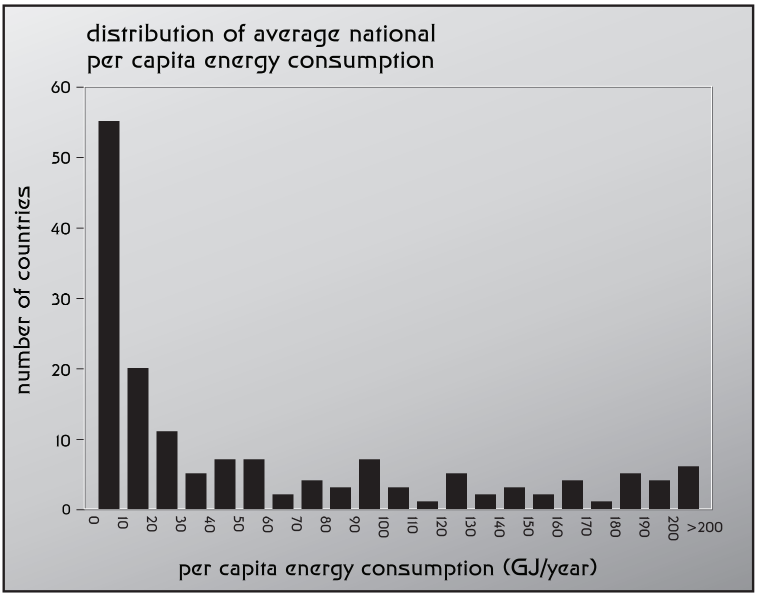
Highly skewed distribution of the TPES is shown even more starkly by the following comparisons. The United States alone, with less than 5% of humanity, consumed about 27% of the world's TPES in 2000, and the seven largest economies of the rich world (commonly known as G7: the United States, Japan, Germany, France, the United Kingdom, Italy, and Canada) whose population adds up to just about one-tenth of the world's total claimed about 45% of the global TPES (BP 2001; fig. 1.21). In contrast, the poorest quarter of mankind—some 15 sub-Saharan African countries, Nepal, Bangladesh, the nations of Indochina, and most of rural India—consumed a mere 2.5% of the global TPES. Moreover, the poorest people in the poorest countries—adding up globally to several hundred million adults and children including subsistence farmers, landless rural workers, and destitute and homeless people in expanding megacities—still do not consume directly any commercial fuels or electricity at all.

National averages for the late 1990s show that annual consumption rates of commercial energy ranged from less than 0.5 GJ/capita, or below 20 kgoe, in the poorest countries of sub-Saharan Africa (Chad, Niger) to more than 300 GJ/capita, or in excess of 7 toe, in the US and Canada (BP 2001; EIA 2001a). Global mean was just over 1.4 toe (or about 60 GJ/capita)—but the previously noted huge and persistent consumption disparities result in the distribution of average national rates that is closest to the hyperbolic pattern rather than to a bimodal or normal curve. This means that the mode, amounting to one-third of the world's countries, is in the lowest consumption category (less than 10 GJ/capita) and that there is little variation in the low frequency for all rates above 30 GJ/capita (fig. 1.21). The global mean consumption rate is actually one of the rarest values with only three countries, Argentina, Croatia, and Portugal, having national averages close to 60 GJ/capita.

Continental averages for the late 1990s were as follows (all in GJ/capita): Africa below 15; Asia about 30; South America close to 35; Europe 150; Oceania 160; and North and Central America 220. Affluent countries outside North America averaged almost 150 GJ/capita (close to 3.5 toe), while the average for low-income economies

Figure 1.21 ►
Two ways to illustrate the highly skewed global distribution of commercial energy consumption at the end of the twentieth century. The first one is a Lorenz curve plotting the national shares of total energy use and showing the disproportionately large claim on the world's energy resources made by the United States and the G7 countries. The second is the frequency plot of per capita energy consumption displaying a hyperbolic shape. Plotted from data in UNO (2001) and BP (2001).


