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ENERGY TRANSITIONS

History, Requirements, Prospects

Vaclav Smil

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The Book's *Raison d'Être*

The generic meaning of transitions—as passages from one condition or action to another—is quite straightforward and hence readily understood, but adding the energy qualifier complicates the comprehension. Energy, a concept that in itself is notoriously hard to define in an easy intuitive manner, encompasses a veritable universe of states and processes, and that is why the term *energy transitions* deserves some annotation. The focus should be always on a process, not just on its initial and concluding stages, but the most revealing analysis must deal with several key variables and use different measures to trace their change.

There is no formal or generally accepted hierarchy of meanings, but the term *energy transition* is used most often to describe the *change in the composition (structure) of primary energy supply*, the gradual shift from a specific pattern of energy provision to a new state of an energy system. This change can be traced on scales ranging from local to global, and a universally experienced transition from biomass to fossil fuels is certainly its best example. Many specific inquiries are possible within this grand shift: For example, the focus can be on transitions from wood to charcoal in heating, from coal to oil in households and industries, from oil to natural gas in electricity generation, or from direct combustion of fossil fuels to their increasingly indirect use as thermal electricity.

These studies of changing structure of energy supply often focus on the time elapsed between an introduction of a new primary energy source and its rise to claiming a substantial share (arbitrarily defined) of the overall market, or even becoming the single largest contributor or the dominant supplier on a local, national, or global scale. But given an often impressive growth of energy supply over time, close attention should be also given to absolute quantities involved in the transitions as well as to qualitative changes that result in wider availabilities of energies that are more flexible, more efficient, and more convenient to use even as they create substantially lower environmental impacts. Combination of all of these approaches would provide the best understanding of the transition process.

But the study of energy transitions should be also concerned with *gradual diffusions of new inanimate prime movers*, devices that had replaced animal and human muscles by converting primary energies into mechanical power. Focus on the prime movers also brings to the forefront the notion of a transition as a process of successful technical and organizational innovation, and energy transitions can be also studied as specific subsets of two more general processes of technical innovation and resource substitution. I will use all of these approaches in my examination of global and national energy transitions.

There is only one thing that all large-scale energy transitions have in common: Because of the requisite technical and infrastructural imperatives and because of numerous (and often entirely unforeseen) social and economic implications (limits, feedbacks, adjustments), energy transitions taking place in large economies and on the global scale are inherently protracted affairs. Usually they take decades to accomplish, and the greater the degree of reliance on a particular energy source or a prime mover, the more widespread the prevailing uses and conversions, the longer their substitutions will take. This conclusion may seem obvious, but it is commonly ignored: Otherwise we would not have all those repeatedly failed predictions of imminent triumphs of new sources or new prime movers.

And an inherently gradual nature of large-scale energy transitions is also the key reason why—barring some extraordinary and entirely unprecedented financial commitments and determined actions—none of today's promises for greatly accelerated energy transition from fossil fuels to renewable energies will be realized. A world without fossil fuel combustion is highly desirable and (to be optimistic) our collective determination, commitment, and persistence could hasten its arrival—but getting there will exact not only a high financial and organizational cost but also persistent dedication and considerable patience. As in the past, the coming energy transitions will unfold across decades, not years—and a few facts are as important for appreciating energy prospects of modern civilization as is an informed appreciation of this reality. This, in just half a dozen paragraphs, is the book's *raison d'être*.

Units and prefixes used in this book

Units

a	are	area
g	gram	mass
Hz	hertz	frequency
J	joule	energy
K	Kelvin	temperature
L	liter	volume
m	meter	length
m^2	square meter	area
m^3	cubic meter	volume
Mtoe	million t of oil equivalent	energy
N	newton	force
Pa	pascal	pressure
ppm	part per million	concentration
t	tonne (metric ton)	mass
W	watt	power
Wh	watt-hour	energy

Prefixes

h	hecto-	10^2
k	kilo-	10^3
M	mega-	10^6
G	giga-	10^9
T	tera-	10^{12}
P	peta-	10^{15}
E	exa-	10^{18}
Z	zetta-	10^{21}
Y	yotta-	10^{24}

Chapter 1

Energy Systems: Their Basic Properties

Any anthropogenic energy system—that is any arrangement whereby the humans use the Earth's resources to improve their chances of survival and to enhance their quality of life (and, less admirably, also to increase their individual and collective power and to dominate, and to kill, others)—has three fundamental components: natural energy sources, their conversions, and a variety of specific uses of the available energy flows. The simplest systems in the past tapped only a small number of sources by using just one or two kinds of inefficient energy conversions for basic, and mostly precarious, subsistence, while modern systems can draw energy from numerous natural sources, convert them in many (and increasingly efficient) ways and use them in a myriad of ways in order to power complex high-energy societies.

Existence of the earliest hominin foragers was not that different from the survival of scavenging omnivorous animals as their somatic energy (conversion of food into muscle power) was just a segment of naturally cascading energy degradation beginning with solar radiation and ending with the dissipation of heat during walking, running, and gathering food. Our hominin ancestors may have used the first deliberate extrasomatic energy conversion as early as nearly 800,000 years ago by mastering the control of fire (Goren-Inbar et al., 2004). In contrast, modern high-energy societies tap many natural energy stores and flows, convert them by using some astonishingly sophisticated devices, and use them for purposes ranging from intensive food production to rapid long-distance travel. In today's world final per capita energy consumption ranges over two orders of magnitude, from the miseries of the sub-Saharan Africa to the excesses of the richest urban societies of America, Europe, and Asia. And in the most affluent societies even the average per capita energy use is now well beyond the level required for healthy and comfortable living.

All energy systems require infrastructures and their operation consumes considerable amounts of energy. Energy infrastructures comprise not only tangible components (exemplified by high-voltage transmission lines or pipelines) but—in order to extract, store, and process fuels and harness energy flows—they also include intangible organizational and managerial arrangements. Energy cost of energy is obviously a critical determinant of the viability of any energy system as only high-energy returns can create affluent societies with plenty of time left for leisure. These inescapable costs of energy are not measured in energy terms but are monetized as capital and operating costs. In the long run, most energy prices have shown some very impressive declines, particularly when compared in terms of actually delivered energy services (such as the cost of a lumen of light or a passenger-kilometer flown).

All anthropogenic energy systems also create environmental impacts, ranging from locally devastating deforestation to globally worrisome changes of the atmospheric composition, above all the emissions of CO_2, CH_4, SO_2, NO_x, and volatile organic compounds from fossil fuel combustion that have been responsible for increasing tropospheric temperatures, acid deposition, photochemical smog, and higher ground ozone levels. Some of the potentially highly damaging externalities arising from energy conversions have been either completely eliminated or reduced to acceptable levels by resorting to better production techniques and to efficient controls: Surface coal extraction and flue gas desulfurization are two excellent examples. Others, most notably the greenhouse gas emissions, are yet to be factored into the real cost of energy.

And, obviously, all energy systems evolve. During the preindustrial era there were only very slow changes in the composition of the primary energy supply (dominated by biomass fuels) and in the use of prime movers (dominated by human and animal muscles)—but the last two centuries have seen a series of remarkable energy transitions. These changes can be traced (and where statistics allow, be studied in revealing quantitative details) as shifts in the shares of individual fuels and in the origins of electricity generation as well as the adoption and diffusion rates of new prime movers and as new patterns of final energy uses. Scores of books could be consulted to get a more detailed understanding of the matters introduced in this chapter: Fouquet (2008), Smil (2003, 2008), and WEC (2007) might be convenient places to start.

RESOURCES AND PRIME MOVERS

Energies used by human societies can be classified dichotomously according to their origins either as renewable and nonrenewable or primary and secondary. Renewable energies include solar radiation (radiant or electromagnetic energy) and all of its biospheric transformations: plant mass (phytomass) formed by photosynthetic conversion of solar radiation into chemical energy of plant tissues; wind, arising from pressure gradients created by differential heating of the ground; moving water originating in radiation-driven evaporation and precipitation (stream flows) or as wind-driven waves and ocean currents; and the temperature difference between the surface of tropical oceans and dark cold waters below the thermocline (water layer, usually about 200 m thick, whose

temperature fluctuates in contrast to deeper layers that stay at about 4°C). There is yet another renewable flux, the Earth's heat (geothermal energy) generated by the decay of heat-producing isotopes in the planet's crust and by heat rising from its core.

The spectrum of solar radiation contains the shortest gamma rays and x-rays, ultraviolet light (<400 nm), visible wavelengths (400–700 nm), and infrared (>700 nm). Nearly all of the UV wavelengths are screened by the stratospheric ozone layer, almost exactly 30% of the incoming radiation is reflected back to space and 20% is absorbed by the atmosphere; as a result, solar energy reaching the ground is only half of the solar flux in space. Active use of solar energy to generate electricity or to produce hot water is still rather limited, but all buildings have always benefited from passive solar heating, and architectural design can enhance this reality by optimizing the orientation of buildings, ingress of winter rays into rooms, and blocking of summer rays.

Photosynthesis uses only a small part of available wavelengths (principally blue and red light amounting to less than half of the energy in the incoming spectrum) and its overall conversion efficiency is no more than 0.3% when measured on the planetary scale and only about 1.5% for the most productive terrestrial (forest) ecosystems. Phytomass produced by photosynthesis is dominated by carbohydrates and absolutely dry phytomass has a fairly uniform energy density of about 18 MJ/kg; air-dry wood, the most important fuel for household heating and cooking and small-scale manufacturing in all preindustrial societies, contains about 15 MJ/kg, as do various cereal and legume straws and stalks that have been burned by households in arid and deforested regions.

Only a very small part of insolation (no more than 2%) energizes the global atmospheric circulation but the total power of winds generated by this differential heating is a meaningless aggregate when assessing resources that could be harnessed for commercial consumption because the Earth's most powerful winds are in the jet stream at altitude around 11 km above the surface, and in the northern hemisphere their location shifts with seasons between 30° and 70° N. Even at altitudes reached by the hubs of modern large wind turbines (70–100 m above ground) only less than 15% of winds have speeds suitable for large-scale commercial electricity generation. Moreover, their distribution is uneven, with the Atlantic Europe and the Great Plains of North America being the premiere wind-power regions and with large parts of Europe, Asia, and Africa having relatively unfavorable conditions.

Similarly, the total potential energy of the Earth's runoff (nearly 370 EJ, or roughly 80% of the global commercial energy use in 2010) is just a grand sum of theoretical interest: Most of that power can be never tapped for generating hydroelectricity because of the limited number of sites suitable for large dams, seasonal fluctuations of water flows, and the necessity to leave free-flowing sections of streams and to store water for drinking, irrigation, fisheries, flood control, and recreation uses. As a result, the aggregate of technically exploitable capacity is only about 15% of the theoretical power of river runoff (WEC, 2007), and the capacity that could be eventually economically exploited is obviously even lower.

There are four other water-based energy resources: tidal power and, as already noted, wind-driven waves, ocean currents, and the difference in temperature between the warm ocean surface and cold deeper waters. Each of them has a significant overall global potential but none of them is easy to harness. Large-scale tidal projects have remained in the conception/proposal stage for decades, wave-harnessing devices are in their early development stage, there have been no serious attempts to capture the power of major ocean currents, and even in the warmest tropical seas (where the difference between the surface and deep water surpass 20°C) the ocean thermal differences can be tapped for electricity generation only with a very low efficiency and none of a few isolated experiments with such generation had progressed to commercial projects.

Fossil fuels are by far the most important nonrenewable energies: All coals and most hydrocarbons (crude oils and natural gases) are transformations of ancient biomass, buried in sediments and processed by high pressures and temperatures (for millions to hundreds of millions of years), but a significant share of natural gases may be of abiogenic origin. All fossil fuels share the dominant presence of carbon, whose content ranges from nearly 100% in the best anthracite coals to 75% in methane; most common bituminous coals used in electricity generation, as well as most hydrocarbons, contain sulfur (a mere trace in some gases, up to 4% in some coals, with 2% being a common mean). Coals also contain varying shares of incombustible ash and moisture, as well as traces of heavy metals that are also present in many crude oils, and natural gases often contain dissolved nitrogen, water, and hydrogen sulfide.

Energy density of coals ranges from just 8 MJ/kg for low-quality lignites to about 30 MJ/kg for the best anthracites, with most bituminous (steam) coals between 20 and 25 MJ/kg. Crude oils are much more uniform (40–42 MJ/kg), as are the natural gases (mostly between 35 and 40 MJ/m^3). Resources of fossil fuels (their total mass present in the Earth's crust) are not known with a high degree of certainty, and their reserves (that part of resources that is recoverable with existing technical means and at profitable costs) keep changing as new techniques (such as horizontal drilling or steam-assisted recovery of oil from oil sands) lower their extraction cost to the point that previously uneconomical deposits become profitable sources of energies.

Resource recovery and depletion has engendered passionate debates about an imminent peak of global crude oil production, about the eventual magnitude of natural gas resources, and about the durability of coal deposits. What is not in doubt is that a large share of fossil fuel resources will be never exploited because their extraction and conversion would be technically forbidding or exceedingly costly: This is true about thin seams of poor-quality coal located at great depths

as well as about many tiny hydrocarbon reservoirs or very heavy oils or deeply buried oil sands and oil shales. The same conclusion applies to fissionable materials abundant in very low concentrations in many rocks as well as in seawater.

