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ENERGY IN THE TWENTIETH CENTURY: Resources, Conversions, Costs, Uses, and Consequences

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■ **Abstract** Civilization's advances during the twentieth century are closely bound with an unprecedented rise of energy consumption in general, and of hydrocarbons and electricity in particular. Substantial improvements of all key nineteenth-century energy techniques and introduction of new extraction and transportation means and new prime movers resulted in widespread diffusion of labor-saving and comfort-providing conversions and in substantially declining energy prices. 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 and social accomplishments. International comparisons show a variety of consumption patterns and a continuing large disparity between affluent and modernizing nations. The necessity of minimizing environmental impacts of energy use, particularly those with potentially worrisome global effects, is perhaps the greatest challenge resulting from the twentieth century's energy advances.

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1. HIGH-ENERGY CIVILIZATION

An appraisal of a distinct era of energy developments, and of its environmental and social consequences, may not fit best between the beginning and end of a century—but the just ended century comes comfortably close. A good argument can be made that the nine decades between 1882–1973, from the bold Edisonian beginnings of electric systems to the OPEC's first oil price rise, may be a better choice for delimiting a distinct energy era of fundamental innovations and rapid growth. However, the post-1973 response to OPEC's high prices shaped the late twentieth-century global energy system no less decisively than did the preceding decades of progressively cheaper fuel supply, and the mass diffusions of fundamental late nineteenth-century inventions that defined the twentieth century (from Parsons' steam turbine and Tesla's electric motor to Otto's and Diesel's engines) took place after 1900 (1–3).

An even more persuasive argument to set the beginning of a new energy era at the dawn of the twentieth century is that fossil fuels became dominant sources of the world's primary energy at that time. Although the epochal transition from renewable to fossil energies had proceeded rather rapidly, fossil fuels began supplying more than half of the world's primary energy sometime during the 1890s, when their consumption rose by half, from about 15 to 22 exajoules(EJ)/year (1 EJ $= 10^{18}$ J) (3, 4). A century later, biomass fuels, burned mostly by households and industries in low-income countries, contained about 25 EJ/year—but fossil energies delivered about 320 EJ/year, and primary electricity added 35 gigajoules (GJ)/year (4–7). The twentieth century was thus the first era dominated by fossil fuels, and the 16-fold rise of their use since 1900 created the first high-energy global civilization in human history.

Incessant technical innovation has been by far the most important determinant of this fundamental transformation: It has been responsible for impressive growth of capacities, flexibilities, and efficiencies of energy convertors, as well as advances in exploration, extraction, transportation, and transmission. These developments created new, complex, and ubiquitous infrastructures of electric generation and transmission, seaborne and piped distribution of hydrocarbons, and highway, air, and electronic networks. Declining costs of commercial energies, higher incomes, and less time spent at work have brought an unprecedented degree of personal mobility, while the universal electrification of modern societies has played a critical role in such profound social changes as female emancipation and surfeit of information.

The only way to review and appraise this multitude of epochal changes in a reasonably comprehensive manner within the confines of a single paper is to be selective (concentrating on fundamental trends and on critical shifts) and quasi-telegraphic (leaving much unsaid and unexplained, but providing relevant references), and to bolster key conclusions by vivid examples instead of by offering extended, systematic explanations.

1.1 Unprecedented Growth of Energy Consumption

In spite of the near quadrupling of global population—from 1.6 billion in 1900 to 6.1 billion in 2000 (Table 1)—the average annual per capita supply of commercial energy more than quadrupled from 14 GJ to roughly 60 GJ, or about 1.4 t of oil equivalent (toe) (3, 6, 7). However, because of large national and income disparities (see section 7.1) it is more revealing to quote the means for the world's three largest economies. Between 1900 and 2000 annual per capita energy supply in the United States more than tripled to about 340 GJ/capita (8, 9), and in Japan it more than quadrupled to just over 170 GJ/capita (10). In 1900 China's per capita fossil fuel use was negligible, but between 1950 and 2000 it rose 13-fold from just over 2 to about 30 GJ/capita (11, 12). These gains are even more impressive when expressed in terms of actual energy services rather than by comparing the initial energy content of commercial supply.

Although any global mean can only be approximate, 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. Higher efficiencies of traditional energy convertors, and of new machines and devices introduced since 1900 (see sections 1.2, 3.1, and 3.2), mean that affluent nations now derive twice, or even three times, as much useful energy per unit of primary supply than they did a century ago. Consequently, these economies experienced eight- to twelve-fold increases in per capita supply of energy services during the twentieth century, and the corresponding multiples exceed 20, or even 30, in many industrializing countries. Contrasts between energy flows controlled directly by individuals in the course of their daily activities, and between the circumstances experienced by the users, are no less stunning.

In 1900 even a well-off Great Plains farmer holding the reins of six large horses while plowing his wheat field controlled—with considerable physical-exertion while perched on a steel seat and often enveloped in dust—sustained delivery of no more than 5 kW of animate power (3). A century later his counterpart

TABLE 1 Energy in the twentieth twentieth century: major trends

	Population[a] (10^9)	Primary Energy[b] Consumption (PEC) (EJ)	Shares of PEC[b] Coal (%)	Shares of PEC[b] Oil & Gas (%)	Electricity Generation[b] (TWh)	Carbon Intensity[c] (tC/TJ)	Gross world Product[d] (10^{12} \$1990)	Energy Intensity[e] (MJ/\$1990)
1900	1.6	22	95	5	8	24.3	2.0	11.0
1910	1.7	34	93	7	35	24.1	2.5	13.6
1920	1.8	40	88	11	85	23.3	2.7	14.8
1930	2.1	47	79	20	180	22.2	3.7	12.7
1940	2.3	57	74	25	340	22.6	4.2	13.6
1950	2.5	70	61	37	600	23.0	5.4	13.0
1960	3.0	115	52	46	2,300	22.0	8.5	13.5
1970	3.7	189	34	64	5,000	21.2	3.8	13.7
1980	4.4	250	31	65	8,000	20.6	20.0	12.5
1990	5.3	320	30	61	11,800	18.6	27.4	11.9
2000	6.1	355	26	64	13,500	18.3	32.0	11.1

[a]Data from 7(a).
[b]Data from 4–7.
[c]Carbon emissions from the combustion of fossil fuels (98) divided by the PEC.
[d]Data from 20 supplemented by the latest UN estimates.
[e]PEC/GWP.

driving a large tractor effortlessly controls more than 250 kW while sitting in the air-conditioned and stereo-enlivened comfort of his elevated cabin. 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, the maximum rating of main-line machines permitted by manual stoking of coal (13). In 2000 a pilot of a Boeing 747-400 retracing the same route 11 km above the Earth's surface merely supervises computerized discharge of up about 120 MW at a cruising speed of 900 km/h (2).

1.2 Universal Trends

Increased efficiency of energy conversion was perhaps the most notable universal twentieth-century trend brought about by technical innovation and invention. In 1900 small coal-fired stoves converted generally less than 20% of the fuel to useful heat, and incandescent light bulbs with osmium filaments transformed less than 0.6% of electricity into light; in contrast, the best natural gas–fired household furnaces are now as much 96% efficient, and the best household fluorescent lights are almost 10% efficient (14, 15).

Substantial gains in industrial energy efficiency can be best illustrated by comparing the costs of smelting the twentieth century's most important metal, iron, and of producing one of the world's two leading synthetic compounds, ammonia, whose output during the late 1990s was about as large as that of H_2SO_4 (Figure 1). Smelting of pig iron required at least 60 GJ/t of hot metal in 1900, whereas today's best blast furnaces need less than 20 GJ/t (2, 16). Production of ammonia consumed around 100 GJ/t when it was commercially introduced in 1913 by the Badische Anilin & Soda-Fabrik, whereas today's state-of-the-art Kellogg Brown & Root or Haldor Topsøe plants need as little as 26 GJ/t NH_3 (17).