Lorenz curve of global commercial energy consumption
share of the global TPES
share of the global population
0
20
40
60
80
100


distribution of average national per capita energy consumption
number of countries
per capita energy consumption (GJ/year)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
>200

was just 25 GJ/capita (0.6 toe). Leaving the small, oil-rich Middle Eastern states (Kuwait, United Arab Emirates) aside, the highest per capita gains during the second half of the twentieth century were made, in spite of some very rapid population growth rates, in Asia (UNO 1976; UNO 2001). The most notable individual examples are those of Japan (an almost elevenfold gain since 1950) and South Korea (about a 110-fold increase). More than a score of sub-Saharan countries at the opposite end of the consumption spectrum had either the world's lowest improvements or even declines in average per capita use of fuels and electricity.

Formerly large intranational disparities have been greatly reduced in all affluent countries, but appreciable socioeconomic differences remain even in the richest societies. For example, during the late 1990s the U.S. households earning more than U.S. $50,000 (1997)/year consumed 65% more energy than those with annual incomes below U.S. $10,000 (1997) did (U.S. Census Bureau 2002). Large regional difference in household consumption are primarily the function of climate: during the late 1990s the average family in the cold U.S. Midwest consumed almost 80% more energy than those in the warmer Western region (EIA 2001a).

Analogical differences are even larger in low-income economies. During the same period China's annual national consumption mean was about 30 GJ/capita but the rates in coal-rich Shanxi and in the capital Shanghai, the country's richest city of some 15 million people, were nearly 3 times as high and the TPES of the capital's 13 million people averaged about 2.5 times the national mean (Fridley 2001). In contrast, the mean for more than 60 million people in Anhui province, Shanghai's northern neighbor, was only about 20 GJ/capita and for more than 45 million people in landlocked and impoverished Guangxi it was as low as 16 GJ/capita (fig. 1.22). And the differences were even wider for per capita electricity consumption, with the annual national mean of about 0.9 MWh/capita and the respective extremes 3.4 times higher in the country's most dynamic megacity (Shanghai) and 50% lower in its southernmost island province (Hainan).

Household surveys also show that during the late 1990s urban families in China's four richest coastal provinces spent about 2.5 times as much on energy as did their counterparts in four interior provinces in the Northwest [National Bureau of Statistics (NBS) 2000]. Similar, or even larger, differences in per capita energy consumption and expenditures emerge when comparing India's relatively modernized Punjab with impoverished Orissa, Mexico's *maquilladora*-rich Tamaulipas with conflict-riven peasant Chiapas, or Brazil's prosperous Rio Grande do Sul with arid and historically famine-prone Ceará.

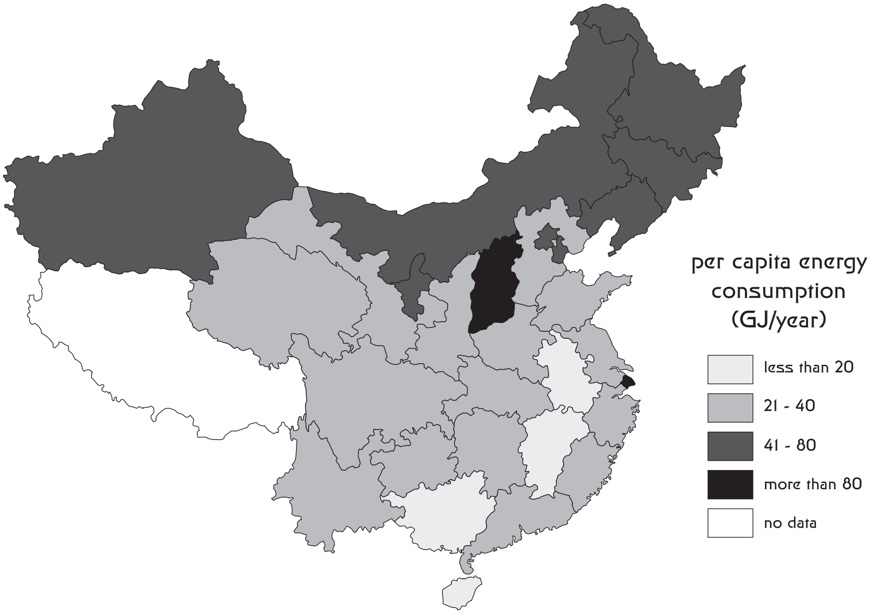


Figure 1.22
In China provincial averages of per capita energy consumption span more than a sevenfold range, from just over 10 GJ/year in Hainan in the tropical south to more than 80 GJ/year in the coal-rich Shanxi in the north. Nationwide annual mean is about 30 GJ/capita. Plotted from 1996 data in Fridley (2001).