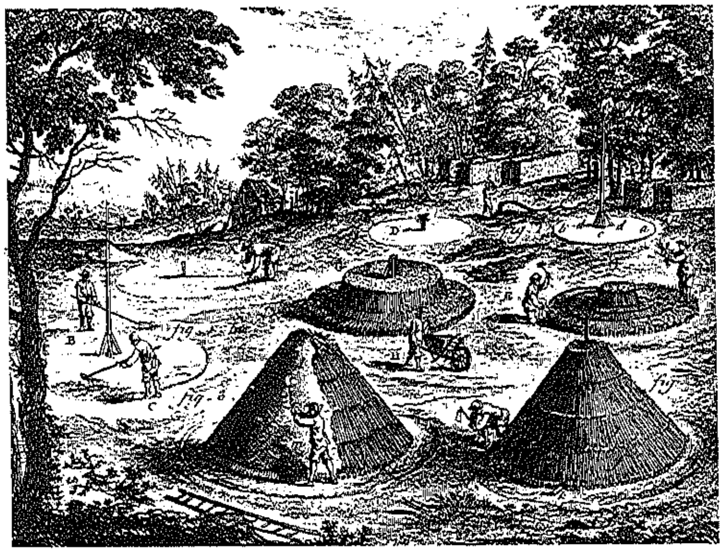
Nuclear energy can be released either by fission of the isotopes of the heaviest natural elements (a process exploited in all nuclear electricity-generating plants) or by fusion of the lightest ones (a process whose commercial realization has been a frustratingly receding mirage). Since the late 1950s uranium fission has been used in commercial nuclear stations to generate electricity by the same means as in fossil-fueled stations (i.e., expanding the pressurized steam in a turbine that rotates a generator). In contrast, there are no fusion-based plants; none are even on a distant horizon and fusion may remain nothing but an ever-receding promise.

Division of energies into primary and secondary categories is based on the method of their production. Primary fuels (stores of chemical energy) are harvested (wood, crop residues) or extracted from the uppermost strata of the Earth's crust (all fossil fuels, including peats, coals, crude oils, and natural gases). Their combustion provides heat (thermal energy) or light (electromagnetic or radiant energy). Their processing to yield secondary fuels may change only their physical state (making solid briquettes by compressing coal dust, with or without binders), but it usually involves chemical transformation.

The only secondary fuel in preindustrial societies was charcoal made by pyrolysis (thermal decomposition in the absence of oxygen) of woody phytomass. With all volatile components driven out, the fuel is virtually pure carbon, nearly smokeless (its well-oxidized combustion produces only CO_2), and with high energy density of almost 30 MJ/kg (see Figure 1.1). Coke, made by high-temperature pyrolysis of coal, was first used in England during the 1640s in malt roasting, but only when its cost declined sufficiently did it begin to replace charcoal as a fuel in blast furnaces by the middle of the eighteenth century, and it has remained the fuel of choice for all primary iron production ever since. During the nineteenth century another secondary fuel—coal gas (town gas or manufactured gas)—became a common urban illuminant (in- and outdoors) as well as a fuel for cooking; it was eventually displaced by electric lights and natural gas, but in some cities its use lingered until after World War II.

Today's most important, as well as by far the most common, secondary fuels are various liquids produced by refining crude oils. Refining was done initially by simple thermal distillation (fractions separated by temperature); now the crude oils are transformed with the help of catalytic cracking used to produce higher shares of gasoline and jet fuel (kerosene), lighter and more valuable fuels that power passenger cars and airliners. Heavier diesel oil is also used to fuel cars but its principal consumer is truck and railways transport, while the heaviest residual oil powers the marine transportation. Diesel oil and residual fuel oil are also used in stationary generation of electricity.

Figure 1.1 Steps in preparing wood piles for charcoaling illustrated in Diderot and D'Alembert's *L'Encyclopédie* (1769–1772).



Commercial electricity generation and transmission added a new dimension to human energy use and, as in the case of fuels, electricity's origin is classified as either primary or secondary. Primary electricity involves all conversions of natural, renewable energy flows including those of water and wind, the Earth's heat, and solar radiation. Primary electricity could also be generated by harnessing ocean waves and the temperature differences between the surface layer of the warmest ocean and constantly cold waters underneath. Nuclear electricity is yet another form of primary energy, with steam for large turbogenerators derived from controlled splitting of uranium. Secondary electricity uses heat released from the combustion of fossil fuels, mainly coal for steam turbogenerators and natural gas for gas turbines.

Prime movers are energy converters able to produce kinetic (mechanical) energy in forms suitable for human uses. Human muscles (somatic energy) were the only prime movers (converting chemical energy in food to kinetic energy of walking, running, and countless manual tasks) until the domestication of animals provided more powerful animate prime movers used in fieldwork, transportation, and for some industrial tasks. Animate prime movers continued to dominate energy use long after the introduction of first mechanical prime movers, beginning with simple sails, followed, millennia later, by small water wheels, and roughly another millennium afterwards by small windmills.

During the eighteenth century the steam engine became the first mechanical prime mover powered by the combustion of fuels. Steam turbine and two key types of internal combustion engines (sparking gasoline-fueled machine and non-sparking engine fueled by heavier fuels or by residual oils) were invented before the end of the nineteenth century, and gas turbine became practical during the 1930s. Electric motors present a classification dilemma: They are, obviously, prime movers in the sense of the definition I offered at the outset of the preceding paragraph, but they are powered by electricity that has been produced by prima facie prime movers, be it steam turbogenerators or gas, water, and wind turbines.

Major criteria used to classify energy uses, as well as the deployment of prime movers, are the location of the conversion process, temperature of the final use, and principal economic sectors. Stationary combustion provides space heating for households, public institutions, and industries, as well as hot air and steam for industrial processes. Stationary prime movers (dominated by steam turbogenerators and water turbines) produce the world's electricity and electric motors and internal combustion engines power most of the modern industrial processes. Heavy horses were the most powerful commonly used mobile prime movers in preindustrial societies. Mobile steam engines, introduced between 1805 and 1835, revolutionized both land and water transportation and dominated the two sectors until the middle of the twentieth century.

Mobile steam turbines were first used in ship propulsion at the beginning of the twentieth century, but marine transport became eventually dominated by diesel engines. Diesels also power heavy road transport and a variety of off-road vehicles, while the automotive gasoline-fueled internal combustion engines emerged as the world's most numerous mobile prime movers. Commercialization of gas turbines began during the late 1930s but their widespread adoption had to wait until the 1960s. Larger stationary machines are used mostly in electricity generation and, starting in the 1950s, lighter and increasingly powerful gas turbines rapidly displaced reciprocating internal combustion engines in long-distance air travel. During the 1980s modified jet engines began to be used also for stationary applications as aeroderivative turbines for peak demand or decentralized electricity generation.

CONVERSIONS AND USES

Modern societies use many forms of energy in order to satisfy many final uses. While there is no single binding classification of the uses that provide individuals, households, cities, and economies with essential energy services, the principal categories include heat, light, industrial (overwhelmingly stationary) power, and freight and passenger transport. All energy conversions involve some loss of the capacity to perform useful work. This is the essence of the second law of thermodynamics: in any closed system (i.e., one without any external supply of energy), availability of useful energy can only decline. Energy remains conserved (the first law of thermodynamics) but its practical utility is diminished because disordered, dissipated low-temperature heat (the final product of all energy conversions) can be never reconstituted as the original, highly organized fuel or electricity. This is an irreversible process, as no action can reconstitute a tank full of gasoline or a truckload of coal from the diffuse heat in the atmosphere.

While such considerations as comfort and convenience are hardly unimportant, the quest for higher conversion efficiencies underlies the evolution of modern energy systems. The simplest definition of energy conversion is as the ratio of output or transfer of the desired energy kind achieved by a converter to the initial energy input (be it to an organism, a mechanical device or a complex system). This rate does not capture the efficiency limitations due to the second law. The second-law (or exergy) efficiency is expressed as the ratio of the least available work that could have performed the task to the available work that has been actually used in performing it. This measure provides a direct insight into the quality of performance relative to the ideal process, and it is concerned with a task to be performed, not with a device or a system used for that end.

As a result, all conversions using high-temperature combustion (flame in excess of 1200°C) to supply low-temperature heat (to pasteurize food at 72°C, to heat bath water to no more than 49°C in order to avoid third-degree burns) will be particularly wasteful when judged in terms of the second-law efficiency. But, as the following examples show, applying that efficiency to many human actions may be actually irrelevant or inappropriate. One of the most efficient ways to produce animal protein is carp aquaculture (as those cold-blooded herbivorous species have inherently low metabolic needs) while the most inefficient way to produce animal protein is beef from cattle fed a mixture of corn and soybeans in a giant feedlot. But most people with good incomes prefer to buy beef, not carp. Similarly, corn is the most efficient staple grain crop—but unlike gluten-rich hard wheat, its flour cannot be used to bake leavened breads. And a periodic bleeding of cattle by Kenya's Maasai is a vastly more efficient means of converting grasses to food than slaughtering cattle for meat—but how many societies would be ready to make such a switch?

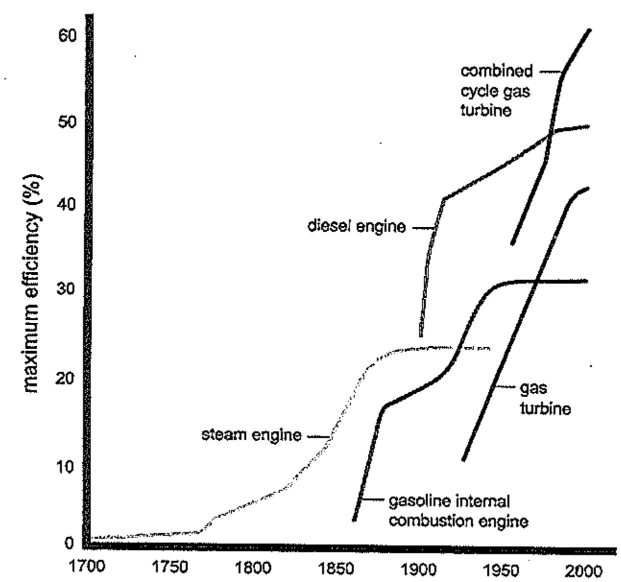
Combustion, that is, rapid oxidation of carbon and hydrogen in biomass and fossil fuels, has been the dominant energy conversion since the early stages of human evolution. For hundreds of thousands of years of hominin evolution it was limited to wood burning in open fires, and combustion of biomass fuels remained the principal means of securing heat and light until the advent of industrialization—and even the most advanced of today's postindustrial societies derive most of their useful energies from the burning of fossil fuels. What has changed, particularly rapidly during the past 150 years, are the typical efficiencies of the process. In open fires less than 5% of wood's energy ended up as useful heat that cooked the food; simple household stoves with proper chimneys

(a surprisingly late innovation) raised the performance to 15–20%, while today's most efficient household furnaces used for space heating convert 94–97% of energy in natural gas to heat.

The earliest commercial steam engines (Newcomen's machines at the beginning of the eighteenth century) transferred less than 1% of coal's energy into useful reciprocating motion—while the best compound steam engines of the late nineteenth century had efficiencies on the order of 20% and steam locomotives never surpassed 10% (see Figure 1.2). The first internal combustion engines (stationary machines powered by coal gas) had lower efficiencies than the best contemporary steam engines, and even today's best-performing gasoline-fueled engines do not usually surpass 25% efficiency in routine operation.

But the very first working prototype of Rudolf Diesel's non-sparking engine (officially tested in 1897) surpassed that rate and the world's largest marine diesel engines are now the only internal combustion machines whose efficiency can reach, and even slightly surpass, 50%. For comparison, today's best gas turbines (used in aviation and electricity generation) are about 40% efficient (Figure 1.2). When the hot gas ejected by large stationary gas turbines is used to heat water for a steam turbine, this combined cycle gas turbine can reach overall efficiency of about 60%. In contrast, the maximum efficiency of coal-fired electricity-generating

Figure 1.2 Maximum efficiency of prime movers, 1700–2000. There has been an order of magnitude gain during the last two centuries, from about 6% for steam engines to about 60% for the combined-cycle gas turbines.



plants using the standard configuration of a boiler and a steam turbogenerator is just over 40%.

Rising efficiency of individual conversions has been reflected in the improving performance of entire economies. As a result, the difference between average per capita energy use in modern and traditional societies is significantly greater when compared in useful terms rather than as the rates of gross energy consumption. For example, thanks to a relatively easy access to extensive and rich forests, the average U.S. wood and charcoal consumption was very high: about 100 GJ/capita in 1860, compared to about 350 GJ/capita for all fossil and biomass fuel at the beginning of the twenty-first century. But as the typical 1860 combustion efficiencies were only around 10%, the useful energy reached only about 10 GJ/capita. Weighted efficiency of modern household, industrial, and transportation conversions is about 40% and hence the useful energy serving an average American is now roughly 150 GJ/year, nearly 15-fold higher than during the height of the biomass era.

Energy uses have undergone some significant changes even during the preindustrial period when most fuels were used by households and in small-scale artisanal manufactures, and when most prime movers were deployed in subsistence agriculture. Expansion of manufactures and metallurgy led to a spreading use of water power (most efficiently by larger vertical water wheels) and iron metallurgy and the preference for smokeless fuel in richer urban homes had also created higher demand for charcoal. Crop rotations including leguminous food and cover crops enabled farmers to divert a greater share of harvests to animal feeding and made it possible to deploy larger numbers of more powerful animals in agriculture.