The higher share of electricity has been the principal reason for a greater convenience and flexibility of energy uses. Very high efficiency of nearly all final uses (only lighting is still generally less than 20% efficient), instant and effortless access, easily adjustable flow that allows high precision, speed and process control, cleanliness and silence at the point of use, and no need for carrying an inventory make electricity a superior choice for all but a few common final energy uses (18, 19). These advantages override inherently high energy losses in thermal electricity generation.

In 1900 less than 2% of the world's fossil fuel production were converted to electricity; by 1950 the share surpassed 10%, and in 2000 it topped 30%. Latecomers to modernization are catching up fast: China's share of fossil fuels converted to electricity surpassed 25% in 1995 (12). In addition, hydro generation, negligible in 1900, and nuclear fission, commercially available since 1956, produced nearly 40% of the world's electricity during the late 1990s (6, 7).

Mass introduction of high-pressure mobile steam engines after 1830 was the first radical change in transportation after millennia of reliance on draft animals and sails. However, only inexpensive refined liquid fuels, reliable internal combustion

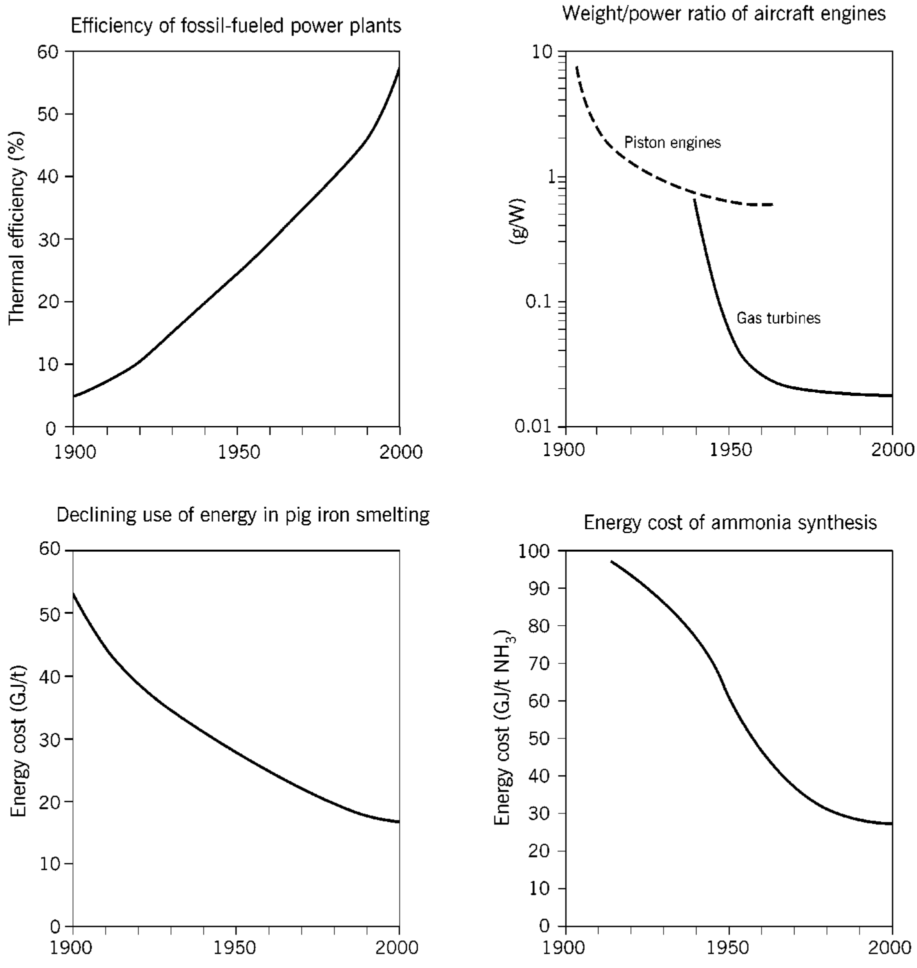

Figure 1 Higher efficiencies of energy conversions transformed the use of fuels and electricity during the twentieth century. The four graphs trace efficiency of best coal-fired electricity-generating plants (including cogeneration), weight/power ratio of aircrat engines, smelting of pig iron in blast furnaces, and synthesis of ammonia from its elements in the Haber-Bosch process. (Modified and updated from original illustrations in 2, 3, 17.)

engines, and even more reliable gas turbines allowed the unprecedented personal mobility that now encompasses distances from 10^0–10^2 km in ubiquitous daily car trips to far less routine, but increasingly common, journeys on commercial jet planes to destinations 10^2–10^3 km away. The 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 (20). At the same time, personal travel consists increasingly of nonessential trips, and more than a third of all international trade involves exchange of very similar goods.

The fourth relentless universal trend characterizing our high energy–use 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 (21). For nearly four decades these innovations were increasingly exploited only for military, research, and business applications; a rapid diffusion among the general population began in the early 1980s, and its pace was speeded up with the mass adoption of the Internet during the 1990s.

2. ENERGY SOURCES: APPRAISALS AND PRODUCTION

Although concerns about the exhaustion of fossil fuels were raised repeatedly during the twentieth century, the actual availability of all fuel reserves continued to grow. Biomass fuels are still essential sources of heat for hundreds of millions of households and for some local industries in low-incomes countries, but the only globally important contributions of nonfossil energies to large-scale commercial supply are hydro and nuclear generation of electricity. The latter endeavor, seen just a generation ago as the leading source of future supplies, has undergone a dramatic devolution in all but a few countries that pioneered its rise, and its contribution to the global energy supply is a small fraction of the total anticipated before 1980.

2.1 Availability of Fossil Fuels

Reserves are small, well-explored shares of total mineral resources in the Earth's crust that can be extracted with available techniques at an acceptable cost; advances in exploration and extraction constantly transfer fossil fuels from the broader, and only poorly known, resource category to the reserve pool (22). Resource exhaustion is thus not a matter of actual physical depletion but rather one of eventually unacceptable costs. The highly dynamic nature of the exploitation process means that although the fossil-fueled civilization is energized by the recovery of finite, nonrenewable resources, it is unlikely that specific exhaustion forecasts will be correct.

In spite of enormous cumulative recoveries during the past century—almost 250 gigatonnes (Gt) of coal, nearly 125 Gt of oil, and more than 60 tera meters^3 of gas—reserve/production (R/P) ratios of all fossil fuels in the year 2000 were substantially higher than in 1900. Coal's R/P ratio of about 230 years (7) and the large amounts of coal resources make the fuel's cost and environmental consequences of its combustion, rather than its availability, the foremost concerns determining its future use. The situation appears to be different for crude oil, as the twentieth century saw many forecasts pinpointing the onsets of irreversible decline of its extraction.

The frequency of these forecasts increased sharply after OPEC's first round of oil price increases. In 1977 the Workshop on Alternative Energy Strategies predicted that oil supply would peak between 1994–1997 and fail to meet rising demand afterwards (23). A year later the U.S. Central Intelligence Agency (24) concluded that the global output "must fall within a decade ahead," and that the world "does not have years in which to make a smooth transition to alternative energy sources." Latest exhaustion forecasts see the decline of conventional oil output setting in before 2010 (25, 26).

Once again, this outcome is not preordained (27). Advances in exploration and in oil recovery have been making available a great deal of new oil from old fields, and technical innovation has been steadily shifting the divide between conventional (liquid) and nonconventional oil resources. In 2000 the global crude oil R/P ratio was about 41 years, higher than for most of the time in its recorded history (2, 7). Also, the world's natural gas reserves are substantially larger than just a generation ago: In spite of the doubled extraction since 1970, global R/P ratios of the late 1990s were above 60 years, compared to just over 40 years in the early 1970s (7).