Finally, I have to address the changing pattern of final energy uses. Structural transformation of modern economies has brought several major shifts in the sectoral demand for commercial energy. Although universal in nature, these changes have proceeded at a highly country-specific pace. Their most prominent features are the initial rise, and later decline, of the energy share used in industrial production; gradual rise of energy demand by the service sector; steady growth of energy used directly by households, first for essential needs, later for a widening array of discretionary uses; and, a trend closely connected to rising affluence and higher disposable income, an increasing share of energy use claimed by transportation. And although agriculture uses only a small share of the TPES, its overall energy claims, dominated by energies embodied in nitrogenous fertilizers and in field machinery, had grown enormously during the twentieth century, and high energy use in farming now underpins the very existence of modern civilization.

In affluent nations, agriculture, the dominant economic activity of all preindustrial societies, consumes only a few percent of the TPES, ranking far behind industry, households, transportation, and commerce. Agriculture's share in final energy consumption rises when the total amount of fuels and electricity used directly by field, irrigation, and processing machinery is enlarged by indirect energy inputs used to produce machinery and agricultural chemicals, above all to synthesize nitrogen fertilizers (Stout 1990; Fluck 1992). National studies show that in affluent countries during the last quarter of the twentieth century the share of total energy use claimed by agriculture was as low as 3% (in the United States) and as high as 11% in the Netherlands (Smil 1992a). In contrast, direct and indirect agricultural energy uses claimed about 15% of China's TPES, making it one of the major final energy uses in those countries. This is understandable given the fact that the country is now the world's largest producer of nitrogen fertilizers (one-fourth of the world's output) and that it irrigates nearly half of its arable land (Smil 2001; FAO 2001).

The global share of energy used in agriculture is less than 5% of all primary inputs, but this relatively small input is a large multiple of energies used in farming a century ago and it is of immense existential importance as it has transformed virtually all agricultural practices and boosted typical productivities in all but the poorest sub-Saharan countries. In 1900 the aggregate power of the world's farm machinery added up to less than 10 MW, and nitrogen applied in inorganic fertilizers (mainly in Chilean $NaNO_3$) amounted to just 360,000 t. In the year 2000 total capacity of tractors and harvesters was about 500 GW, Haber–Bosch synthesis of ammonia fixed almost 85 Mt of fertilizer nitrogen, fuels and electricity were used to extract, process and synthesize more than 14 Mt P in phosphate fertilizers and 11 Mt K in potash, pumped irrigation served more than 100 Mha of farmland, and cropping was also highly dependent on energy-intensive pesticides (FAO 2001).

I calculated that these inputs required at least 15 EJ in the year 2000 (about half of it for fertilizers), or roughly 10 GJ/ha of cropland. Between 1900 and 2000 the world's cultivated area grew by one-third—but higher yields raised the harvest of edible crops nearly sixfold, a result of more than a fourfold rise of average productivity made possible by roughly a 150-fold increase of fossil fuels and electricity used in global cropping (fig. 1.23). Global harvests now support, on the average, four people per hectare of cropland, compared to about 1.5 persons in 1900. Best performances are much higher: 20 people/ha in the Netherlands, 17 in China's most populous provinces, 12 in the United States on a rich diet and with enough surplus for large-scale food exports (Smil 2000c).