Industrialization brought a radical change in the composition of national energy use as coal mining, metallurgy, and heavy machinery sectors became eventually the leading consumers of energy, followed by light manufactures (textiles and various consumer items) and a rapidly expanding land and sea transportation. In Europe and North America this shift was accomplished already before 1900. Households claimed a relatively small share of overall energy use during the early phases of industrialization, first only as coal (or coal briquettes) for household stoves, later also as low-energy coal (town) gas, and (starting during the 1880s) as electricity for low-power light bulbs, and soon afterwards also for numerous household appliances.

Subsequently, modern energy use has seen a steady decline of industrial and agricultural consumption and increasing claims of transportation and household sectors. For example, in 1950 industries consumed more than half of the world's primary commercial energy, at the time of the first oil crisis (1973) their share was about one-third, and by 2010 it declined to about 25%. Major appliances (refrigerators, electric stoves, washing machines) became common in the United States after World War I, in Europe only after World War II, and private car ownership followed the same trend. As a result by the 1960s households became

a leading energy-using sector in all affluent countries. There are substantial differences in sectoral energy use among the industrializing low-income nations and postindustrial high-income economies. Even after excluding all transportation energy, U.S. households have been recently claiming more than 20% of the country's primary energy supply in 2006, while in China the share was only about 11%.

But the boundaries of standard sectoral classification can be redrawn to yield a different breakdown. Perhaps most notably, modern agriculture consumes directly only a few percent of the total energy supply as fuels and electricity to operate field machinery (tractors, combines, irrigation pumps) and mostly as electricity for heating, cooling, and machinery used in large-scale animal husbandry. But the indirect energy cost of agricultural production (to produce agricultural machinery, and to synthesize energy-intensive fertilizers, pesticides, and herbicides) and, even more so, energy costs of modern industrial food processing (including excessive packaging), food storage (the category dominated by refrigeration), retailing, cooking, and waste management raise the aggregate cost of the entire food production/distribution/preparation/disposal system to around 15% of total energy supply.

Inevitably, changing sectoral requirements have affected the final uses. Before the advent of extensive steam-driven electricity generation (during the 1890s), coal had four major final uses: as the leading household fuel, as the principal source of both process heat and steam and mechanical power in industries, as the prime energizer of land and water transport, and as the feedstock to produce metallurgical coke needed to smelt pig iron. A century later, coal ceased to be an important transportation fuel, only in a few countries was it still used for household heating and cooking, and its rising use was confined largely to only two markets, the dominant one for electricity generation and a smaller one for coke production.

Similarly, refined oil products were used first as illuminants and lubricants and only the mass ownership of cars (the era that began in the United States with Ford's Model T in 1908) required mass production of gasoline. After World War I diffusion of Diesel's efficient engine in trucking and shipping claimed the heaviest fuel oils, and the post–WWII commercialization of jet engines made kerosene the third most important refined product. And natural gas became the world's premiere source of household heat only after 1950. There were also some notable shifts in non-energy uses of fuels: During the late nineteenth century coal became an important feedstock for chemical industries, but its use was soon displaced by crude oil and natural gas. Currently on the order of 10% of all extracted oil and slightly more than 5% of all natural gas are used as chemical feedstocks, above all for syntheses of ammonia and various plastics.

Another revealing classification that ignores the traditional sectoral divisions is according to the prevailing temperature of final uses. Most energy needs are for low-temperature heat, dominated by space heating (up to about 25°C), hot water for bathing and clothes washing (maxima of, respectively, about 40°C and 60°C), and cooking (obviously 100°C for boiling, up to about 250°C for baking). As already noted, ubiquitous heat waste is due to the fact that most of these needs are supplied by high-temperature combustion of fossil fuels. Steam and hot water produced by high-temperature combustion also account for 30–50% of energy needs in food processing, pulp and paper, chemical and petrochemical industries. High-temperature heat dominates metallurgy, production of glass and ceramics, steam-driven generation of electricity, and operation of all internal combustion engines.

INFRASTRUCTURES AND IMPACTS

Only the simplest harnessing and conversion of energies (gathering of woody debris and its burning in primitive stoves) does not require special infrastructures whose existence must either precede a particular form of energy use or must accompany its expansion. Some early infrastructures could be relatively simple. For example, in the eighteenth century an unpaved road leading to a coal seam outcropping in a previously uninhabited valley would make it possible to bring in the material necessary for opening a small mine and to haul the mined coal in horse-drawn wagons to the nearest settlement. But a large nineteenth century mine would have to be connected to its markets by a railroad, or its coal would be shipped by barges, and the mining of deeper seams could not be accomplished without first installing adequate steam-powered water pumping and ventilation facilities.

Infrastructural needs reached an entirely new level with the exploitation of hydrocarbons whose large-scale extraction requires complex and expensive infrastructures. Pipelines are needed to carry the crude oil and natural gas to markets (or to the nearest coast for overseas exports) and a pretreatment (separation of water, brine, petroleum gases, or hydrogen sulfide) may be required before sending such fuels by a pipeline. When natural gas is used for household heating it is necessary to have voluminous storages to meet high winter peak demand. Crude oil is too valuable a resource to be burned as is and it needs expensive refining that converts it into gasoline, kerosene, diesel oil, residual oil, and non-energy products (lubricants, paving materials).

Electricity generation presents an even more demanding case of infrastructural prerequisites. Not only it is necessary to have extensive networks of transmission and distribution lines in place before any large-scale generation can take place, it is also necessary to have large numbers of converters (lights, appliances, electric motors, electric furnaces, electrochemical processes) ready to use the delivered electricity. Consequently, size of electricity-generating stations has been driven by rising demand—and it has been also constrained by the existing (and anticipated) load. For example, the maximum size of turbogenerators in

the U.S. thermal stations stopped growing (and the average size had actually declined) as the demand weakened during the 1970s. Perhaps the most exacting infrastructural challenge has been presented by the exports of liquefied natural gas (LNG). High costs of liquefaction plants, LNG tankers, and regasification facilities mean that the economies of scale dictate the construction of a system capable to deliver at least a million tonnes of gas a year.

Energy systems have also become more interdependent and their integration has been steadily expanding. Preindustrial energy systems were just patchworks of independent entities. Their spatial extent could have been as small as a village that relied on nearby forests and on crop residues for all of its fuel and feed needs and that produced virtually all of its food by growing a variety of crops in rotations. Modernization began to enlarge the boundaries of energy systems, first with railway and shipborne transport of coal, then with increasingly large-scale production of industrial manufactures that were traded not only nationwide but even overseas and with adoption of simple agricultural machines.

Today's energy system is truly global, with nearly 50 countries exporting and almost 150 nations importing crude oil (and with nearly as many trading refined oil products), with more than 20 states involved in natural gas sales (either by cross-border pipelines or by using tankers carrying liquefied gas), and with nearly a dozen major coal importers and a similar number of countries with substantial coal imports. Electricity is traded relatively less than coal, but even so at least two dozen countries have interconnections of sufficient capacity to carry on exchanges on a GW scale. Moreover, there are no national autarkies as far as extraction, transportation, and processing of energy is concerned: Mining machinery, oil and gas drilling rigs, pipelines, tankers, and coal-carrying vessels and refineries are designed and made by a relatively small number of producers in about a score of countries and used worldwide.

And design and production of the most powerful prime movers have seen an even greater degree of concentration, with as few as two or three companies dominating the global market. All of the world's largest marine diesel engines that power virtually all large commercial vessels (oil and gas tankers, bulk carriers, container ships) come from the duopoly of MAN Diesel and Wärtsilä (and the companies license their engines to a small number of makers in Europe and Asia) and all of the world's most powerful jet engines are designed and made by America's General Electric and Pratt & Whitney and Britain's Rolls-Royce, or by alliances of these companies.

Because of energy's central place in nature and in human affairs it is inevitable that the massive burning of fossil fuels, fissioning of uranium, and capture of renewable energy flows have many profound consequences for the performance of economies and for the state of the environment, and hence for the overall quality of life. Consequently, it is incredible that energy has never been a primary, not even a major, concern of modern economic inquiry. This also helps to explain why modern societies began to deal with widespread environmental impacts of energy use only after World War II. Modern studies of energy–economy links have uncovered some broad commonalities that have marked the path from traditional to industrial to postindustrial societies—but they are perhaps no less notable for revealing many singularities and peculiarities. Environmental impacts of energy use are often so difficult to appraise because there can be no generally acceptable metric for valuing their consequences for biota, climate, and human health.

Global growth of primary energy consumption has corresponded fairly closely to the expansion of the world's economic product: During the twentieth century a roughly 17-fold expansion of annual commercial energy use (from about 22 to approximately 380 EJ) produced a 16-fold increase of annual economic output, from about $2 to $32 trillion in constant 1990 dollars (Maddison, 1995; World Bank, 2001). Similarly close relationship is revealed by studying historical statistics of many individual countries—but comparisons among the countries clearly indicate that a given level of economic development does not require an identical, or not even very similar, level of the total primary energy consumption. This is true among low-income economies as well as among affluent nations: France has certainly a much higher standard of living than Russia even though the two countries consume primary energy at a very similar per capita rate.

Fewer exceptions are found as far as the secular decline of average energy intensity (energy use per unit of GDP) is concerned. That rate's rise during the early stages of industrialization (reflecting energy needs for new industrial and transportation infrastructures) is usually followed by a prolonged decline. The British peak came early in the nineteenth century, the U.S. and Canadian peaks followed six to seven decades later—but Japan reached its highest energy intensity only in 1970, and China's energy use per unit of the country's GDP continued to rise until the late 1970s but since that time the Chinese rate has fallen faster than in any previous case: By 1990 it was 40% below the 1980 level, and by 2005 the decline reached just over 70% (Fridley et al., 2008). But comparisons of national energy intensities and their secular trends require careful interpretation because their differences are caused by factors ranging from climate to consumer preferences, with the composition of primary energy consumption and the structure and efficiency of final conversions as key factors.

Countries with harsh climate, generously sized houses, large territories, and numerous energy-intensive industries will have relatively high national energy intensities even if their specific energy conversions are highly efficient, while countries undergoing modernization will have much higher intensities than postindustrial economies. These realities help to explain why, for example, Canada's energy intensity is more than twice as high as that of Italy, and China's intensity is still more than twice that of Japan. Another long-term trend has been the decarbonization of the global energy supply: The relative shift away from coal (usually more than 30 kg of carbon/GJ) to liquid hydrocarbons

(averaging about 20 kg C/GJ) and natural gas (less than 15 kg C/GJ) and rising generation of carbon-free primary electricity had lowered the carbon content of the world's primary energy supply by about 25% during the twentieth century, and the slowly increasing share of renewable conversion will continue to lower that rate.

Technical innovation, economies of scale, and competitive markets have combined to bring some impressive long-term declines of energy prices, particularly when compared to rising disposable incomes or when expressed in terms of value for delivered service. None of these declines has been more impressive than the cost of electricity for lighting traced as constant monies per lumen: Fouquet (2008) found that rising incomes, higher conversion efficiencies, and lower generation costs made the household lighting in the United Kingdom in 2000 about 160 times more affordable than in 1900. In contrast, inflation-adjusted prices of coal and oil do not show a general declining trend but a great deal of fluctuation and a remarkable constancy in the long run. When expressed in constant monies crude oil prices were very low and very stable between the beginning of the twentieth century and the early 1970s, they retreated rapidly after two OPEC-driven price rises of 1973–1974 and 1979–1981, but their recent fluctuations offer no safe foundation for looking ahead.

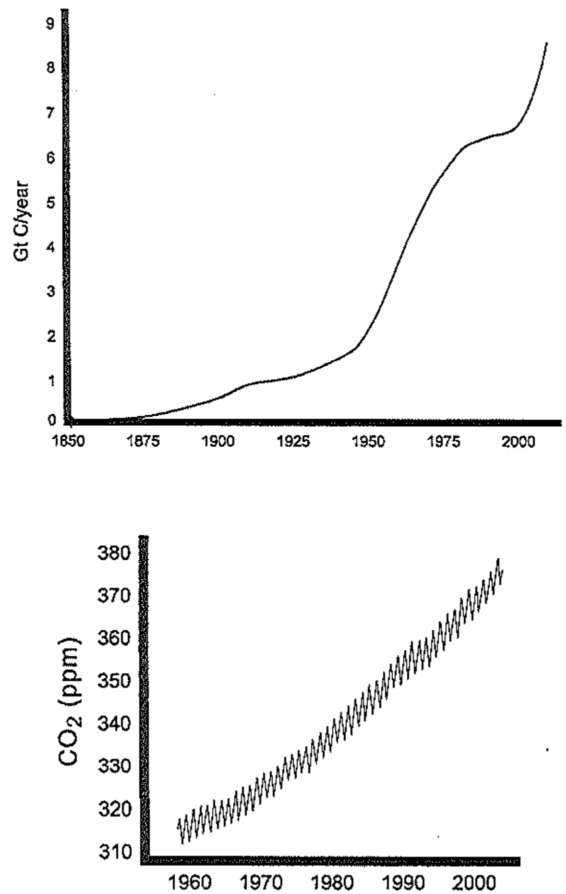
But energy prices have not been usually determined by free-market operation, as energy industries in general (and oil industry and nuclear electricity generation in particular) have been among the greatest beneficiaries of government subsidies, tax breaks, and special regulation. Some prices have been subject to cartel control: In the United States the Texas Railroad Commission fixed prices by allocating production quotas until March 1971, and since 1973 OPEC has used its production quota to manipulate the global crude oil supply. Even more importantly, no energy price expresses the real cost of the delivered service, as the costs of often significant environmental and health externalities are not included in the prices of fuels or electricity.