2.2 Coal's Dominance and Retreat

In 1900 raw coal production of less than 800 Mt of hard coals and lignites supplied about 95% of the world's commercial energy (4; Table 1). Doubling of this extraction before World War II (WWII) was overwhelmingly due to the expansion of traditional manual mining. The post-WWII rise to the peak of nearly 4.9 Gt (about 3.6 Gt of hard coals and 1.3 Gt of lignites) in 1989 (6) was brought about largely by mechanized extraction and by an increasing share of surface operations. Impressive gains in fuel recovery, labor productivity, and occupational safety have accompanied these shifts. Whereas traditional room-and-pillar mining left at least 50% of coal in place, both underground longwall extraction and open cast mining recover over 90% of coal in seams suitable for deployment of these techniques (28).

Productivity of underground mining rose from less than 1 t/man-shift to 4–6 t in highly mechanized mines. Growth of earth-moving machinery (exemplified by electric shovels with dippers over 100 m^3) made it possible to exploit seams under as much as 200 m of overburden, with productivities exceeding 30 t/man-shift. The United States, Russia, Germany, and Australia opened up very large (capacities of 15–50 Mt/year) open cast mines. However, China, the world's largest producer of coal, still gets about 90% of it from underground mines; China also uses more than 80% of it as a raw fuel, although elsewhere nearly all coal is first washed, crushed, and sorted.

In spite of these huge quantitative and qualitative gains, coal's share in the global fuel supply declined to less than 50% by the early 1960s (Table 1). OPEC's oil price rises of the 1970s appeared to make room for coal's come-back—but such hopes

(29) proved unrealistic: In 2000 coal supplied less than 30% of global commercial energy. Affluent countries now use it in just two ways: to generate electricity and to produce metallurgical coke. Almost 60% of U.S. electricity is generated in coal-fired plants (9), with the largest stations located near mines or supplied by unit coal trains (with capacities up to 10,000 t). Worldwide demand for metallurgical coke now amounts to about 10% of extracted hard coal (6). Coal still supplies about 75% of all primary energy and dominates the household market in China.

2.3 Dependence on Hydrocarbons

In 1900 only about 20 Mt of crude oil were extracted worldwide, nearly all of it in a handful of countries. Rapid progress in production followed, thanks to the universal adoption of rotary drilling (a method used for the first time at the Spindletop well in Beaumont, Texas in 1901), and of the rolling cutter rock bit introduced by Howard Hughes in 1909 (30). Refining was transformed by the introduction of high-pressure cracking (after 1913) and of catalytic cracking (in 1936). These processes produce lighter distillates from intermediate and heavy compounds that dominate most crude oils.

Discoveries of the largest Middle Eastern oilfields began during the 1930s and continued for more than two decades: Kuwaiti Burgan, the world's second largest supergiant, was found in 1938, Saudi Ghawar, the world's largest oilfield, a decade later (31). The deepest oil wells surpassed 3,000 m during the 1930s, and in 1947 the first well was completed out of sight of land off Louisiana (30). By 1950 the world consumed just over 500 Mt/year of refined products, which supplied 25% of all primary commercial energy. The next two decades saw a global expansion of the oil market led by rapidly rising European and Japanese imports, and further large increases of oil demand in North America. Maximum tanker sizes, which had changed little since after World War I, began doubling in less than 10 years, culminating in ships of about 500,000 dead-weight tons by the early 1980s, and pipeline diameters grew to more than 50 cm (32).

Hydrocarbon exploration was revolutionized by advances in geophysical prospecting, including three-dimensional imaging of reservoirs and extraction by a widespread use of horizontal drilling (33). Offshore production also moved to deeper, and stormier, waters: After 1980 semisubmersible rigs began working in waters up to 2000 m deep, and production platforms installed at large offshore fields are among the most massive structures ever built (34). The world's longest pipelines were laid during the 1970s to move the Western Siberian crude oil to Europe. Crude oil is now the most important fossil fuel of the maturing fossil-fueled civilization: Global extraction of 3.4 Gt in 2000 provided 40% of the world's commercial energy (6, 7).

Oil's contribution is even more profound than is suggested by its high share of the total supply: Refined fuels provide more than 90% of the world's transportation energy, and claim similar shares of commercial energy supply in dozens of nations that had moved directly from dependence on biomass fuels to reliance on liquid fuels. Although only about 10% of the global hard coal output is traded, almost 60% of the world's crude oil extraction is exported from about 45 producing countries, and more than 130 countries import crude oil and refined oil products. No other commodity is traded so massively (almost 2 Gt/year). The 6 largest exporters (Saudi Arabia, Iran, Russia, Norway, Kuwait, and the United Arab Emirates) sell just over 50% of the traded total, and the 6 largest importers (the United States, Japan, Germany, South Korea, Italy, and France) buy 70% of all shipments (6, 7).

Post-1973 slowdown in oil output growth contrasts with continuing high increases of natural gas extraction that had expanded by about 50% during the century's last two decades (6, 7). This cleanest, and the least carbonaceous, of all fossil fuels now supplies 25% of the world's commercial primary energy. About 20% of the production was exported during the late 1990s, three-quarters of it through pipelines (the largest and longest ones, 2.4 m in diameter and nearly 6500 km long, carry Siberian gas to Western Europe); the rest goes by liquefied natural gas tankers that began moving gas in the 1960s (35). Russia, Canada, The Netherlands, and Norway are the largest pipeline exporters, whereas Indonesia, Algeria, and Malaysia dominate the liquefied natural gas trade. The largest importers of piped gas are the United States, Germany, Italy, and France, whereas Japan, South Korea, and the United States buy most of the liquefied natural gas (6, 7).

2.4 NonFossil Energies

Traditional biomass fuels continued to be a critical source of heat throughout the developing world. During the last two decades of the twentieth century biomass supplied in excess of 80% of fuel for most of sub-Saharan Africa, and 30%–50% in densely populated rural areas of South and East Asia (36–38). Areas of worst biomass fuel deficits include China's arid interior, large parts of the Indian subcontinent, and much of Central America. Building of more than 130 million improved stoves in China demonstrated a large potential for saving biomass fuels in household combustion (39).

A conservative estimate for the poor world's annual phytomass consumption at the end of the twentieth century would be at least 20 EJ (75% of it being woody phytomass), with China, India, Brazil, and Indonesia being the largest consumers. Woody biomass consumed in the rich countries, mostly by lumber, pulp, and paper industries and only secondarily for household heating, added over 5 EJ (14). Global biomass energy consumption in 2000 was thus at least 25 EJ, an equivalent of roughly 8% of worldwide fossil fuel combustion.

Harnessing of hydroenergy by larger and more efficient water wheels and, beginning in 1832, by water turbines was a leading source of mechanical power in the early stages of industrialization. Innovative turbine designs (by Pelton in 1889 and Kaplan in 1920) ensured that water power retained its niche as a major source of electricity in the fossil-fueled world (40). Potentially utilizable global water power capacity is more than 1.1 terawatts (1 terawatt $= 10^{12}$ watts), and by 2000 about 60% of it was harnessed by stations ranging from a few kilowatts to about 150 projects in more than 30 countries with capacities in excess of 1 GW. The largest of these are Brazil's Itaipu with 12.6 GW and China's 18.2-GW Sanxia (under construction); the largest water turbines are in excess of 500 MW, the highest dams surpass 200 m, and the most voluminous reservoirs store more than 100 Gm^3 (41). Global generation of 2.5 petawatthours (1 petawatthour = 10^{15} Wh) in 2000 accounted for just over 20% of all electricity; Canada, the United States, China, and Russia are the largest producers of hydroelectric power, but it is relatively most important in tropical countries, where it accounts for 80%–90% of all electricity (6).

Crude oil price rises in the 1970s engendered huge interest in the possibilities of early, large-scale commercialization of renewable energies ranging from biogas and wind to corn ethanol and photovoltaics. Many detailed appraisals showed immense global and national potentials for these flows, and many neglected or marginal techniques suitable for their harnessing underwent a vigorous research and development renaissance (42–44). However, the overall practical impact of this activity has remained limited. In 2000 small-scale, decentralized renewable conversions (i.e. excluding large hydro generation) contributed a mere 3.5% of the U.S. primary energy supply (9). This is no more than about 10% of the share projected in 1976 by Lovins in his scenario of the soft-energy future for America (45)—but many recent technical advances promise to boost this contribution in future decades.