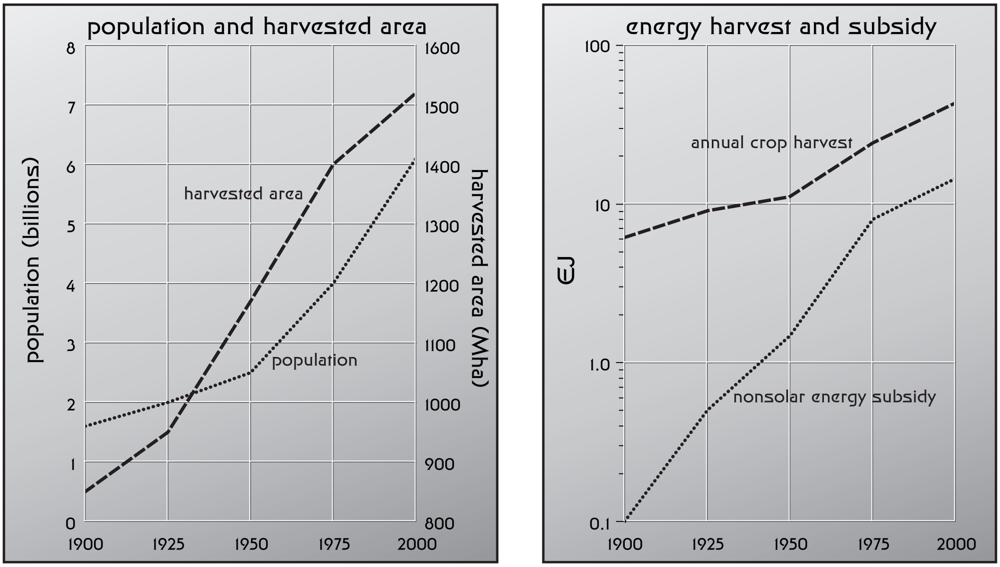


Figure 1.23
One hundred years of agricultural advances are summed up by the trends in harvested area and energy contents of global harvests and nonsolar energy subsidies. Based on Smil (1994a) and unpublished calculations.

In 1900 global crop harvest prorated to just 10 MJ/capita a day, providing, on the average, only a slim safety margin above the minimum daily food needs, and greatly limiting the extent of animal feeding. Recent global harvests have averaged 20 MJ/capita, enough to use a significant part of this biomass (more than 40% globally, up to 70% in the richest countries) for feed. As a result, all affluent nations have surfeit of food (average daily per capita availability in excess of 3,000 kcal) and their diets are extraordinarily rich in animal proteins and lipids. Availability of animal foods is much lower in low-income countries but, on the average and with the exception of chronically war-torn countries, the overall food supply would be sufficient to supply basically adequate diets in highly egalitarian societies (Smil 2000c).

Unfortunately, unequal access to food is common and hence the latest FAO estimate is that between 1996 and 1998 there were 826 million undernourished people, or about 14% of the world's population at that time (FAO 2000). As expected, the total is highly unevenly split, with 34 million undernourished people in the high-income economies and 792 million people in the poor world. The highest shares of undernourished population (about 70% of the total) are now in Afghanistan and

Somalia, and the highest totals of malnourished, stunted, and hungry people are in India and China where dietary deficits affect, respectively, about 20% (total of some 200 million) and just above 10% (nearly 130 million) of all people.

In early stages of economic modernization primary (extractive) and secondary (processing and manufacturing) industries commonly claim more than a half of a nation's energy supply. Gradually, higher energy efficiencies of mineral extraction and less energy-intensive industrial processes greatly reduce, or even eliminate, the growth of energy demand in key industries. As already noted, these improvements have been particularly impressive in ferrous metallurgy and in chemical syntheses. Synthesis of ammonia (the world's most important chemical in terms of synthesized moles; in terms of total synthesized mass ammonia shares the primary position with sulfuric acid) based on the hydrogenation of coal required more than 100 GJ/t when it was commercially introduced in 1913 by the BASF. In contrast, today's state-of-the-art Kellogg Brown & Root or Haldor Topsøe plants using natural gas both as their feedstock and the source of energy need as little as 26 GJ/t NH_3 (Smil 2001; fig. 1.24).

Increasing importance of commercial, household, and transportation uses in maturing economies can be seen in secular trends in those few cases where requisite national statistics are available, or by making international comparisons of countries at different stages of modernization. In the United States the share of industrial energy use declined from 47% in 1950 to 39% in 2000 (EIA 2001a), while in Japan a rise to the peak of 67% in 1970 was followed by a decline to just below 50% by 1995 (IEE 2000). In contrast, industrial production in rapidly modernizing China continues to dominate the country's energy demand: it has been using 65–69% of primary energy ever since the beginning of economic reforms in the early 1980s (Fridley 2001).