Internalization of these costs has been done adequately in some cases (electricity cost is higher due to highly efficient capture of particulate matter by electrostatic precipitators and removal of SO_2 by flue gas desulfurization; all modern passenger cars have three-way catalytic converters to reduce NO_x, CO, and volatile organic hydrocarbon emissions) but it remains a challenge in most instances, above all because health effects account for most of the cost but are notoriously difficult to monetize—as are the long-term ecosystemic effects of such complex processes as photochemical smog, acid deposition, nitrogen enrichment, or climate change. Strategic considerations further complicate the quest for the real price of energy: Perhaps most notably, the Pentagon had been devoting a significant share of its budget to the Middle East even before the 1991 Gulf War or before the Iraqi invasion of 2003.

As for the environmental impacts of energy industries and uses, it is clear that the anthropogenic emissions of CO_2 from the combustion of fossil fuels have become one of the most prominent concerns of modern civilization.

Their global total rose from just over 0.5 Gt C in 1900 to nearly 8.5 Gt C by 2007, and they have been the major reason (deforestation, mainly in the tropics, was the second most important contribution) for the rise of tropospheric CO_2 concentration (since 1957 continuously monitored at the Mauna Loa observatory in Hawaii) from about 295 ppm in 1900 to 386 ppm by 2008 (Figure 1.3). This is a truly global phenomenon, as the average tropospheric concentrations rise no matter where the emissions take place. After being the leading emitter for more than a century, the United States was surpassed in 2007 by China (but in per capita terms there is a nearly four-fold difference).

Figure 1.3 Global emissions of CO_2, 1850–2008 (in Gt C/year) and tropospheric CO_2 concentrations, 1958–2008. Plotted from emissions data in Rotty and Marland (2009) and from Mauna Loa concentrations data in NOAA (2009).



Extraction and conversion of energy has many other environmental consequences. Deforestation in the Mediterranean and in North China was the first environmental manifestation of the growing human use of energy as emerging cities and expanding metal smelting (first copper, then iron) needed more wood and charcoal. Underground coal mining created aboveground disturbances (subsidence, mountains of mine spoils) and localized water pollution (acid runoff), but emissions of particulate matter and SO_2 were the most important environmental consequences of coal combustion as the two pollutants often reached very high concentrations in large cities. After 1950 electrostatic precipitators virtually eliminated particulate pollution from large sources but long-distance transport of SO_2 (and also NO_x) created serious regional to semi-continental problems with acid deposition.

Extraction and transportation of crude oil created local water pollution and accidental oil spills, and combustion of refined oil products provided the key starting ingredients (NO_x, CO, and volatile organic compounds) for photochemical smog. Beginning in 1956 generation of electricity by fissioning uranium introduced an entirely new set of environmental problems, ranging from possibilities of accidental contamination to challenges of long-term storage of high-level radioactivity waste. And renewable energy flows have a multitude of their own environmental consequences, ranging from the alterations of water quality and age caused by large dams (lower temperature, water aging behind dams) to problems with esthetic acceptability of large wind turbine farms and with their noise and effect on birds.

ENERGY TRANSITIONS

As this brief review of energy system fundamentals makes clear, there are many components whose importance and performance evolve and hence there are many energy transitions whose origins, progress, and accomplishments can be studied on levels ranging from local to global. Not surprisingly, transitions to new energy sources (be they gradual diffusions of new fuels or new modes of electricity generation) have attracted a great deal of attention and I will quantify the key shifts—from wood and charcoal to coal and then to hydrocarbons, followed by transitions to a higher share of primary energies consumed in a secondary form as electricity—from the global perspective as well as by focusing on some notable national trajectories.

Perhaps even more attention has been paid by the historians of technical advances to the diffusion of new fuel and electricity converters ranging from better stoves and lights to more efficient furnaces and boilers, with particular interest in the evolution and diffusion of new engines and turbines and new electricity-powered motors and appliances. Technical innovation, emergence of new mass energy markets, and a steadily rising demand for more efficient, more affordable, and more flexibly delivered energy services were both the driving factors behind these changes and, thanks to numerous reinforcing feedbacks, also their beneficiaries.

In addition to tracing the transitions to new energy sources and new energy converters it is also revealing to look at the changing uses of individual fuels (most notable, coal losing all of its transportation markets but becoming the leading fuel for electricity generation, and the principal use of refined oil products shifting from illuminants and lubricants to transportation fuels) and at changing patterns of sectoral consumption. The latter shifts are actually an excellent means of tracing a nation's trajectory of modernization and its rise to affluence: Diversification of final commercial energy uses proceeds from the initial pattern dominated by industrial consumption to a combination characterized by the absence of any dominant use, where each of the four key sectors (households, industries, commerce, and transportation) claims a major share of the final demand.

As this book's principal aim is a comprehensive appraisal of energy transitions—on levels ranging from global to national and looking at trends ranging from aggregate provision of primary energies to specific supplies of individual fuels and progress of important conversion techniques—I will use this introductory section only in order to make several general observations by resorting to analogies. When appropriately understood—that is, in an illuminating, suggestive manner and not as rigid templates—analogies are a useful tool to emphasize important features of a complex process. I think that two of them, of widely differing provenience, are particularly relevant to the understanding of energy transitions.

The first one draws on Tolstoy's famous observation (in *Anna Karenina*) regarding families: "Happy families are all alike; every unhappy family is unhappy in its own way." Analogically, notable similarities can be seen when looking at all rapid and apparently easily accomplished energy transitions—while the reasons for prolonged, complicated, and delayed transitions are usually very specific, bound with unique environmental, social, economic, and technical circumstances. Rapidity of energy transitions is most evident when looking at small countries with compact territories that have either relatively few people or a high density of population. No matter if they are affluent economies or still essentially premodern societies with very low per capita economic product, once they discover a new rich source of primary energy they can develop it rapidly and end up with completely transformed energy foundations in less than a single generation.

The Netherlands—thanks to the discovery of a giant Groningen natural gas field in the municipality of Slochteren in the northern part of the country on July 22, 1959 (Whaley, 2009)—is perhaps the most apposite example of an affluent economy following this path (for more detail, see chapter 3), while Kuwait's rapid development of its giant oilfields is an iconic example in the second category. Kuwaiti oil development began only in 1934 with the concession given to the Kuwait Oil Company, a joint undertaking of the APOC (Anglo-Persian Oil Company, later BP) and Gulf Oil. The concessionary agreement was signed after the APOC was assured by an expert it hired to evaluate the country's oil prospects

that "the absence of geological structure suitable for the accumulation of oil in commercial quantity shows that there is no justification for drilling anywhere in Kuwait" (Howard, 2008, p. 152).

At that time that small country (with an area less than half that of the Netherlands) was an impoverished British protectorate with fewer than 100,000 people, a single town, and mostly empty interior with a small number of desert nomads; export of pearls, harvested by diving, was declining and traditional maritime trading (horses, spices, coffee) was the only notable economic activity. The concession was signed on December 23, 1934, and the supergiant al-Burqān oilfield (a Cretaceous sandstone trapped above a massive swell of about 750 km^2 of salt) was discovered on February 23, 1938. The field was later proved to be the world's second largest accumulation of oil, following the Saudi al-Ghawār (Stegner, 2007; Howard, 2008). In 1946, when it began its oil exports, Kuwait produced about 800,000 t of oil, a year later 2.25 Mt, annual output surpassed 50 Mt by 1955 and 100 Mt by 1965 when the country was, ahead of Saudi Arabia, the world's fourth largest producer of oil (behind the United States, USSR, and Venezuela). In energy terms Kuwait thus moved from a premodern society dependent on imports of wood, charcoal, and kerosene to an oil superpower in a single generation.

In contrast, large economies, particularly those with relatively high per capita demand and with extensive infrastructures serving an established fuel, cannot accomplish the substitutions so rapidly. Comparing the Dutch and the British experience is particularly revealing in this respect, as both of these countries benefited from major natural gas discoveries. The first discoveries of natural gas in the British sector of the North Sea were made by BP in 1965 but despite an aggressive development of those rich and relatively near-shore deposits, Britain could not accomplish even in 30 years what the Netherlands did in a decade: Its share of natural gas stood at a bit less than 5% of the primary energy supply in 1970 and it peaked only 30 years later at about 39%.

Principal reasons for the difference include a much higher total of the absolute supply needed to provide an identical share of the primary energy (by 1970 the UK's primary energy supply was nearly 220 Mtoe/year compared to 60 Mtoe/year in the Netherlands), UK's traditionally high dependence on coal-fired electricity generation, the country's pioneering role in nuclear generation (it would have been very costly to shut down those stations and replace them with gas-fired plants), a higher cost and longer lead times to develop offshore resources rather than hydrocarbons fields on land (particularly in such an inhospitable environment as the North Sea), and also the much larger size of the country (about 244,000 km^2) necessitating longer trunk and distribution lines.

And the Japanese progress shows that when the gas has to be imported from overseas then the pace of substitution must be even slower—regardless of the fact that the country was one of the pioneers of LNG imports (starting in 1969 with *Polar Alaska* and *Arctic Tokyo*, each with capacity of 71,500 m^3 to carry gas from Alaska) and that when it commenced its LNG imports it was not only one of the world's leading economies but one with an enormous experience in shipbuilding. At the same time, a slow pace of substitution comes as no surprise given the size of Japan's economy and its nearly total dependence on fossil fuel imports: This means that despite its relatively high efficiency the country now requires annually more than 500 Mtoe (nearly 22 EJ) of primary energy. Given these circumstances Japan's LNG progress could be actually seen as rather impressive, as the country had increased the share of natural gas in its energy supply from 5% in 1979 to about 16% by 2008.

The second analogy illuminating the process of energy transitions is their comparison with aircraft accidents. Careful studies of those events show that they are nearly always due to a number of factors and that the final outcome is a result of a specific sequence of errors (be they actions or inactions) taken by crews in response to a sudden change, be it a faulty indicator light, erroneous instrument reading, or (an increasingly rare occurrence with modern gas turbines) mechanical failure of one or more of the airplane's engines. And so it is with energy transitions: They are never brought about by a single factor, and in the second chapter I will show that this was the case even with perhaps the most commonly cited claim, portraying English wood shortages as the decisive factor forcing the country's early transition to coal.

And, as with the aircraft accidents, a careful investigation of energy transitions always reveals that their progress requires a specific sequence of scientific advances, technical innovations, organizational actions, and economic and political and strategic circumstances. Missing a single component in such a sequence, or delaying its introduction or effects because of some unforeseen events, results in very different outcomes and in lengthier transition periods. Once again, an excellent example illustrating this necessity of a specific sequence, and of assorted events delaying its progress, is provided by the recent emergence of LNG as a globally available fuel traded competitively on an intercontinental basis.

A long road toward this accomplishment had to include the invention and commercialization of gas liquefaction, establishment of LNG supply chain (liquefaction, tanker-borne transport, regasification), increase of typical liquefaction and LNG tankers' capacities in order to lower unit costs of the delivered gas, a greater number of importing countries in order to justify the construction and expansion of larger terminals, and extensive trunk and distribution pipelines in those importing countries that had previously no natural gas supply. And the process needed to create this new global industry was delayed by factors ranging from predictable (high capital costs of the first generation of LNG systems) to unforeseeable (OPEC-driven energy price increases, the Shah's fall and Khomeini's assumption of power in Iran, hydrocarbon price deregulation in the United States, concerns about early peak of oil extraction).

The road toward global LNG industry began in 1852 when the pioneering work done by James Prescott Joule and William Thomson (Lord Kelvin) on liquefaction of gases demonstrated that as a highly compressed air flows through a porous plug (a nozzle) it expands to the pressure of the ambient air and cools slightly (Almqvist, 2003). Repetition of this sequence creates a cooling cascade, the temperature of the gas expanded at the nozzle gradually declines and it eventually liquefies. Practical designs for commercial liquefaction of oxygen and nitrogen followed during the last three decades of the nineteenth century, with the most important contribution made by Carl von Linde (1842–1934), whose patented process (in 1895) combined the Thomson–Joule effect with what Linde termed countercurrent cooling, with compressed air expanded through a nozzle at the bottom of an insulated chamber used to pre-cool the incoming compressed air in a countercurrent cooler (Linde, 1916).

Because the United States was the only notable user of natural gas before World War II there was no commercial need for LNG: That is why Godfrey Cabot's patented handling and transporting liquid natural gas (Cabot, 1915) did not have any practical consequences. The first small LNG storage was built in West Virginia in 1939 and a larger one in Cleveland in 1941 to provide fuel for the periods of peak demand; in 1944 one of its tanks failed and the ignited vaporized gas killed 128 people in the plant's neighborhood. This accident used to be cited by those who wanted to portray LNG industry as very risky—but the investigation report concluded that the accident was caused by a poor tank design and that properly done the gas liquefaction and storage are not exceptionally dangerous (USBM, 1946).