3. CONVERSION AND DISTRIBUTION TECHNIQUES

Several substantially improved late nineteenth-century inventions—above all, electricity generation and transmission systems, and internal combustion engines—shaped twentieth-century societies. Their diffusion was set back by WWI, as well as by the economic crisis of the 1930s, but WWII accelerated the introduction of three major innovations: nuclear fission, gas turbines, and rocket propulsion. The two decades following WWII saw a rapid growth of all energy systems, but since the late 1960s nearly all of their components—from turbines to transmission voltages, and from tankers to pipeline diameters—reached growth plateaus. Mature markets, excessive unit costs, and unacceptable environmental impacts, rather than technical limits, were the key reasons for this change, as higher efficiency, reliability, and environmental compatibility became the dominant design goals of the last two decades of the twentieth century.

3.1 Improving the Nineteenth-Century Techniques

The steam engine continued to be an important prime mover during the first few decades of the twentieth century, but its inherently low efficiency and high mass/power ratio led to its rapid displacement by electricity in manufacturing, by steam turbines in large stationary applications and marine propulsion, and by internal combustion engines in land and water transport. All of these replacements were late nineteenth-century inventions whose performance was raised, and environmental impacts reduced, by innovation.

Efficiencies of thermal electricity generation (as low as 5% in 1900) were improved by replacing lump coal on moving grates by finely pulverized fuel in multistorey boilers (starting in the 1920s), and by designing larger turbines. Parsons' first 1-MW steam turbine was built in 1900; 100-MW units were not widely used until after 1950, and the first 1-GW unit went on line in 1967 (3). The largest turbines now rate just over 1.5 GW, but units of 200–800 MW are dominant. Today's best plants with cogeneration have conversion efficiencies approaching 60% (46). Transmission losses were cut by using better and larger transformers (their peak capacity grew 500 times during the century), higher voltages (69 kV was typical for main lines of the 1920s, 345 kV by 1970), and direct current links (up to 600 kV) between large plants and major load centers. Creation of national or regional grids improved supply security and reduced the requirements for reserve capacities.

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. Subsequent development of Otto-cycle engines has been remarkably conservative (47). Most important twentieth-century changes included doubling of compression ratios (to 8–9) and declining engine weight: Mass/power ratio fell from more than 30 g/W during the 1890s to just around 1 g/W a century later. Diesels, too, became both lighter (down to 2 g/W) and much more powerful (particularly in stationary applications).

Average U.S. car power ratings and specific fuel consumption kept on increasing until the mid 1970s. Ford's celebrated Model T (1908–1927) rated less than 16 kW, whereas even small cars of the early 1970s had in excess of 50 kW. Average fuel consumption of new passenger cars became as poor as 13.4 miles per gallon (mpg) by 1973. This undesirable trend was finally reversed by OPEC's price hikes: Performance of new cars doubled to 27 mpg by 1987, and by 1990 average fuel consumption of the entire U.S. car fleet surpassed 20 mpg (9, 48). Stagnation of overall efficiency followed as vans, sport utility vehicles, and light trucks, with power often in excess of 100 kW and with performance of just around 20 mpg, became the best-selling vehicles.

3.2 New Prime Movers

The first designs of gas turbines emerged, concurrently and independently, during the late 1930s when Frank Whittle in England and Hans Pabst von Ohain in Germany built experimental engines for military planes (49). Rapid development, spearheaded by military designs, followed after WWII. The speed of sound was surpassed on October 14, 1947, with a Bell X-1 plane; the British Comet became the first (failed) passenger jet in 1951. Boeing's 707 was the first successful commercial jet plane, in 1958, and the plane that revolutionized intercontinental flight, the wide-bodied Boeing 747, entered scheduled service in 1970 (50). Gas turbines also found very important stationary applications by powering centrifugal compressors used in natural gas pipelines, and in chemical and metallurgical industries, and by driving electricity generators (51).

The only prime movers capable of more power per unit of mass than gas turbines are rocket engines. Their large-scale development began with ethanol-powered units used for German missiles during WWII. The superpower rocket race, driven by the quest for more powerful, but also more accurate, intercontinental ballistic missiles, started with the launch of the Earth's first artificial satellite, the Soviet *Sputnik* in 1957. The U.S. Saturn C 5 rocket, which on July 16, 1969, sent the Apollo spacecraft on its journey to the Moon, developed about 2.6 GW during its 150-second burn. The greatest practical impact of rocket propulsion on everyday life has been the launches of scores of spy, communication, global positioning, and Earth-observation satellites (52).

3.3 Nuclear Fission

In retrospect, it is obvious that the commercial development of nuclear generation was far too rushed. The first reactor delivered power in 1956, just 14 years after the sustained chain reaction was demonstrated in Chicago on December 2, 1942 (53). The pressurized water reactor became the dominant type worldwide not because of its superior design, but owing to its early adoption following its initial use on U.S. nuclear submarines (54). The 10 years between 1965 and 1975 saw the greatest number of new nuclear power plant orders. Expert consensus in the early 1970s foresaw a world shaped by ubiquitous and inexpensive nuclear energy (55). A combination of realities turned these forecasts into embarrassing exaggerations.

By the early 1980s a rapid decline in the growth of demand for electricity (from traditional 7%–8%/year to less than 2%, or even to no growth at all), escalating construction costs in the era of high inflation, changing safety requirements, and the unresolved problem of long-term disposal of high-level radioactive wastes checked the industry's growth everywhere in the Western world, with the exception of France. Safety concerns and public perception of intolerable risks were strengthened by an accident at the Three Mile Island plant in Pennsylvania in 1979 (56), and seven years later by a much more serious core meltdown and the release of radioactivity during the Chernobyl disaster in Ukraine (57). By 2000 nuclear fission accounted for about 17% of global electricity (22% in the United States, 70% in France), but prospects for major capacity additions outside China and Japan appear remote.

4. CHANGING ENERGY USES

The structural transformation of modern economies left clear marks on the pattern of energy consumption. Universal sectoral shifts have been unfolding within an overall rise of demand for commercial energy and proceeding at country-specific paces: initial rise, and later decline, of energy shares used in industrial production; gradual rise of energy for services; steady growth of energy used directly by households, first for essential needs, later for discretionary uses; and, a trend closely connected to rising affluence, an increasing share claimed by transportation. Although agriculture directly uses only a small share of total consumption, its overall energy claims, dominated by energies embodied in nitrogenous fertilizers and field machinery, have grown enormously during the twentieth century, and high energy use in farming now underpins the very existence of modern civilization.

4.1 Structural Transformations

Primary and secondary industries may claim over 50% of a nation's energy supply in early stages of economic modernization. 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. These improvements have been particularly impressive in chemical syntheses and in both ferrous and color metallurgy (58). Within these industries there are many individual processes whose energy intensity is, as already indicated by the ammonia and steel examples, a small fraction of their typical 1900 levels.

Rising prominence of commercial, household, and transportation uses in maturing economies can be seen in trends in those few cases where requisite national statistics are available, or by making international comparisons of countries at different stages of modernization. The U.S. share of industrial energy declined from 43% in 1970 to 37% in 2000 (9), while in Japan a rise to the peak of 67% in 1970 was followed by a decline to just below 50% by 1995 (10). In contrast, industrial production in rapidly modernizing China has been using 65%–69% of primary energy ever since the beginning of economic reforms in the early 1980s (12).

The rising share of energy used by households—a trend attributable largely to remarkable declines in average energy prices (see section 5.2)—is an excellent indicator of growing affluence: In the United States it now stands at about 25%, compared to 15% in Japan, and just over 10% in China. Substantial increases in nonessential uses of energy by households are rather recent: For most of North America's middle-class families they began after the WWII, in Europe and Japan, during the 1960s. These trends slowed down, or were temporarily arrested, after 1973, but during the 1990s they were once again in full flow, and they were accompanied by increasingly common displays of ostentatious over-consumption.