Rising share of energy use by households—a trend attributable largely to remarkable declines in average energy prices (see the next chapter for examples of secular trends)—is an excellent indicator of growing affluence. U.S. households now use on-site about 20% of the TPES, compared to 15% in Japan and to only just over 10% in China. Moreover, there has been an important recent shift within this rising demand as nonessential, indeed outright frivolous, uses of energy by households are on the rise. For most of North America's middle-class families these luxury uses began only after World War II, in Europe and Japan only during the 1960s. These trends slowed down, or were temporarily arrested, after 1973, but during the 1990s

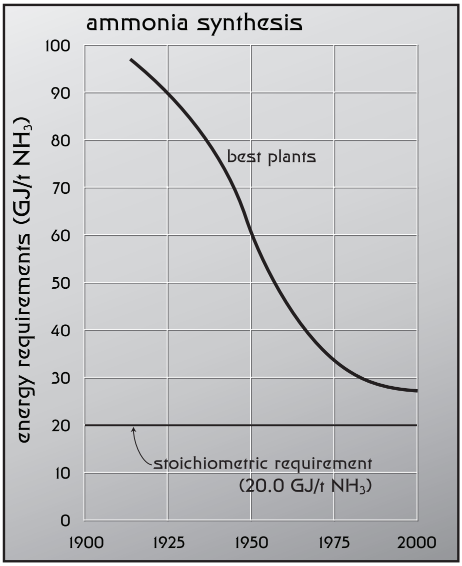


Figure 1.24
Declining energy intensity of ammonia synthesis using the Haber–Bosch process first commercialized in 1913, gradually improved afterward, and made much more efficient by the introduction of single-train plants using centrifugal compressors during the 1960s. From Smil (2001).

they were once again in full flow, energizing the increasingly common displays of ostentatious overconsumption.

Comparisons of electricity use illustrate well this transformation. In 1900 installed capacity of electricity converters in a typical urban U.S. household was limited to a few low-power light bulbs adding up to less than 500 W. Fifty years later at least a dozen lights, a refrigerator, a small electric range with an oven, a washing machine, a television, and a radio in a middle-class house added up to about 5 kW. In contrast, in the year 2000 an all-electric, air-conditioned exurban (i.e., more than 50 km from a downtown) house with some 400 m^2 of living area and with more than 80 switches and outlets ready to power every imaginable household appliance (from a large-capacity freezer to an electric fireplace) can draw upward of 30 kW.

But much more power commanded by that affluent American household is installed in the family's vehicles. Every one of its three cars or SUVs will rate in excess of 100 kW, and a boat or a recreation vehicles (or both, with some of the latter ones equalling the size of a small house), will boost the total power under the household's control close to half of 1 MW! This total is also being enlarged by a proliferation of outdoor energy converters, ranging from noisy gasoline-fueled leaf blowers to massive natural gas-fired pool heaters. Equivalent power—though nothing like the convenience, versatility, flexibility, and reliability of delivered energy services—would have been available only to a Roman *latifundia* owner of about 6,000 strong slaves, or to a nineteenth-century landlord employing 3,000 workers and 400 big draft horses. A detailed survey of the U.S. residential energy use shows that in 1997 about half of all on-site consumption was for heating, and just over one-fifth for powering the appliances (EIA 1999a). But as almost half of all transportation energy was used by private cars the U.S. households purchased about one-third of the country's TPES.

Energy use in transportation amounted to by far the largest sectoral gain and most of it is obviously attributable to private cars. In 1999 the worldwide total of passenger cars surpassed 500 million, compared to less than 50,000 vehicles in 1900, and the grand total of passenger and commercial vehicles (trucks and buses) reached nearly 700 million (Ward's Communications 2000). U.S. dominance of the automotive era had extended almost across the entire century. In 1900 the country had only 8,000 registered vehicles but 20 years later the total was approaching 10 million; in 1951 it surpassed 50 million (USBC 1975). By the century's end it reached 215 million, or 30% of the world total, but the European total was slightly ahead (fig. 1.25).