Post–WWII surfeit of cheap crude oil and rapid expansion of North American gas extraction had postponed the beginning of the LNG era for another generation: The first demonstration shipment of LNG (from Lake Charles, LA to Canvey Island on the Thames) took place in 1959 with a tanker of just 5,000 m^3 (*Methane Pioneer*, a converted WWII Liberty class freighter). The first methane liquefaction plant was completed in Arzew, Algeria in 1964 and LNG exports to the United Kingdom began in the same year with two specifically designed tankers (*Methane Princess* and *Methane Progress*) of 27,400 m^3 each (Corkhill, 1975). They were followed by the Japanese imports from Alaska in 1969 and the French imports from Libya in 1970. But then the Groningen and the North Sea gas made the LNG imports uneconomical and when the Arzew–Canvey contract expired in 1979 it was not renewed.

Similarly, during the 1970s the United States built four regasification terminals for the import of Algerian gas (the first one in Everett, MA, in 1971) only to reduce their operation or to shut two of them down as the availability of domestic natural gas increased with the post-1993 wellhead price deregulation. This left Japan (with no domestic gas resources) as the world's leading importer of LNG, adding new long-term contracts for the gas from Abu Dhabi and Indonesia (in 1977), Malaysia (1983), and Australia (1989): By 1984 Japanese imports accounted for 75% of all LNG trade; by 1999 they were still 66% of the total. And while Taiwan (in 1990) and South Korea (in 1991) joined Japan as the other major Asian importers, the LNG trade remained confined by uncompetitive long-term contracts served by dedicated plants and ships along inflexible routes.

These realities were not conducive to any bold technical advances. For more than a generation, between the mid-1960s and the late 1990s, typical capacities of LNG trains (liquefaction units) remained at just 1–2 Mt/year, while the aggregate outputs of entire plants increased only gradually, from the pioneer Arzew's rate of 0.45 Mt/year in 1964 to 1 Mt/year in 1970, 1.5 Mt/year in 1980, 2.2 Mt/year in 1990, and 3.5 Mt/year in 2000. Some of these large-scale liquefiers have used the classic cascade cycle but most of them have relied on a mixed refrigerant cycle (using such gases as butane, propane, ethane, and nitrogen) devised by A. P. Kleemenko in 1960. And although the largest ship capacities increased fairly rapidly during the first decade of LNG trade—from 27,400 m^3 for the two pioneering ships in 1964 to 71,500 m^3 in 1969 and 126,227 m^3 in 1975—three decades later the dominant sizes (largely due to the Japanese restrictions on the maximum tonnage of LNG tankers) were still between 125,000 and 130,000 m^3.

Given a limited number of exporting countries (1 in 1964, 6 by 1980, 12 by 2000) and LNG tankers (fewer than 60 vessels until 1984, 100 by 1997), this slow capacity growth meant that the total LNG trade surpassed 50 Mt/year only by 1991 and that only in 1999 did it carry more than 5% of all exported gas (Castle, 2007). The industry began to change rapidly at the century's turn. Qatar joined the ranks of LNG exporters in 1997, in 1999 a new LNG plant in Trinidad and Tobago led to the reactivation of the two closed U.S. regasification plants (Elba Island in 2001, Cove Point in 2003), Nigeria and Oman began shipping LNG in 2000, followed by Egypt in 2005, Equatorial Guinea in 2007, and Russia (from Sakhalin) in 2009.

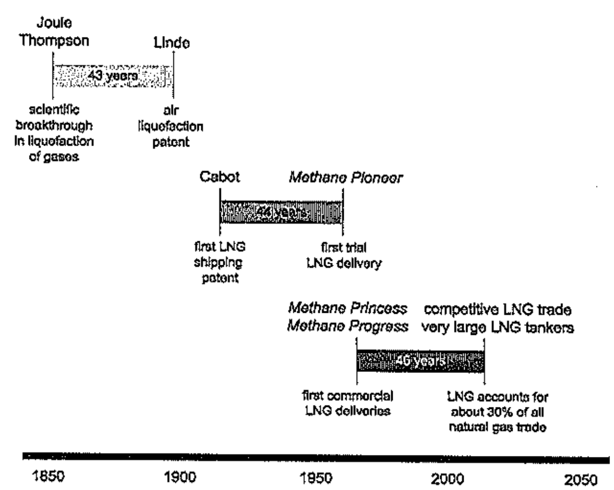
Increasing train size (maxima of 5 Mt/year by 2005, more than 8 Mt/year by 2008) and decreasing costs of train and tanker construction resulted in rapid capacity increases and bold plans for further expansion. Total export capacity rose from 100 Mt/year in 2000 to about 220 Mt/year by 2009. For three decades the standard LNG tanker design used large aluminum spheres (Kvaerner-Moss shells introduced in 1971) covered with insulation inside steel tanks and bolted to the vessel's hull. This design wastes storage space and steel spheres increase the ship's draft, making voluminous vessels impractical. In contrast, membrane design has insulated tanks of thin stainless steel shaped to fit the inner hull. As a result, average size of ships ordered in 2007 was about 180,000 m^3 and Qatargas has taken delivery of the first tankers belonging to new Q-Flex (210,000 m^3) and Q-Max (266,000 m^3) classes of ships. The company will eventually have 45 of these large vessels (Qatargas, 2009).

By 2008 there were 250 LNG tankers with the total capacity of 183 Mt/year and the global LNG trade carried about 25% of all internationally traded natural gas (BP, 2009). LNG was imported by 17 countries on four continents, and before the economic downturn of 2008 plans envisaged more than 300 LNG vessels by

2010 with the total capacity of about 250 Mt/year as the global LNG trade has moved toward a competitive market. LNG trade has been finally elevated from a marginal endeavor to an important component of global energy supply, and this has become true in terms of total exports (approaching 30% of all natural gas sold abroad) and number of countries involved (now more than 30 exporters and importers) as well as the flexibility of transactions (with a true market emerging).

This brief recounting of LNG history is an excellent illustration of the decades-long spans that are often required to convert theoretical concepts into technical possibilities and then to adapt these technical advances and diffuse them to create new energy industries (Figure 1.4). Theoretical foundations of the liquefaction of gases were laid down more than a century before the first commercial application; the key patent that turned the idea of liquefaction into a commonly used industrial process was granted in 1895, but at that time natural gas was a marginal fuel even in the United States (in 1900 it provided about 3.5% of the country's fossil fuel energy), and in global terms it had remained one until the 1960s, when its cleanliness and flexibility began to justify high price of its shipborne imports. Even then the first long-term contracts delivered gas only to affluent countries that could afford the price and that used most of the gas for shore-based electricity generation (Japan) or had preexisting trunk and distribution pipelines carrying domestically produced gas in place (United Kingdom, France, United States) that could be used to sell the imported gas to households and enterprises.

Figure 1.4 History of LNG shipments illustrates often very long time spans required for the maturation and diffusion of innovations in energy extraction, transport, and conversion.



Industry's subsequent growth was affected by a combination of events that could not have been predicted during the 1960s: by the two oil price crises of the 1970s, by the collapse of the Iranian monarchy in 1979, by the deregulation of U.S. natural gas prices (and the consequent boost of the domestic extraction), and by the collapse of the world oil price in 1985. As a result, many plans were postponed or cancelled. In 1975 it was expected that by 1981 Nigeria would begin its LNG exports to Europe, and Iran to Europe, the United States, and Japan (Faridany, 1975), but Nigerian exports began only nearly two decades later (in 1999) and Iranian shipments have yet to begin. The industry that began in 1964 moved only about 2% of all traded gas by 1980 and 5% of all natural gas exports only in 1999. At that time it was clearly an important earner for a few major exporters (Algeria, Indonesia, Brunei) and a significant source of fuel for the three leading importers (Japan, South Korea, Taiwan), but it still could not qualify as a key ingredient of the global primary energy supply.

If we take the years between 1999 (when worldwide LNG exports surpassed 5% of all natural gas sales) and 2007 (when the number of countries exporting and importing LNG surpassed 30, or more than 15% of all nations) as the onset of LNG's global importance, then it had taken about four decades to reach that point from the time of the first commercial shipment (1964), about five decades from the time that natural gas began to provide more than 10% of all fossil energies (during the early 1950s), more than a century since we acquired the technical means to liquefy large volumes of gases (by the mid-1890s)—and about 150 years since the discovery of the principle of gas liquefaction.

By 2007 it appeared that nothing could stop an emergence of a very substantial global LNG market. But then a sudden supply overhang that was created in 2008—and that was due to the combination of rapid capacity increases, lower demand caused by the global financial crisis, and the retreat of U.S. imports due to increased domestic output of unconventional gas—has, once again, slowed down global LNG prospects, and it may take years before the future course will become clear. In any case, the history of LNG remains a perfect example of the complexities and vagaries inherent in major energy transitions.

Chapter 2

Global Transitions: Universal Patterns

The most obvious reality that emerges from the study of energy transitions done from the global perspective and across the entire historical time span is a highly skewed division of their progress: Stasis, stagnation, marginal adjustments, and slowly proceeding innovations marked the entire preindustrial era—while the process of industrialization and the evolution of postindustrial societies have been marked (indeed formed) by rapid, often truly precipitous diffusion of new inventions and widespread adoption of technical and organizational innovations. As a result, nearly five millennia of preindustrial history were almost completely dominated by reliance on inefficiently burned biomass fuels as the source of heat for households, metallurgy, and artisanal manufactures, and by exertions of human and animal muscles to provide nearly all requirements for mechanical energy (sails being the only early exception).

This situation did not change fundamentally even during the early modern era when some Western European societies began a small-scale extraction of coal (or peat) and when they adopted increasingly more efficient and more powerful water wheels and windmills. The two fundamental transitions, from biomass to fossil fuels and from animate to inanimate prime movers, have taken place only during the last few centuries (roughly three in the case of some European societies) or just a few recent decades (six in China's, four in India's case), and the emergence of electricity as the energy form of the highest quality began only during the 1880s. Inevitably, these transitions began on small local scales, evolved into nationwide developments, and eventually became truly global phenomena. Only the earliest innovators were able to maintain their advantage for a period of time, while the more recent advances have been diffusing with only a minimum lag (a phenomenon perhaps best illustrated by China's rapid post-1980 modernization).

I will trace all of these developments by following first the grand fuel sequence of millennia-long dependence on biomass energies that was replaced by now virtually universal dependence on fossil fuels. In the next section I will emphasize importance of electricity in modern societies and review the development of thermal, hydro, and nuclear generation. Then I will offer a brief history of a critical transition from animate to mechanical prime movers, and the chapter

This was followed by a precipitous slump (caused by OPEC's record-high demand-destroying price run-up between 1979 and 1981) to just 172 Mt by the year 1985, but after the demise of the USSR the country became the world's largest oil producer by surpassing the Russian extraction in 1992, and it has continued to maintain this primacy ever since. In contrast to rapidly rising exports, the Saudi domestic consumption remained rather low until the mid-1970s (in 1975 it was virtually unchanged from the 1965 level), but then it tripled by 1985 and nearly tripled again by 2008, reaching about 175 Mtoe or roughly 270 GJ/capita (compared to about 175 GJ/capita for the richest EU countries). This means that by the late 1970s Saudi per capita use of primary energy surpassed the means of the richest European states and that the country's transition from preindustrial subsistence to a high-energy society took just 40 years when measured from the first oil discovery in 1938 or (when using a more meaningful delimitation) only about 25 years when measured from the beginning of the post–WWII modernization during the early 1950s.

But two important caveats are in order. The high mean of the Saudi per capita energy consumption is misleading because a large part of the overall energy demand is claimed by the oil and gas industry itself and because it also includes substantial amounts of bunker fuel for oil tankers exporting the Saudi oil and refined products. Average energy use by households remains considerably lower than in the richest EU countries. Even more importantly, Saudi Arabia's high energy consumption has not yet translated into a commensurately high quality of life: Infant mortality remains relatively high and the status of women is notoriously low. As a result, the country has one of the world's largest differences in the ranking between per capita GDP and the Human Development Index (UNDP, 2009). In this it is a typical Muslim society: In recent years 20 out of 24 Muslim countries in North Africa and the Middle East ranked higher in their GDP per capita than in their HDI—and in 2007/2008 the index difference for Saudi Arabia was −19 while for Kuwait and Bahrain it was −8 and for Iran it was −23.

The Soviet and Saudi examples illustrate the rapidity with which even a large economy or a latecomer to modern development can accomplish its energy transition—but it must be remembered that this would not have been possible without those countries' exceptionally rich fossil fuel (and in the Russian case also of water power) endowment. Consequently, the Soviet or Saudi energy transitions have limited implications for economies that have minimal, or no, domestic resources and (to make the bridge to the next chapter) they offer no insight into the coming shift from fossil fuels to renewable energies. Moving away from fossil fuels will be a protracted affair even in those countries where the requisite resources are readily available, because every society will have to deal with the twin challenge of low power density and intermittent flows of renewable energies.

Chapter 4

COMING TRANSITIONS: EXPECTATIONS AND REALITIES

The history of energy transitions—long, complex, and not easily amenable to simple judgments, sweeping generalizations, and crisp deductions—can be used to support a range of conclusions. Moreover, as is always the case with long-term perspectives, even the most robust and conservatively stated conclusions based on careful examination of this evidence may not have a great deal of relevance for outlining the most likely pace and extent of any future developments. This may be because of an extraordinary difficulty and exceptional nature of the coming energy transition—but, given the enormous challenges of ushering in a post-fossil world, it may also be because of the possibility of an unprecedented and persistent commitment to a rapid change.