Comparisons of electricity use illustrate this transformation well. In 1900 installed capacity of electricity convertors 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 TV, and a radio in a middle-class house added up to about 5 kW. In contrast, a late 1990s all-electric, air-conditioned exurban 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 upwards of 30 kW.

Much more power commanded by that affluent American household is installed in the family's vehicles: Every one of its three cars or sport utility vehicles will rate in excess of 100 kW, and a boat or an RV (or both) will boost the total power under the household's control close to half a MW! 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 6000 strong slaves, or to a nineteenth-century landlord employing 3000 workers and 400 big draft horses.

During the late 1990s the worldwide total of private cars surpassed 500 million, compared to less than 50,000 in 1900. Passenger travel now accounts for more than 20% of the final energy use in many affluent countries (but not in Japan), compared to just around 5% in low-income countries. Whereas car traffic in affluent countries shows signs of saturation, air travel continues to grow rapidly. Passenger-kilometers flown globally by scheduled airlines multiplied about 75 times during the second half of the twentieth century (59)—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 (60).

4.2 Energy in Modern Agriculture

Twentieth-century cropping has been profoundly transformed by fuel and electricity inputs used directly by field machines and by irrigation, and indirectly to produce machinery and agricultural chemicals, above all to synthesize nitrogen fertilizers (61). In 1900 the world's farm machinery had a power capacity of less than 10 MW, and nitrogen applied in inorganic fertilizers (mainly in Chilean $NaNO_3$) amounted to just 360,000 t; in 2000 the total capacity of tractors and harvesters was about 500 GW, Haber-Bosch synthesis fixed about 80 Mt of fertilizer nitrogen, pumped irrigation served more than 100 megahectares of farmland, and cropping was highly dependent on energy-intensive pesticides (62).

These inputs required at least 15 EJ in 2000 (about half of it for fertilizers), or roughly 10 GJ/hectare of cropland. In the United States they translated into a mere 3% of the country's primary energy use, while the share of about 15% is one of China's major final energy uses: China is now the world's largest producer of nitrogen fertilizers, and it irrigates nearly half of its arable land (12, 63). The global share of energy used in agriculture is less than 5% of all primary inputs, but this relatively small input is immensely important. Between 1900 and 2000 the world's cultivated area grew by a third—but higher yields raised the harvest of edible crops nearly six-fold, a result of a more than four-fold rise of average productivity made possible by a roughly 150-fold increase in fossil fuels and electricity used in global cropping.

Global harvest now supports, on the average, 4 people per hectare of cropland, compared to about 1.5 person in 1900. Best performances are much higher: 20

people/hectare in The Netherlands, 17 in China's most populous provinces, 12 in the United States on a rich diet and with large-scale food exports (64). In 1900 global crop harvest prorated to just 10 MJ/capita a day, providing, on average, only a slim safety margin above the minimum daily food needs, and greatly limiting the extent of animal feeding. The recent daily crop harvest mean of 20 MJ/capita secured high meat and dairy diets in all affluent nations and was sufficient, on average, to supply enough food in all but a few low-income countries: Persistent undernutrition, stunting, and hunger must be ascribed to an unequal access to food, not to its physical shortages (65).

5. ENERGY AND THE ECONOMY

Modern economies have depended on incessant flows of fossil fuels and electricity, but the relationship between energy use and economic growth has been both dynamic and complex: It changes with developmental stages, and although it displays some predictable regularities, a closer look reveals many national specificities that preclude any normative conclusions about desirable rates of energy consumption. Simple generalizations are also misplaced as far as energy prices are concerned. Their worldwide decline has been essential for turning fuels and electricity into hidden, mundane commodities whose reliable, abundant, and inexpensive supply is now taken for granted. However, long-term trends appear in a different light once we consider that energy prices have been repeatedly manipulated, and that they largely exclude many health and environmental costs associated with high rates of energy use.

5.1 Complex Links

An impressive correlation is revealed by comparing the global consumption of commercial energy with the best available reconstruction of the world's economic product during the twentieth century [done in constant monies, and using purchasing power parities to convert gross domestic products (GDP)]: Growth rates of both variables coincide almost perfectly, showing an approximately 16-fold increase in 100 years (5, 6, 20). Closeness of the relationship is also revealed by a very high correlation between national GDPs and energy uses for the world's nearly 200 countries: The line of the best fit in an often reproduced scattergram runs diagonally from Laos to the United States. However, the twentieth-century experience also showed that the obvious conclusions based on these correlations are wrong: Economic growth does not have to be supported by virtually identical expansion of energy use, and countries do not have to attain specific levels of energy use to enjoy a high quality of life (66).

Global intensity of economic output was approximately the same in 1900 and 2000, about 11 MJ/(1990)$—but it had not been stable in between: It peaked around 1970, and it had declined since that time by about a fifth (Table 1). These

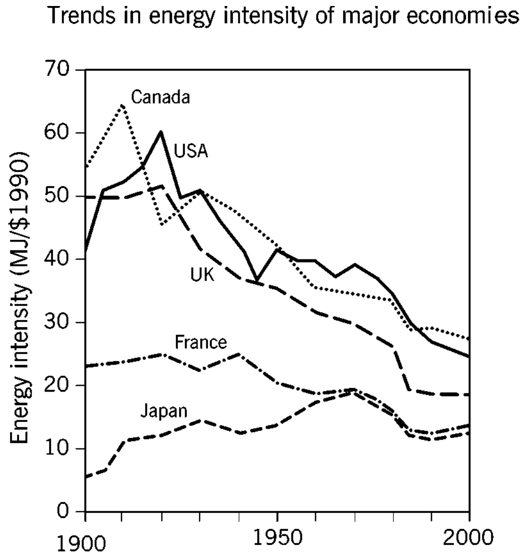

Figure 2 Energy intensities of the world's major economies during the twentieth century. (Calculated from data in 4–7, 20.)

shifts were a product of a complex combination of both concordant and countervailing national trends that follow a broadly universal pattern of transitions but do so at country-specific times and rates. Energy intensities rise during the early stages of industrialization, peak, and then decline as economies use energy more efficiently (Figure 2). However, national ascents and declines may have very different slopes, and peaks can be sharp or can appear as extended plateaus.

The energy intensity of the U.S. economy peaked rather sharply around 1920, and by 2000 it was down by nearly 60%; however, between 1949–1973 it remained stable, a constancy that suggested, wrongly, an immutable long-term link. More remarkably, in spite of very different circumstances, pre-1949 and post-1973 declines were very similar, indicating that autonomous technical advances, rather than prices, are the key reason for higher efficiency (58). In contrast, Japan's twentieth-century record shows a gradual, steady rise of energy intensities until 1970, followed by a wavy decline that brought them about 30% below the peak level by 2000 (10). The energy intensity of China's Maoist economy rose about four-fold between 1950 and 1977—but then, in spite of a very rapid pace of modernization, a combination of structural changes, technical innovation, and conservation drives halved the country's energy intensity between 1978 and 1993 (67).

Clearly, the long-term record shows that energy intensities are not preordained and that they can be altered both by gradual technical change and by determined policies. Disaggregated analyses of GDP and energy use reveal a similarly complex situation as the globally robust energy-economy correlation masks large variations at all levels of economic development. Maximum differences among equally rich countries within the European Union are twofold (i.e. The Netherlands and Austria), and even neighboring countries with virtually identical GDP/capita can be far apart: The Belgian economy of the 1990s was about 30% more energy intensive than the French economy, and, at a very different level of development, China's mid-1990s energy intensity was more than 50% above the Indonesian rate (6, 20).