Passenger travel now accounts for more than 20% of the TPES in many affluent countries, compared to just around 5% in low-income countries. Although the U.S. ownership of passenger cars (2.1 persons per vehicle in 2000) is not that much higher than in Japan (2.4), it is the same as in Italy and is actually lower than in Germany (2.0), the United States remains the paragon of car culture. This is because the mean distance driven annually per American vehicle is considerably longer than in other countries and, incredibly, it is still increasing: the 1990s saw a 16% gain to an average of about 19,000 km/vehicle (EIA 2001a). Average power of U.S. cars is also higher and the annual gasoline consumption per vehicle (about 2,400 L in 2000 compared to 580 L in 1936, the first year for which the rate can be calculated) is commonly 2 to 4 times as high as in other affluent nations. As a result, the country uses a highly disproportionate share of the world's automotive fuel consumption. In 1999 energy content of its liquid transportation fuels (almost 650 Mtoe) was 25%

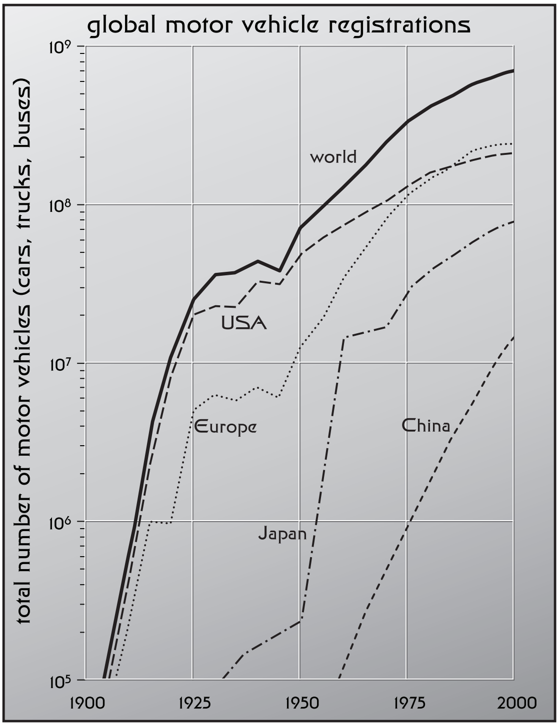


Figure 1.25
Global, United States, European, and Japanese vehicle fleets, 1900–2000. European totals of passenger cars, trucks, and buses surpassed the U.S. vehicle registrations during the late 1980s. Based on a figure in Smil (1999a) with additional data from Ward's Communications (2000).

higher than Japan's *total* primary energy consumption, and it amounted to more than 7% of the global TPES (EIA 2001a; BP 2001).

In contrast to the automobile traffic that has shown signs of saturation in many affluent countries during the 1990s, air travel continued to grow rapidly during the twenty-first century's last decades. Passenger-kilometers flown globally by scheduled airlines multiplied about 75 times between 1950 and 2000 (ICAO 2000)—but in the United States a combination of better engine and airplane design nearly doubled the average amount of seat-kilometers per liter of jet fuel between 1970–1990 (Greene 1992). As with so many other forecasts, any predictions of long-term growth rates of the global aviation will depend on September 11, 2001 being either a tragic singularity or the first in a series of horrific terrorist attacks.

Looking Back and Looking Ahead

Beginnings of new centuries, and in this case also the start of a new millennium, offer irresistible opportunities to look back at the accomplishments, and failures, of the past 100 years and to speculate about the pace and form of coming changes. The next chapter of this book is an extended argument against any long-range particular quantitative forecasting, and even a perfect understanding of past developments is an insufficient guide for such tasks. At the same time, recurrent patterns and general trends transcending particular eras cannot be ignored when outlining the most likely grand trends and constructing desirable normative scenarios. Many energy lessons of the twentieth century are thus worth remembering.

Slow substitutions of both primary energies and prime movers should temper any bold visions of new sources and new techniques taking over in the course of a few decades. The first half of the century was dominated by coal, the quintessential fuel of the previous century, and three nineteenth-century inventions—ICE, steam turbine, and electric motor—were critical in defining and molding the entire fossil fuel era, which began during the 1890s. In spite of currently fashionable sentiments about the end of the oil era (for details see chapter 4), or an early demise of the internal combustion engine, dominant energy systems during first decades of the twenty-first century will not be radically different from those of the last generation.