Regrettably, my interpretation of the past evidence and my understanding of the current capabilities to act, and to persist, favors the first reason: Lessons of the past energy transitions may not be particularly useful for appraising and handicapping the coming transition because it will be exceedingly difficult to restructure the modern high-energy industrial and postindustrial civilization on the basis of non-fossil—that is, overwhelmingly renewable—fuels and flows. I use the qualifier "overwhelmingly" in order to leave some room for a possibility of substantially increased nuclear electricity generation—although the combined challenges of the industry's public acceptance, long-term fuel availability, permanent waste storage, and nuclear weapons proliferation do not make any early vigorous and widespread renaissance very likely.

At the same time, any unbiased *sine ira et studio* approach must recognize that affluent countries could make the coming transition considerably easier by substantially reducing their clearly excessively high per capita energy use and by making the shift to new energy foundations one of its key concerns to be pursued with persistence and determination. As yet, there is very little evidence of any determination to embark on such a challenging, costly long-term commitment but this does not mean that the future course of energy use is inescapably predetermined and that we are inexorably entering a dangerous energy *cul-de-sac*. Nothing concentrates minds as much as acute crises do, and so it is possible that a future deep and protracted disruption of existing production/consumption arrangements will help to accelerate the coming energy transition.

Our energy choices have not been foreclosed—but we have to recognize that they are, at least in the near- to mid-term, restricted by availability and convertibility of individual resources and by the pace of technical innovation and social adaptation. Following my long-standing practice of not making any quantitative point forecasts I will not offer any absolute predictions for particular years or time periods, be it on the global scale or for individual nations. Instead, I will examine first the fundamental contours of the coming energy transition by explaining the magnitudes of available non-fossil resources and major constraints on their conversions, above all their low power densities.

British, French, and U.S. histories of energy use show that all early modernizers had experienced a slow (even very slow) transition from biomass fuels to coal. This is not surprising, because that epochal shift took place during the earliest stages of Western industrialization: Indeed, it had largely defined it. During that time gaps between invention, innovation, and large-scale commercial diffusion were often so long because of the limited abilities to perfect newly invented production methods and prime movers and because of the restricted or disrupted capacities for their widespread adoption. Several reasons for those slow advances stand out: Scientific understanding of the underlying processes was often inadequate, suitable high-performance materials needed for mass production (steel in particular) were either unavailable or in short supply, manufacturing processes were inadequate as far as both qualities and capacities were concerned, requisite infrastructures took a long time to complete, and large-scale competitive markets were absent.

In contrast, it appears that today's situation is markedly different, a state of affairs that should make the coming transition to non-fossil energies a less taxing experience. After all, we have now an enormous wealth of relevant scientific understanding, as yet no disruptive shortages of high-performance metals and materials that are needed at every stage of energy harnessing and conversion are imminent, advanced manufacturing processes are able to prototype new designs rapidly and to take advantage of the economies of scale (recent scaling-up of wind turbines to multi-MW ratings is an excellent example of these capabilities), our technical capacities to put in place new infrastructures are unprecedented, and there are highly competitive global markets for nearly all important techniques and products.

As a result, there has been a growing perception that—given the abundant renewable energy resources and steadily improving technical capabilities to harness those flows—all that is needed to bring about a relatively rapid shift away from fossil fuels is a determined effort that, at least in its opening stages, should be guided and supported by far-sighted government interventions, and many governments have expressed these expectations in terms of binding targets to be supplied by renewable flows at specified future dates. I will address the future rate of these developments in two ways, first by putting the expected pace of the coming transitions into a wider context by looking at some inexplicably neglected but universally valid aspects of technical innovation, including infrastructural demands and a remarkable inertia of prime movers, and then by describing some notable cases of past and present national aspirations of shifting toward renewable energies. I will not offer any grand, overarching conclusions: Instead, I will end with some qualified observations and with summaries worded as cautious anticipations.

RENEWABLE ENERGIES: RESOURCES, CONVERSIONS, AND CONSTRAINTS

Two reasons for moving toward non-fossil futures stand out at the beginning of the twenty-first century: concerns about long-term effects of global climate change, and worries about rapidly approaching depletion of low-price, high-quality fossil fuels. The first concern stems from a widely accepted understanding that, as complex as climate change may be, anthropogenic emissions of fossil carbon have emerged as its most pronounced and certainly the most readily identifiable driver (IPCC, 2007; see Figure 1.3). Continuing reliance on fossil fuels could be possible if it were accompanied by mass-scale underground or undersea sequestration of carbon or by (an even less technically mature option) planet-wide geoengineering interventions (such as shading the Earth, boosting the planet's albedo, increasing the atmospheric aerosol loading). But certainly the surest way to prevent excessive global warming and to keep the average global temperature increase within acceptable limits (most likely no more than 2°C above the preindustrial mean) is to reduce the reliance on fossil fuels by gradually shifting the world's energy supply to a renewable basis and eventually eliminating coals and hydrocarbons.

The second concern is related above all to the alleged imminence of global peak oil extraction to be followed by a fairly rapid decline of global oil production, but there have been also some indications that the world's coal resources may be significantly less abundant than the widespread impressions would indicate (Rutledge, 2008).

This is not a place to assess the merits of these concerns; many recent works have done so in a great detail. But even if the current perceptions of these threats turned out to be exaggerated, there are many other good reasons for favoring a shift of the global energy supply away from fossil fuels, whose extraction and conversion has many undesirable environmental impacts including the emissions of CH_4 (a more powerful greenhouse gas than CO_2), black carbon (another important factor in atmospheric change), and oxides of sulfur and nitrogen (both being the precursors of acid deposition and the latter one also a key ingredient in the formation of photochemical smog).

An entirely different set of concerns favoring transition to a non-fossil world stems from financial and strategic considerations arising from unpredictably rising (and fluctuating) costs of fossil fuels. The world's oil-importing countries spent almost $1.5 trillion in 2007 and $2 trillion in 2008 to purchase crude oil whose imports create a permanent drag on balance of payments in many nations. Most notably, crude oil purchases cost the United States nearly $350 billion (16% of its total imports) in 2008 (USCB, 2009). Moreover, most of the remaining crude oil resources are in the notoriously unstable Middle East, and the past economic and military costs of safeguarding their production and delivery may pale compared to the investments, political concessions, and military interventions that may be required in the future.

Transition from an energy supply dominated by fossil fuels to a world relying mostly on non-fossil fuels and generating electricity by harnessing renewable energy flows is thus definitely desirable and, given the finite nature of fossil resources, it is eventually inevitable—but it is imperative to realize that the process will be considerably more difficult than is commonly realized. Five reasons explain the challenge: the overall scale of the coming shift, be it on the global level or in the world's largest economies; magnitudes of renewable energy resources and their surprisingly uneven distribution; the intermittent, and to a significant degree unpredictable, nature of most renewable energy flows; lower energy density of the fuels produced to replace solid and liquid fossil fuels; and, perhaps most importantly, substantially lower power densities with which we can harness renewable energies.

The scale of the coming energy transition is best illustrated by comparing the future demand for non-fossil fuels and primary electricity with the past demand for fossil energies that were needed to complete the epochal shift from biomass to coal and hydrocarbons. By the late 1890s, when the share of biomass energies slipped just below 50% of the world's total primary energy supply, less than 20 EJ of additional fossil fuel supply were needed to substitute all of the remaining biomass energy consumption. By 2010 the global use of fossil energies runs at the annual rate of roughly 400 EJ, which means that the need for new non-fossil energy supply to displace coal and hydrocarbons is 20 times greater in overall energy terms than was the need for fossil energies during the 1890s.

And the challenge is relatively even more daunting for all high-energy economies in general, and for the United States in particular. In 1884, when the U.S. primary energy supply was split between biomass and fossil fuels, the total energy demand was below 6 EJ, and hence only less than 3 EJ were needed to substitute the remaining biomass use (as already explained, this substitution never happened completely but by the year 2000 only 3% of U.S. commercial energy came from biomass). In contrast, recent U.S. energy demand has been approaching 100 EJ, of which only some 7% are now drawn from renewable energies (including hydroelectricity) and 8% from nuclear generation. This means that replacing all of America's fossil fuel demand will require about 85 EJ of additional non-fossil contributions, nearly 30 times the total of fossil fuels the country needed in the mid-1880s to complete its shift from biomass to coal and hydrocarbons.

There are nine major kinds of renewable energies: solar radiation; its six transformations as running water (hydro energy), wind, wind-generated ocean waves, ocean currents, thermal differences between the ocean's surface and deep waters, and photosynthesis (primary production); geothermal energy and tidal energy complete the list. As with fossil fuels, it is imperative to distinguish between renewable resources (aggregates of available fluxes) and reserves, their smaller (or very small) portions that are economically recoverable with existing extraction or conversion techniques. This key distinction applies as much to wind or waste cellulosic biomass as it does to crude oil or uranium, and that is why the often-cited enormous flows of renewable resources give no obvious indication as to the shares that can be realistically exploited.

Global reserves of renewable flows can be accurately determined only by careful assessment of regional and local limits, not by applying some generic fractions. For example, storing too much water for hydro generation could weaken many environmental services provided by flowing river water (including silt and nutrient transportation, channel cutting, and oxygen supply to aquatic biota), large-scale biofuel cultivation and repeated removal of excessive shares of photosynthetic production could further undermine the health of many natural ecosystems and agroecosystems by extending monocultures and opening ways for greater soil erosion and pest infestation, and harnessing significant shares of wind energy could affect regional climates and conceivably even the global air circulation.

Magnitude of annual flows (resources) of renewable energies is best appreciated by comparing them to the global extraction of fossil fuel that reached about 425 EJ or 13.5 TW in 2010. Solar radiation reaching the biosphere (after subtracting about 30% of the incoming radiation that is reflected by clouds and surfaces) amounts to 3.8 YJ or 120 PW, nearly four orders of magnitude greater than the annual fossil fuel consumption, and the total absorbed by land is roughly 790 ZJ or 25 PW, still nearly 2,000 times the current fossil fuel extraction. Even after excluding half of the terrestrial surfaces (polar and subpolar regions with the relatively weakest insolation, and the areas difficult to access, ranging from steep mountains to wetlands) as unsuitable location, there are still at least 15 PW of potentially usable flux, roughly a thousand times today's annual fossil fuel consumption.

Theoretically available wind resources are large but (as has been so well demonstrated with the harnessing of water power) only their small share will be practically exploitable. Peixoto and Oort (1992) estimated that about 870 TW of solar radiation (more than 60 times the current fossil flux) is transferred to wind's kinetic energy (and is dissipated as friction), and Archer and Jacobson (2005) put the accessible global wind flux at 80 m above ground at

72 TW. Lu, McElroy and Kiviluoma (2009) simulated global winds 100 m above ground and concluded that when using 2.5-MW turbines, excluding areas covered with ice, snow, forest, water and settlements, and assuming an average 20% capacity factor it could be possible to harness 78 TW.

How much of this theoretically available flux will be actually captured remains highly uncertain; a 10% share (about 7 TW) would be half of today's fossil fuel extraction. Potential energy of the global stream runoff adds up to nearly 10 TW, of which slightly more than 10% can be economically exploited by dams, and more than a third of that has been already harnessed. Wind-driven ocean waves have kinetic energy of some 60 TW of which only 3 TW (5%) are dissipated along the coasts. Ocean currents have power of at least 100 GW but only a very small part (on the order of a few GW) can be converted.

Tidal energy amounts to about 3 TW, of which only some 60 GW are dissipated in coastal waters. Ocean thermal gradient totals some 100 TW but because of the small temperature difference (maximum of about 20 K) its large-scale commercial use remains questionable. Terrestrial photosynthesis proceeds at a rate of nearly 60 TW, and even a tripling of biomass currently used for energy would not yield more than about 9 TW. Finally, the Earth's geothermal flux amounts to about 42 TW (Sclater, Jaupart, & Galson, 1980), but nearly 80% of that large total is through the ocean floor and all but a small fraction of it is a low-temperature diffuse heat. Available production techniques using hot steam could tap up to about 140 GW for electricity generation by the year 2050 (Bertani, 2009), and even if three times as much could be used for low-temperature heating the total would be less than 600 GW.

Reviewing the potentially usable maxima of renewable energy flows shows a sobering reality. First, direct solar radiation is the only form of renewable energy whose total terrestrial flux far surpasses not only today's demand for fossil fuels but also any level of global energy demand realistically imaginable during the twenty-first century (and far beyond). Second, only an extraordinarily high rate of wind energy capture (that may be environmentally undesirable and technically problematic) could provide a significant share of overall future energy demand. Third, for all other renewable energies maxima available for commercial harnessing fall far short of today's fossil fuel flux, one order of magnitude in the case of hydro energy, biomass energy, ocean waves, and geothermal energy, two orders of magnitude for tides, and four orders of magnitude for ocean currents and ocean thermal differences.

Consequently—and contrary to common perceptions of a cornucopia of renewable flows—there is only one kind of renewable energy that is so large that even the capture of a mere 0.1% of its land flux would satisfy global energy demand twice as large as the 2010 rate. Unfortunately, large-scale commercial conversions of that flux are still only in very early stages: In 2010 photovoltaic electricity generation produced still less than 0.1% of the world's electricity

and, similarly, solar heating (mainly for household and commercial hot water supply) added less than 0.1% of the global primary energy supply. At the other end of the renewable spectrum are the four oceanic sources (waves, currents, temperature differences, and tides) with a very limited exploitable capacity, either due to their relatively minor aggregate flux or to difficulties in making their conversions economical in the foreseeable future (or both, as is the case of currents and thermal differences).