Key factors behind big differences in national energy intensities are (66) (*a*) country size, (*b*) climate, (*c*) composition of the primary energy supply (coal combustion is inherently less efficient than reliance on hydro electricity), (*d*) degree of energy self-sufficiency (high dependence on highly taxed imports promotes frugality), (*e*) differences in industrial structure (Canada is the world's leading producer of energy-intensive aluminum—while Japan does not smelt primary aluminum at all), and (*f*) discretionary personal consumption of energy (highest in North America). Military demand for energy can also make a large difference: During the 1990s the three U.S. service branches consumed about 25 million tonnes of oil equivalent/year (excluding the Gulf War and Kosovo bombing), more than the total commercial energy consumption of nearly two thirds of the world's countries (6, 9).

5.2 Declining Energy Prices

Where inflation-adjusted series can be reconstructed for the whole century there are impressive secular declines, or at least remarkable constancies, of energy prices, illustrating the combined power of technical innovation, economies of scale, and competitive markets. Electricity became a particularly great bargain during the course of the twentieth century. The earliest available U.S. national average, 15.6 cents/kWh in 1902, would be about $2.50 in 1990 dollars; a decade later the real price was down to $1.12, by 1950 it was about $0.15, and during the late 1990s it was just around $0.06, all in 1990 dollars (9, 68; Figure 3). With quintupled disposable incomes and doubled to tripled efficiency of lights and electric appliances, a unit of useful service provided by electricity in the United States was at least 200, and up to 600 times, more affordable in the year 2000 than it was in 1900!

When expressed in constant monies, the average price of U.S. bituminous coal during the late 1990s was almost exactly the same as in 1950 (or in 1920), and an internationally traded barrel of light Middle Eastern crude was almost exactly as cheap as was the average price of the U.S. crude during the first years of the twentieth century (9, 68; Figure 3). This means that in the United States the actual energy services derived from coal or oil combustion were about 10 times more affordable by the century's end than in 1900. However, it would be naive to see these, and virtually any other twentieth-century energy prices, either as outcomes of free market competition or as values closely reflecting the real cost of energy.

A critical look at the price history of today's most important fossil fuel reveals an extensive, and "universally depressing" (69), record of government intervention

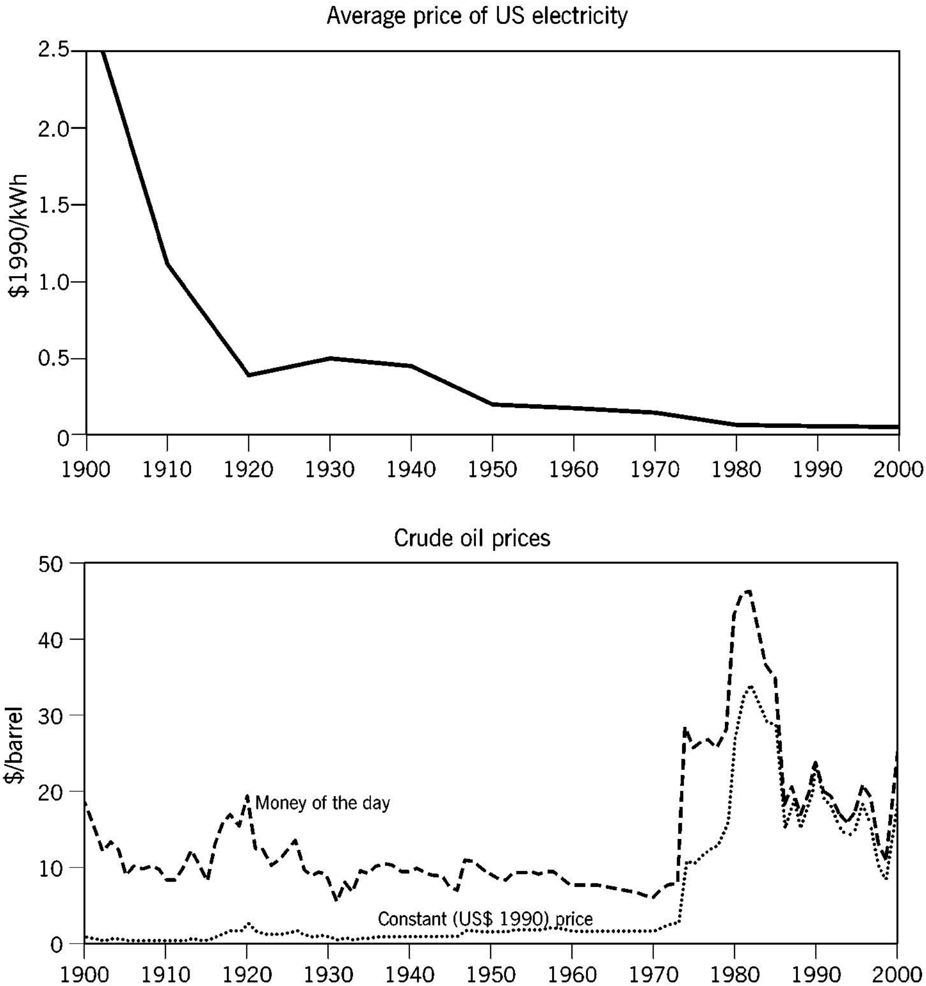

Figure 3 Energy prices expressed in constant monies: average household rates for U.S. electricity, and the price of a barrel of crude oil (U.S. average until 1944; 1945–1985 Arabian light posted at Ras Tanura; 1986–2000 Brent spot). (Based on data in 7, 9, 68.)

in the oil industry. This is true even when leaving notoriously meaningless pre-1991 Soviet prices aside (while the country was the world's largest oil producer!). Until 1971 U.S. oil prices were controlled through prorated production quotas by a very effective cartel (70), the Texas Railroad Commission (TRC). OPEC was set up in 1960 when the foreign producing companies reduced posted crude oil prices; in order to protect their revenue the OPEC members would not tolerate any further reductions of posted prices, an income tax became an excise tax—and "the posted price lost all relation to any market price" (70).

A decade later OPEC countries began raising their excise taxes, and in March 1971 the TRC removed the limits on production: Short-term power to control prices thus shifted from Texas, Oklahoma, and Louisiana to the newly cohesive OPEC. Although there was never any threat of massive physical shortages, production cuts by the OPEC's Arab members (except for Iraq) in October 1973 caused a panicky reaction, and the crude oil price quadrupled within just six months. The second round of oil price increases, a consequence of the fall of the Iranian monarchy and the beginning of Iraq-Iran war, followed in 1979 and 1980, when nominal spot crude prices rose about 3.5 times above their 1974 level, to an average of about $38/barrel of Texas oil (7).

Expectations of further large oil price hikes became the norm (27, 70)—but a combination of lower demand caused by economic recession, conservation efforts, inroads by natural gas, and emergence of substantial non-OPEC oil supplies finally broke the cartel: In August 1985, with prices at about $27/barrel, Saudi Arabia stopped acting as a swing producer, that is limiting crude oil output in order to keep global supply and demand roughly in balance, and a year later prices fell to less than $10/barrel. The Gulf War caused only a temporary price blip (69; Figure 3), and post-1991 prices have been fluctuating in the zone between a monopoly ceiling above $30 and a long-run competitive equilibrium floor that Adelman put at less than $7/barrel (both figures 1990 dollars) (71).

5.3 Real Costs of Energy

Although an excellent argument can be made for even lower prices of energy than those that prevailed during the 1990s, it must also be acknowledged that we do not pay the real costs of fossil fuels and electricity and that the inclusion of numerous externalities would push their prices higher. A long history of governments manipulating energy prices has brought not only unnecessarily higher but also patently lower prices owing to subsidies and special regulations affecting distribution, processing, and conversion of fossil fuels, and generation of electricity. Moreover, most fuel and electricity prices still either ignore, or greatly undervalue, numerous externalities accompanying the production and use of energy.