Because of hasty commercialization, safety concerns, and unresolved long-term storage of its wastes, the first nuclear era has been a peculiarly successful failure, not a firm foundation for further expansion of the industry. And in spite of being heavily promoted and supported by public and private funding, contributions of new nonfossil energy sources ranging from geothermal and central solar to corn-derived ethanol and biogas remain minuscule on the global scale (see chapter 5 for details). Among new converters only gas turbines have become an admirable success in both airborne and stationary applications, and wind turbines have been improved enough to be seriously considered for large-scale commercial generation. Photovoltaics have proved greatly useful in space and in specialized terrestrial applications but not yet in any large-scale generation of electricity.

But the twentieth-century notable lessons go beyond advances in conversions. After all, even a more efficient energy use always guarantees only one thing: higher environmental burdens. Consequently, there remains enormous room for the inverted emphasis in dealing with energy needs—for focusing on deliveries of particular energy services rather than indiscriminately increasing the supply (Socolow

1977). A realistic goal for rationally managed affluent societies is not only to go on lowering energy intensities of their economies but also eventually to uncouple economic growth from the rising supply of primary energy.

And the challenge goes even further. Evolution tends to increase the efficiency of energy throughputs in the biosphere (Smil 1991) and impressive technical improvements achieved during the twentieth century would seem to indicate that high-energy civilization is moving in the same direction. But in affluent countries these more efficient conversions are often deployed in dubious ways. As David Rose (1974, p. 359) noted a generation ago, "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." Addressing this kind of inefficiency embedded in consumer societies will be much more challenging than raising the performance of energy converters.

The task is different in modernizing countries where higher energy supply is a matter of existential necessity. In that respect the twentieth century was also a successful failure: record numbers of people were lifted from outright misery or bare subsistence to a decent standard of living—but relative disparities between their lives and those of inhabitants of affluent nations have not diminished enough to guarantee social and political stability on the global scale. Even when stressing innovation and rational use of energy, modernizing economies of Asia, Africa, and Latin America will need massive increases of primary energy consumption merely in order to accommodate the additional 2–3 billion people they will contain by the year 2050—but expectations based on advances achieved by affluent countries will tend to push the demand even higher.

This new demand will only sharpen the concerns arising from the twentieth-century's most worrisome consequence of harnessing and converting fossil fuels and primary electricity—from the extent to which our actions have changed the Earth's environment. We have managed to control, or even to eliminate, some of the worst local and regional effects of air and water pollution, but we are now faced with environmental change on a continental and global scale (Turner et al. 1990; Smil 1997). Our poor understanding of many intricacies involved in this unprecedented anthropogenic impact requires us to base our actions on imperfect information and to deal with some uncomfortably large uncertainties.

Perhaps the best way to proceed is to act as prudent risk minimizers by reducing the burden of modern civilization on the global environment. As long as we depend heavily on the combustion of fossil fuels this would be best accomplished by striving for the lowest practicable energy flows through our societies. There is no shortage of effective technical means and socioeconomic adjustments suited for the pursuit of this strategy but the diffusion of many engineering and operational innovations will not proceed rapidly and broad public acceptance of new policies will not come easily. Yet without notable success in these efforts the century's most rewarding commitment—to preserve integrity of the biosphere—will not succeed.

These lessons of the twentieth century make it easy to organize this book. After explaining a broad range of linkages between energy and the economy, and environment and the quality of life in chapter 2, I will gather arguments against specific quantitative forecasting and in favor of normative scenarios in chapter 3. Then I will discuss in some detail uncertainties regarding the world's future reliance on fossil fuels (in chapter 4) and opportunities and complications present in the development and diffusion of new nonfossil energies ranging from traditional biomass fuels to the latest advances in photovoltaics (in chapter 5). In the book's closing chapter I will first appraise the savings that can be realistically achieved by a combination of technical advances, better pricing, and management and social changes, then show that by themselves they would not be enough to moderate future energy use and in closing I will describe some plausible and desirable goals. Even their partial achievement would go far toward reconciling the need for increased global flow of useful energy with effective safeguarding of the biosphere's integrity.