Biomass contributions could be increased by large-scale removal and conversion of waste (cellulosic) phytomass, mainly logging residues and cereal straws—but, once again, while this resource is large, its reserves (the share that can be repeatedly taken away without adverse effects) are limited. Logging residues from clear-cutting can yield a relatively high one-time harvest but those at remote sites and those left on steep slopes may not be economically recoverable and even the best efforts to collect the accessible resources may not gather more than half of the available wastes. And in most agroecosystems crop residues are a more valuable resource when they are recycled—in order to maintain soil's organic content, to retain moisture, and to prevent soil erosion—rather than when they are removed for fuel.

And while there is undoubtedly a very large theoretical potential for biomass harvested from new plantings of fast-growing trees and high-yielding grasses on currently unused land, those favoring such mega-planting schemes must first explain how they will supply the requisite water and macronutrients needed to sustain those plantings. Yet another proposal would cultivate nearly 90% of new energy crops on land that is now used for food production but that would be made superfluous by greatly increased efficiency of food cropping. One wishful assessment estimated the future biomass contribution at no less than about 365 EJ (nearly equal to all fossil fuels today) and it put the maximum potential by the year 2050 as high as 1.442 ZJ, more than three times today's total global energy use (Smeets et al., 2007). Improbability of this total led the authors themselves to admit that "such increases in productivity may be unrealistically high" (Smeets et al., 2007, p. 56)—but they use them anyway as the foundation for their meaningless claims.

Environmental impacts of large hydro energy projects have transformed their reputation from formerly desirable options to a highly questionable, and even a stridently opposed, form of renewable energy; in any case, even if all potentially suitable sites were to be developed, their electricity generation will remain a fraction of the coming global demand. Remaining hydro energy resources are also very unevenly distributed, with most of them in just a handful of countries (China, India, Russia, Congo, Brazil) and a similarly highly skewed spatial distribution is the norm, rather than an exception, for most of the renewable energy flows. Many regions (including the Mediterranean, Eastern Europe, large parts of Russia, Central Asia, Latin America, and Central Africa) have relatively low wind-generation potential (Archer & Jacobson, 2005); high geothermal gradients are concentrated along the ridges of major tectonic plates, above all along the Pacific Rim; and tidal power is dissipated mainly along straight coasts (unsuitable for tidal dams) and in regions with minor (<1 m) tidal ranges (Smil, 2008).

The third obvious fact complicating large-scale development of most of the renewable energy flows is their intermittency, some of which is perfectly predictable (daily availability of solar radiation in cloud-free subtropical settings; time and magnitude of local tides) but most of which can be only forecast with varying degrees of probability, particularly as far as longer term outlook is concerned (availability of solar radiation in cloudy mid-latitudes, timing and frequency of winds, seasonal harvests of phytomass affected by climate variations and pest infestations). There are two effective solutions for intermittency: storage in the case of fuels, and long-distance interconnections in the case of electricity generation.

Mass production of liquid biofuels fermented from annual harvests of crop or residual biomass would require large storages of either cereal or cellulosic feedstocks or the produced ethanol (or both), and the bulkiness of residues and relatively low energy densities of all of these materials would make such storages more costly than those of refined oils. New long-distance HV links will be appraised later in this chapter but they, too, would obviously entail significant initial infrastructural investment, a reality that militates against any rapid sustained contributions that renewable conversions sited in locations far away from major load centers could make to future energy balances.

The fourth key consideration is that in terms of energy densities the coming shift will move the global energy system in the opposite, and less desirable, direction than did the epochal transition to fossil fuels that introduced fuels with superior energy densities: transition to non-fossil fuels rests on less energy-dense biofuels whose larger mass (for the equivalent energy supply) will require more handling and larger storages. As already explained (in chapter 1), even ordinary bituminous coal contains 30–50% more energy than air-dry wood, while the best hard coals are nearly twice as energy-dense as wood and liquid fuels refined from crude oil have nearly three times higher energy density than air-dry phytomass. A biomass-burning power plant would need a mass of fuel 30–50% larger than a coal-fired station of the same capacity. Similarly, ethanol fermented from crop carbohydrates has an energy density of 24 MJ/L, 30% less than gasoline (and biodiesel has an energy density about 12% lower than diesel fuel).

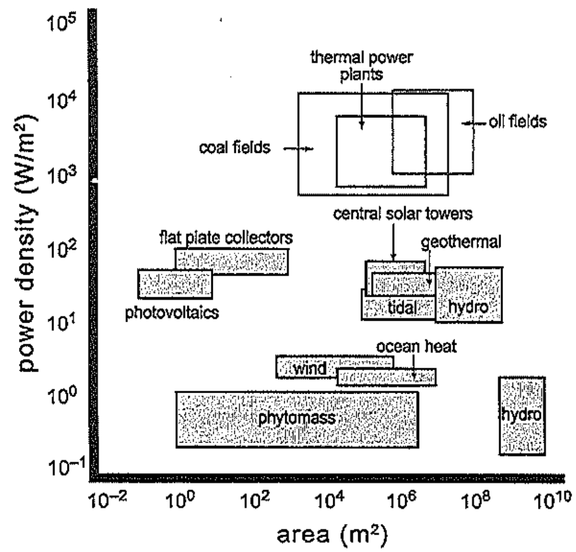
But lower energy density of non-fossil fuels is a relatively small inconvenience compared to inherently lower power densities of converting renewable energy flows into mass-produced commercial fuels or into electricity at GW scales. Power density is the rate of flow of energy per unit of land area. The measure is applicable to natural phenomena as well as to anthropogenic processes, and it can be used in revealing ways to compare the spatial requirements of energy

harnessing (extraction, capture, conversion) with the levels of energy consumption. In order to maximize the measure's utility and to make comparisons of diverse sources, conversions, and uses my numerator is always in watts and the denominator is always a square meter of the Earth's *horizontal* area (W/m^2).

Others have used power density to express the rate of energy flow across a *vertical* working surface of a converter, most often across the plane of a wind turbine's rotation (the circle swept by the blades). When used that way, power density of a 3-MW Vestas machine (now a common choice for large wind farms) is roughly 400 W/m^2 and for the world's largest machine, ENERCON E-126 rated at 6 MW, it is 481 W/m^2. But because the turbines must be spaced at least three, and better yet five, rotor diameters apart in direction perpendicular to the prevailing wind and at least five, and with large installations up to ten, rotor diameters in the wind direction (in order to avoid excessive wake interference and allow for sufficient wind energy replenishment), power densities of wind generation are usually less than 10 W/m^2. Altamont Pass wind farm averages 3.5 W/m^2, while exceptionally windy sites may yield more than 10 W/m^2 and less windy farms with greater spacing may rate just above 1 W/m^2 (Figure 4.1).

Hydroelectricity will make important new contributions to the supply of renewable energy only in the modernizing countries of Asia, Africa, and Latin America. Because of their often relatively large reservoirs, smaller stations have power densities less than 1 W/m^2; for stations with installed capacities of

Figure 4.1 Power densities of renewable energy conversions, fossil fuel extraction, and thermal electricity generation. Plotted from data in Smil (2008).



0.5–1 GW the densities go up to about 1.5 W/m^2; the average power density for the world's largest dams (>1 GW) is over 3 W/m^2; the largest U.S. hydro station (Grand Coulee on the Columbia) rates nearly 20 W/m^2; and the world's largest project (Three Gorges station on the Chang Jiang) comes close to 30 W/m^2 (Smil, 2008). Power densities of hydro generation are thus broadly comparable to those of wind-driven generation, both having mostly magnitude of 10^0 W/m^2 and exceptional ratings in the lower range of 10^1 W/m^2 (Figure 4.1).

Typical power densities of phytomass fuels (or fuels derived by conversion of phytomass, including charcoal or ethanol) are even lower. Fast-growing willows, poplars, eucalypti, leucaenas, or pines grown in intensively managed (fertilized and if need be irrigated) plantations yield as little as 0.1 W/m^2 in arid and northern climates but up to 1 W/m^2 in the best temperate stands, with typical good harvests (about 10 t/ha) prorating to around 0.5 W/m^2 (Figure 4.1). Crops that are best at converting solar radiation into new biomass (C_4 plants) can have, when grown under optimum natural conditions and supplied by adequate water and nutrients, very high yields: National averages are now above 9 t/ha for U.S. corn and nearly 77 t/ha for Brazilian sugar cane (FAO, 2009). But even when converted with high fermentation efficiency, ethanol production from Iowa corn yields only about 0.25 W/m^2 and from Brazilian sugar cane about 0.45 W/m^2 (Bressan & Contini, 2007).

While the direct combustion of phytomass would yield the highest amount of useful energy, it is difficult to envisage the families in densely packed high-rises of Hong Kong, Mumbai, or São Paulo burning wood in small stoves. Realistic options would be the conversion of phytomass to electricity at large stations located near major plantations or the production of liquid or gaseous fuel: Such conversions would obviously lower the overall power density of the phytomass-based energy system (mostly to less than 0.3 W/m^2), require even larger areas of woody plantations, and necessitate major extensions of high-voltage transmission lines, and hence further enlarge overall land claims. Moreover, as the greatest opportunities for large-scale cultivation of trees for energy are available only in parts of Latin America, Africa, and Asia, any massive phytomass cultivation would also require voluminous (and energy-intensive) long-distance exports to major consuming regions.

And even if future bioengineered trees could be grown with admirably higher power densities (say, 2 W/m^2), their cultivation would run into obvious nutrient constraints. Non-leguminous trees producing dry phytomass at 15 t/ha would require annual nitrogen inputs on the order of 100 kg/ha during 10 years of their maturation. Extending such plantations to slightly more than half of today's global cropland would require as much nitrogen as is now applied annually to all food and feed crops—but the wood harvest would supply only about half of the energy that we now extract in fossil fuels. Other major environmental concerns include accelerated soil erosion (particularly before the canopies of many row plantations of fast-growing trees would close) and availability of adequate water supplies (Berndes, 2002).

Constraints are even more obvious as far as the substitution of refined oil products is concerned. Even if all of the world's sugar cane crop were converted to ethanol, the annual ethanol yield would be less than 5% of the global gasoline demand in 2010. Even if the entire U.S. corn harvest was converted to ethanol, it would produce an equivalent of less than 15% of the country's recent annual gasoline consumption. Biofuel enthusiasts envisage biorefineries using plant feedstocks that replace current crude oil refineries—but they forget that unlike the highly energy-dense oil that is produced with high power density, biomass is bulky, tricky to handle, and contains a fairly high share of water.

This makes its transport to a centralized processing facility uneconomical (and too energy intensive) beyond a restricted radius (maximum of about 80 km) and, in turn, this supply constraint limits the throughput of a biorefinery and the range of fuels to be produced—to say nothing about the yet-to-be-traversed path from laboratory benches to mass-scale production (Willems, 2009). A thoughtful review of biofuel prospects summed it up well: They can be an ingredient of the future energy supply but "realistic assessments of the production challenges and costs ahead impose major limits" (Sinclair, 2009, p. 407).

And finally, the proponents of massive biomass harvesting ignore a worrisome fact that modern civilization is already claiming (directly and indirectly) a very high share of the Earth's net terrestrial primary productivity (NPP), the total of new phytomass that is photosynthesized in the course of a single year and that is dominated by the production of woody tissues (boles, branches, bark, roots) in tropical and temperate forests. Most of this photosynthate should be always left untouched in order to support all other nonhuman heterotrophs (from archaea and bacteria to primates) and to perform, directly or indirectly via the heterotrophs, numerous indispensable environmental services.

Given this fact it is astonishing, and obviously worrisome, that three independently conducted studies (Vitousek et al., 1986; Rojstaczer, Sterling, & Moore, 2001; Imhoff et al., 2004) agree that human actions are already appropriating perhaps as much as 40% of the Earth's NPP as cultivated food, fiber, and feed, as the harvests of wood for pulp, timber, and fuel, as grass grazed by domesticated animals, and as fires deliberately set to maintain grassy habitats or to convert forests to other uses. This appropriation is also very unevenly distributed, with minuscule rates in some thinly populated areas of tropical rain forests to shares in excess of 60% in East Asia and to more than 70% in Western Europe (Imhoff et al., 2004). Local rates are even higher in the world's most intensively cultivated agroecosystems of the most densely populated regions of Asia (China's Jiangsu, Sichuan, and Guangdong, Indonesia's Java, Bangladesh, the Nile Delta).

Any shift toward large-scale cultivation/harvesting of phytomass would push the global share of human NPP appropriation above 50% and would make many regional appropriation totals intolerably high. There is an utter disconnect between the proponents of transition to mass-scale biomass use and the ecologists whose Millennium Ecosystem Assessment (2005) demonstrated that essential ecosystemic services that underpin the functioning of all economies have been already modified, reduced, and compromised to a worrisome degree. Would any of numerous environmental services provided by diverse ecosystems—ranging from protection against soil erosion to perpetuation of biodiversity—be enhanced by extensive cultivation of high-yielding monocultures for energy? I feel strongly that the recent proposals of massive biomass energy schemes are among the most regrettable examples of wishful thinking and ignorance of ecosystemic realities and necessities.