During the twentieth century, governments provided direct financing, research funds, tax credits, and guarantees to advance and subsidize particular development and production activities, thus favoring one form of energy over others. State-financed building of large dams and decades of generous public funding for nuclear research in many nations, an even longer period of special tax treatment of U.S. oil companies (and more recently of some renewable energies), and nuclear accident liability limits (the Price-Anderson Act) are among the best examples of these price-distorting practices (69, 72, 73). Military expenditures attributable to securing energy supplies have been also considerable. The U.S. Department of Defense estimated the total incremental cost of the Gulf War at $61.1 billion, but the General Accounting Office put it at over $100 billion (74). Even with an incontestable total there is no easy way to attribute these costs to an average barrel of oil.

As for the environmental externalities, the latter half of the twentieth century saw only some of them internalized. Perhaps the most widely known case is the grounding of the *Exxon Valdez* when the company spent directly about $2 billion (1990 dollars) on oil clean-up and paid half as much to the state of Alaska (75). However, the most notable systemic progress has been made by the U.S. coal industry and coal-fired electricity generation. Regulations now prescribe tolerable dust concentrations in mines, and disability and compensation provisions ease the suffering of black-lung disease (76); every coal-fired power plant has electrostatic precipitators (77), and flue gas desulfurization helps to combat acid deposition (78).

As the U.S. National Acid Precipitation Assessment Program showed only a limited damage to lakes and forests (79), it may be argued that the 1990 tightening of SO_x and NO_x emissions goals for coal-fired power plants already tipped the balance in the direction of excessive controls (69). At the same time, comprehensive inquiries argue that most of the externalities associated with electricity generation have yet to be internalized—but they also acknowledge that fundamental uncertainties regarding their valuation will not make this easy (80). Obviously, much higher externalities would be attributable to the combustion of fossil fuels were we to experience global warming of unprecedented rapidity.

6. ENERGY AND THE ENVIRONMENT

The environmental impacts of producing, moving, processing, and burning coal and hydrocarbons and generating nuclear and hydro electricity embrace an enormous range of undesirable changes. Spectacular accidents—such as the destruction of Chernobyl's unshielded reactor in 1986 (57), or the massive spill of crude oil from the *Exxon Valdez* in 1989 (75)—captured public attention with images of horrifying damage. However, the effects of cumulative gradual changes (such as acidification or eutrophication of ecosystems) are far more worrisome, and the necessity of long-term commitments (disposal of radioactive wastes, reductions of carbon emissions) is far more challenging than dealing with spectacular accidents.

Combustion of fossil fuels has been the largest source of anthropogenic emissions of SO_x and NO_x, whose eventual oxidation produces the sulfates and nitrates responsible for regional and semi-continental acid deposition. In contrast, climate change resulting from emissions of CO_2 (and from releases of other greenhouse gases) will have an indisputably global effect. During the 1990s human interference in the global nitrogen cycle was added to the list of impacts the combustion of fossil fuels is having on the integrity of the biosphere.

6.1 Local and Regional Impacts

Air pollution from combustion of coals and hydrocarbons caused the twentieth-century's most widespread energy-related environmental degradation. The combination of particulate matter (PM) and SO_2 created the classic (London-type) smog that was common in Europe and North America until the 1960s (81). Its marks are greatly reduced visibility, higher frequency of respiratory ailments and, during the most severe episodes (as in London in 1952 or in New York in 1966), increased mortality of infants and elderly with chronic lung and cardiovascular diseases (81). Acid deposition, affecting areas up to about 1000 km downwind from large stationary sources, had the greatest impact on ecosystems in Central and Northern Europe, Eastern North America, and East Asia (79, 82).

Laws to limit ambient air pollution (British Clean Air Act of 1956, U.S. Clean Air Act of 1967), gradual replacement of coal by hydrocarbons, widespread uses of electrostatic precipitators (they can remove in excess of 99% of all PM) beginning in the 1950s, and commercial flue-gas desulfurization of large stationary sources (since the early 1970s) have dramatically lowered PM and SO_2 emissions in all affluent countries (79, 83). These improvements stopped, or even reversed, the decades-long process of environmental acidification whose impact has been particularly severe on sensitive aquatic ecosystems (84). In China, however, very high levels of PM and SO_2 are still common, and the area of acid precipitation is still expanding in that country's southern region (85).

Photochemical smog—generated by complex atmospheric reactions of NO_x, CO, and volatile organic compounds that produce ozone, an aggressive oxidant causing higher incidence of respiratory diseases, reduced crop yields, and damaged forests, rubber, paint, and textiles—is now a more widespread, intractable problem (86). Observed for the first time in Los Angeles in the mid 1940s, it is now a semipermanent or seasonal presence in large cities on every continent. Stationary emissions of NO_x are not easy to control, but since the early 1970s automotive emissions of the three smog precursors have been greatly reduced by installation of catalytic converters (87). With more vehicles, longer travel distances, and more congested traffic these controls merely prevented further deterioration of air quality. Expansion of megacities and of intercity land and air traffic is now creating regional, rather than just urban, photochemical smog problems (88).

Not until the last two decades of the twentieth century did we come to appreciate that indoor air pollution poses often higher health risks than does the outdoor air. High levels of fine PM and carcinogens are especially common in rural areas of poor countries where inefficient combustion of biomass in poorly ventilated rooms commonly leads to chronic respiratory diseases (89). Many modern air-conditioned buildings also have considerable indoor air pollution problems (90).

6.2 Energy and Global Environmental Change

The high probability of relatively rapid atmospheric warming has emerged as the foremost global environmental concern arising from the combustion of fossil fuels. Basic consequences of the process were outlined rather well by Arrhenius just before the end of the nineteenth century (91): a geometric increase in CO_2 producing a nearly arithmetic rise in surface temperatures; minimum warming near the equator, maximum in polar regions, and less warming in the Southern hemisphere. The current period of concern started in 1957 when Roger Revelle and Hans Suess concluded that "human beings are now carrying out a large scale geophysical experiment of a kind that could not have happened in the past nor be reproduced in the future. Within a few centuries we are returning to the atmosphere and oceans the concentrated organic carbon stored in sedimentary rocks over hundreds of millions of years" (92:19).

The first systematic measurements of rising background CO_2 concentrations began in 1958 at two American observatories, Mauna Loa in Hawai'i and the South Pole (93). Expanding computer capabilities made it possible to construct the first three-dimensional models of global climatic circulation during the late 1960s, and their improving versions have been used to forecast changes arising from different future CO_2 levels (94). During the 1980s global climate change studies became increasingly interdisciplinary, and their extensions included a delayed recognition of the importance of other greenhouse gases (CH_4, N_2O, CFCs) and attempts to quantify both hydrospheric and biospheric fluxes and stores of carbon (82).

Key points of broad scientific consensus on all of these matters are best summarized in a series of reports by the Intergovernmental Panel on Climatic Change (95). Although higher atmospheric CO_2 levels would have some beneficial consequences for the biosphere (82, 96, 97), attention has been concentrated on possible, and often indefensibly exaggerated, negative impacts. More disturbingly, practical results in actively moderating greenhouse gas emissions have been meager. Decarbonization of the world's primary energy supply—a 25% decline from about 24 t carbon/terajoule (1 terajoule $= 10^{12}$ J) in 1900 to about 18 t carbon/terajoule in 2000 (Table 1)—has been a consequence of long-term substitutions of coal by hydrocarbons and primary electricity rather than of any concerted action (5, 6, 98).

Although the Kyoto agreement obliges the United States to emit 7% less CO_2 by 2007 than it did in 1990, the country's emissions in the year 2000, responsible for about a fifth of the global total, were well above the 1990 rate (98), and endless rounds of ever more expensive scientific studies, as well as arcane negotiations aimed at eventual global agreements on moderating the emissions of greenhouse gases have not been accompanied by any resolute actions. This is indefensible because there is little doubt that major reductions of greenhouse gas emissions can be achieved with minimal socio-economic costs (99).

During the latter half of the twentieth century the high-energy civilization also began interfering to an unprecedented degree with the global nitrogen cycle (82, 100). Applications of synthetic nitrogen fertilizers and NO_x emissions from fossil fuel combustion are the two largest sources of the anthropogenic enrichment of the biosphere with what is normally a key growth-limiting macronutrient (82). Whereas carbon from fossil fuels (about 6 Gt/year during the late 1990s) is a small fraction of the atmosphere-biosphere exchange (about 150 Gt C/year in each direction) and higher CO_2 levels act as a trigger of global warming, anthropogenic nitrogen flux (about 100 Mt N/year) now rivals the natural terrestrial fixation of this nutrient (82). Obviously, this problem will also require much more effective management.

7. SOCIAL CONSEQUENCES

High-energy civilization 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 have narrowed considerably since the 1960s, an order-of-magnitude difference in per capita consumption of fuels still separates most poor from affluent nations, and the gap in the use of electricity remains even wider. There are also large disparities among different socio-economic groups within both affluent and low-income nations. Whereas per capita energy use is undoubtedly a very good marker of individual and collective well-being, there are no simple linear relationships between that rate and essential measures of rationally defined quality of life. Every one of these links shows unmistakeable saturation levels, often at surprisingly low rates of energy use. This is, of course, a welcome conclusion when contemplating the future of the world's energy supply.

7.1 Persistent Consumption Disparities

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—that is subsistence farmers in Asia, Africa, and Latin America—did not directly use fossil fuels or electricity. In contrast, commercial energy used by affluent households in the U.K. or the United States was already quite considerable: Per capita rates in excess of 150 GJ/year were actually higher than many recent national European means, but with much lower conversion efficiencies, delivered energy services were a fraction of today's supply.

By 1950 industrialized countries still consumed 93% of the world's commercial energy (4). Subsequent economic development of Asia and Latin America reduced this share, but by the century's end affluent countries, containing just 20% of the global population, claimed no less than about 70% of all primary energy; the United States alone, with less than 5% of humanity, consumed about 25% (6). In contrast, the poorest quarter of mankind—some fifteen sub-Saharan African countries, Nepal, Bangladesh, the nations of Indochina, and most of rural India—claimed a mere 2.5%. Moreover, the poorest people in the poorest countries—including subsistence farmers, landless rural workers, and destitute people in expanding megacities—still do not directly consume any commercial fuels or electricity at all.

National averages for the century's end show that annual consumption rates of commercial energy ranged from a mere 0.6 GJ/capita (below 25 kg of oil equivalent) in the poorest countries of sub-Saharan Africa to more than 300 GJ/capita (or about 8 toe) in the United States and Canada (6, 7). The global mean was close to 1.5 toe (60 GJ/capita)— but a sharply bimodal distribution of the world's energy use reflecting the rich-poor divide meant that very few countries (including Argentina and Portugal) were close to this mean. Affluent countries outside North

America averaged almost 150 GJ/capita (close to 3.5 toe), whereas the average for low-income economies was just 25 GJ/capita (0.6 toe).

Formerly large intranational disparities have been greatly reduced in all affluent countries, but appreciable socio-economic and regional differences remain. For example, during the 1990s U.S. households earning more than $75,000/year consumed 75% more energy than those with annual incomes below $50,000 (both in 1993 dollars) (9). Analogical differences are even larger in low-income economies. During the 1990s urban households 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 (12, 67). Similar, or larger, differences emerge when comparing India's relatively modernized Punjab with impoverished Orissa, Mexico's *maquilladora*-rich Tamaulipas with peasant Chiapas, or Brazil's prosperous Rio Grande do Sul with arid Ceara.

7.2 Energy Use and the Quality of Life

The global data set shows highly significant statistical associations between rising per capita energy use and a higher physical quality of life measured by adequate health care, nutrition, and housing—but it also reveals clear saturation levels (2, 66). Life expectancy at birth and infant mortality are perhaps the two best indicators of the physical quality of life: The first variable encompasses long-term effects of nutrition, health-care, and environmental exposures, and the second reflects the impacts of these critical factors on the most vulnerable group. During the late 1990s the longest average national life expectancies (above 70 years) were associated with annual per capita use of at least 40–50 GJ of primary energy—as were infant mortality rates below 40/1000 newborn.

In contrast, increased energy use beyond this range has been associated first with rapidly diminishing improvements of the two variables and then by a near disappearance of any additional gains. Best national rates—combined life expectancies of 75 years and infant mortalities below 1%—prevailed in all countries with per capita energy use of 70 GJ/year, about half of the European mean of the late 1990s, and less than a quarter of the North American average. The same rate of average energy consumption has been associated with literacy in excess of 90% and with a widespread access to higher education (with more than 20% of young adults at post-secondary institutions). Annual consumption of at least 70 GJ/capita thus appears to be a key ingredient—obviously together with effective social organization and with reasonable income distribution—to secure a combination of a high physical quality of life with very good opportunities for intellectual advancement.

Abundant historical evidence shows that energy use above that level is spent overwhelmingly on more ostentatious consumption and more frequent pursuit of high-energy, and often environmentally destructive, pastimes ranging from transcontinental flights to desert casinos to snowmobile runs through national parks. Moreover, abundant food supply and widespread ownership of exertion-saving machines contributed to a veritable epidemic of obesity. In the United

States of the 1990s every third adult was obese, and an astonishing 75% of them had body weights higher than the values associated with the lowest mortality for their height (65). On the other hand, critical social and mental components of a high quality of life—including such intangibles as personal freedoms or satisfying pastimes—do not depend on high energy use. Countless leisure activities need only modest amounts of energy, directly as food for physical exertion or embodied in books, recordings, or tools.

The ideas of personal freedoms were introduced and codified by our ancestors when their energy use was a mere fraction of ours (2). Indeed, the twentieth-century suppression or cultivation of these freedoms had little do to with energy use: They thrived as much in the energy-redolent United States as in energy-poor India, and they were repressed in the energy-rich Stalinist USSR as they still are in energy-scarce North Korea. Higher energy use also does not necessarily enhance feelings of personal and economic security, optimism about the future, and general satisfaction with life. Annual per capita energy use in Germany (175 GJ) is only half, and in Thailand (40 GJ) a mere eighth, of the U.S. rate (340 GJ)—but 1995 polls found that 74% of Germans and Thais were satisfied with their personal life compared to 72% of Americans (101).

8. THE CENTURY'S LEGACY

Many lessons of the twentieth century are 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—the internal combustion engine, the steam turbine, and the electric motor—were critical in defining and molding the entire fossil fuel era that began during the 1890s. In spite of currently fashionable sentiments about the end of the oil era (25, 26, 102), or an early demise of the internal combustion engine, dominant energy systems during the first decades of this century will not be radically different from those of today.

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. In spite of being heavily promoted and supported by public and private funding, contributions of nonfossil energy sources ranging from geothermal and central solar to corn-derived ethanol and biogas remain minuscule on the global scale. Among new convertors 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 (103). Photovoltaics have proved their great usefulness in space and in specialized terrestrial applications but not yet in large-scale generation (103, 104).

However, the twentieth-century's 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 (105) in dealing with energy needs—for focusing on deliveries of particular energy services rather than indiscriminately increasing the supply. A realistic goal for rationally managed affluent societies is not only to go on lowering the energy intensities of their economies, but eventually to uncouple economic growth from the rising supply of primary energy.

The challenge goes even further. Evolution tends to increase the efficiency of energy throughputs in the biosphere (2), and impressive technical improvements achieved during the twentieth century would seem to indicate that high-energy civilization is moving in the same direction. In affluent countries, however, these more efficient conversions are often deployed in dubious ways. As David Rose noted, "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" (106:359). Addressing this kind of inefficiency embedded in consumerist societies will be much more challenging than raising the performance of energy convertors.

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, the 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—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 (80, 97, 107). 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 on the environment. As long as we will 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 to pursue this strategy, but their broad public acceptance will not come easily. Yet without that acceptance this century's most rewarding commitment—to preserve the integrity of the biosphere—will not succeed.

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