Phytomass would have a chance to become, once again, a major component of the global primary energy supply only if we were to design new photosynthetic pathways that did not emerge during hundreds of millions of years of autotrophic evolution or if we were able to produce fuels directly by genetically manipulated bacteria. The latter option is now under active investigation, with Exxon being its most important corporate sponsor and Venter's Synthetic Genomics its leading scientific developer (Service, 2009). Overconfident gene manipulators may boast of soon-to-come feats of algally produced gasoline, but how soon would any promising yields achieved in controlled laboratory conditions be transferable to mass-scale cultivation?

As always in global energy supply, the scale matters: A laboratory bioreactor yields a few liters of a product per day, but if we were to replace half of liquid fuels refined from crude oil with algal hydrocarbons our daily output would have to be on the order of seven billion liters, and ranging from light (gasoline-like) to heavy (residual fuel-like) fraction. And maximized and highly targeted algal photosynthesis will be always predicated on maintaining many environmental optima, namely those of water temperature (minimal fluctuation around a species-specific preference), water oxygen concentration, pH, alkalinity, light intensity, and plant density (high densities depress photosynthesis) and on providing adequate nutrients: Naturally, a great deal of energy would be required to operate such high-throughput cultivation. These realities make it clear that even if we already had superior hydrocarbon-producing algae their adoption as a globally important component of primary energy supply would not be a matter of a decade or two.

We thus come back to direct solar radiation as the only renewable energy flux distinguished not only by its abundance but also by its relatively high power density. No other renewable energy flux comes even close to the amount of solar radiation reaching the Earth at such a relatively high power density—and that density of capture could increase by an order of magnitude if we could harness sunlight in space, a concept that goes back to Glaser (1968), or on the lunar surface (Criswell, 2000) and beam the microwave energy back to the Earth.

These are conceptually very rational proposals—but with no chance of large-scale commercialization during the coming generation or two (although in 2009 Space Energy company claimed it will go commercial in 10 years).

Solar radiation reaching the ground has the highest flux in cloud-free subtropics; for example, in northeastern Saudi Arabia the maximum power densities are more than 1,100 W/m^2 during the peak insolation hours and the highest daily means go up to 350 W/m^2 (Sahin, Aksakal, & Kahraman, 2000). Annual continental average has the global mean of about 170 W/m^2 and the oceanic means is slightly higher at 180 W/m^2. Average insolation densities of 10^2 W/m^2 mean that even with today's relatively low-efficiency PV conversions (the best rates in everyday operation are still below 20%) we can produce electricity with power densities of around 30 W/m^2, and if today's best experimental designs (multijunction concentrators with efficiency of about 40%) become commercial realities we could see PV generation power densities averaging more than 60 W/m^2 and surpassing 400 W/m^2 during the peak insolation hours.

As impressive as that would be, fossil fuels are extracted in mines and hydrocarbons fields with power densities of 10^3–10^4 W/m^2 (i.e., 1–10 kW/m^2), and the rates for thermal electricity generation are similar (see Figure 4.1). Even after including all other transportation, processing, conversion, transmission, and distribution needs, power densities for the typical provision of coals, hydrocarbons, and thermal electricity generated by their combustion are lowered to no less than 10^2 W/m^2, most commonly to the range of 250–500 W/m^2. These typical power densities of fossil fuel energy systems are two to three orders of magnitude higher than the power densities of wind- or water-driven electricity generation and biomass cultivation and conversion, and an order of magnitude higher than today's best photovoltaic conversions.

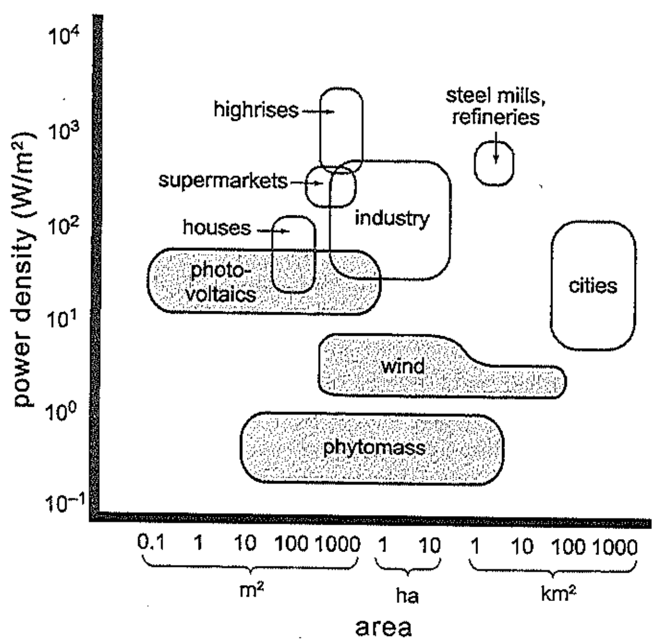
I have calculated that in the early years of the twenty-first century no more than 30,000 km^2 were taken up by the extraction, processing, and transportation of fossil fuels and by generation and transmission of thermal electricity (Smil, 2008). Spatial claim of the world's fossil fuel infrastructure is thus equal to the area of Belgium (or, even if the actual figure is up to 40% larger, to the area of Denmark). But if renewable energy sources were to satisfy significant shares (15–30%) of national demand for fuel and electricity, then their low power densities would translate into very large space requirements—and they would add up to unrealistically large land claims if they were to supply major shares of the global energy need.

Even if we assume (quite optimistically) that the cultivation of phytomass for energy could average 1 W/m^2, then supplanting today's 12.5 TW of fossil fuels would require 12,500,000 km^2, roughly an equivalent of the entire territories of the United States *and* India, an area more than 400 times larger than the space taken up by all of modern energy's infrastructures. If only half of today's fossil fuel consumption were replaced by woody biomass, its plantations would require an area a bit larger than that of all existing forests in North America.

Low extraction power densities would be the greatest challenge in producing liquid fuels from phytomass. If all of America's gasoline demands were to be derived from corn-based ethanol, the crop would have to be grown on an area roughly 20% larger than is the country's total arable land. And land claims of corn-based ethanol would be much worse outside the United States: Global corn-yield averages only a bit more than half of the U.S. mean.

At the same time, energy is consumed in modern urban and industrial areas at increasingly higher power densities, ranging from less than 10 W/m^2 in sprawling cities in low-income countries (including their transportation networks) to 50–150 W/m^2 in densely packed high-income metropolitan areas and to more than 500 W/m^2 in downtowns of large northern cities during winter (Smil, 2008). Industrial facilities, above all steel mills and refineries, have power densities in excess of 500 W/m^2 even prorated over their entire fence area—and high-rise buildings that will house an increasing share of humanity in the twenty-first century megacities go easily above 1,000 W/m^2. This mismatch between the inherently low power densities of renewable energy flows and relatively high power densities of modern final energy uses (Figure 4.2) means that a solar-based system will require a profound spatial restructuring with major environmental and socioeconomic consequences.

Figure 4.2 Power densities of renewable conversions and typical industrial, urban, and household energy uses. Plotted from data in Smil (2008).



In order to energize the existing residential, industrial, and transportation infrastructures inherited from the fossil-fuel era, a solar-based society would have to concentrate diffuse flows to bridge power density gaps of two to three orders of magnitude. Mass adoption of renewable energies would thus necessitate a fundamental reshaping of modern energy infrastructures, from a system dominated by global diffusion of concentrated energies from a relatively limited number of nodes extracting fuels with very high power densities to a system that would collect fuels of low energy density at low power densities over extensive areas and concentrate them in the increasingly more populous consumption centers. This is not impossible, but the challenges of this massive infrastructural reorganization should not be underestimated, and the tempo of this grand transformation would have to be necessarily slow. But, given our new high-tech prowess, could not these processes be accelerated, could not faster rates of coming energy transitions turn all past experiences into irrelevant examples of only a limited historical interest?

PACE OF TRANSITIONS: INNOVATION, INFRASTRUCTURES, AND INERTIA

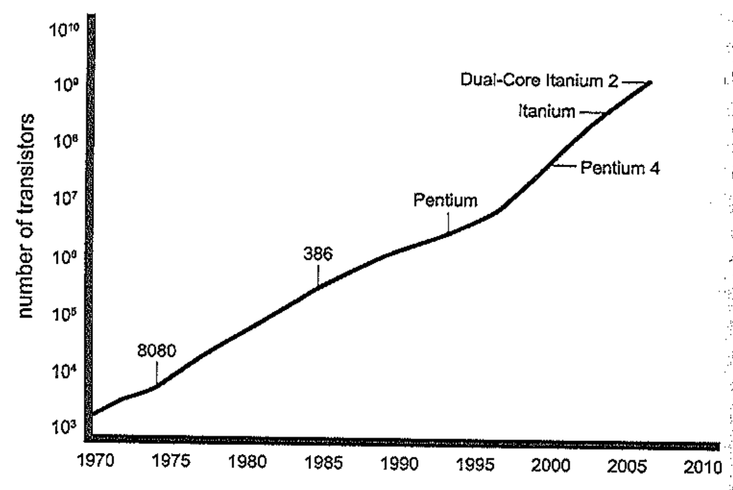
I must address first an important notion of accelerating technical advances and then look at more reasons why the coming transition from a system dominated by conversions of fossil fuels to a new arrangement relying on non-fossil energies, and mostly on harnessing renewable resources, will be more difficult than is commonly realized. Not surprisingly, the notion of generally accelerating pace of technical innovation has been driven primarily by some admirable advances in computing capacities. Extending this undeniable specific reality to a generally applicable conclusion is a clear *pars pro toto* error. Some of its expressions are truly breathtaking: According to Ray Kurzweil (a leading techno-enthusiast eager to elevate the past computing experience to a universal norm), the twentieth century was "equivalent to 20 years of progress at today's rate of progress . . . and because of the explosive power of exponential growth, the 21st century will be equivalent to 20,000 years of progress at today's rate of progress" (Kurzweil & Meyer, 2003, p. 2).

And—as attested by the existence of the Accelerating Innovation Foundation, the Center for Accelerating Innovation, and the Institute for Accelerating Change—Kurzweil's is hardly an isolated belief. Perhaps nothing expressed the hoped-for impact that this acceleration is to have on the coming energy transition than former Vice President Al Gore's appeal for repowering U.S. electricity generation in a single decade. In his speech on July 17, 2008, Gore repeated a standard mantra that "as the demand for renewable energy grows, the costs will continue to fall" and he illustrated the expected price declines with what he called one revealing example, the price of specialized silicon used to make solar cells that "was recently as high as $300 per kilogram. But the newest contracts have prices as low as $50 a kilogram." Then he continued: "You know, the same thing happened with computer chips—also made out of silicon. The price paid for the same performance came down by 50 percent every 18 months—year after year, and that's what's happened for 40 years in a row" (Gore, 2008, p. 6).

There are two fundamental problems with this unfortunate comparison. Steadily rising performance of microprocessors (chips) has hardly anything to do (as implied by Gore: "also made out of silicon") with any declines in price of silicon. True, that exacting process of producing extremely pure polycrystalline silicon and converting it into crystals that are sliced into thin wafers has become less expensive over time—but a blank silicon wafer represents only about 2% of the total value of a finished microprocessor. That phenomenal increase in microchip performance (and hence a huge drop in cost per unit operation) has been due overwhelmingly to the ability of crowding more transistors on the miniature wafer (Smil, 2006). In 1965, when the early integrated circuits contained just 50 transistors, Gordon Moore predicted that their density will be doubling every 12 months (Moore, 1965), and 10 years later he lengthened the doubling period to two years.

The world's first universal microprocessor, released by Intel in November 1971, had 2,250 metal oxide semiconductor transistors (Mazor, 1995). By 2009 their highest count on central processing units surpassed 1 billion, the result of 19 consecutive doublings. For nearly four decades Moore's law has stood the test of time (or Intel's efforts have made it a self-fulfilling prophecy) and its relentless progress has brought the combination of exponentially rising performance of microprocessors, their increasing affordability, and their still expanding applications, including in all important processes of energy extraction, harnessing, and conversion (Figure 4.3).

Figure 4.3 Moore's law. Plotted from data in Intel (2003, 2007).



Microprocessors have made exploration, production, and conversion of energy easier, more reliable, and more efficient, but their use has not changed the fundamental parameters of these established procedures and techniques. This contrast underscores the fact that an ever-denser packing of transistors on microchips has been an exceptional case of technical progress and that the advances in energy extraction, harnessing, and conversion have not been governed by rapid doublings of performances accompanied by relentless decline in prices. Even if Moore's average doubling period were relaxed and doubled to four years, we still could not find any established energy production or conversion technique that would have followed such a path of improving performance coinciding with the microchip era that began in 1971.

Even the most rapid past transitions to more efficient energy converters and to more powerful prime movers did not come anywhere close to the rates dictated by Moore's law. For example, the largest marine diesel engines increased their power rating about six-fold between 1950 and the year 2000, while gas turbines in flight increased their maximum power roughly ten-fold in 25 years, from de Havilland's Ghost engine with thrust of 22 kN in 1945 to Pratt & Whitney's JT9D with the thrust of 210 kN certified in 1969 (Smil, 2010b). More importantly, for some basic energy production processes and conversions—be it surface extraction and unit train transportation of coal, crude oil shipment by tankers and the fuel's processing in refineries, turbogenerators in thermal power plants, or long-distance transmission voltages—there have been either no, or only marginal, gains in the best performance or in maximum ratings and unit capacities during the past four decades.

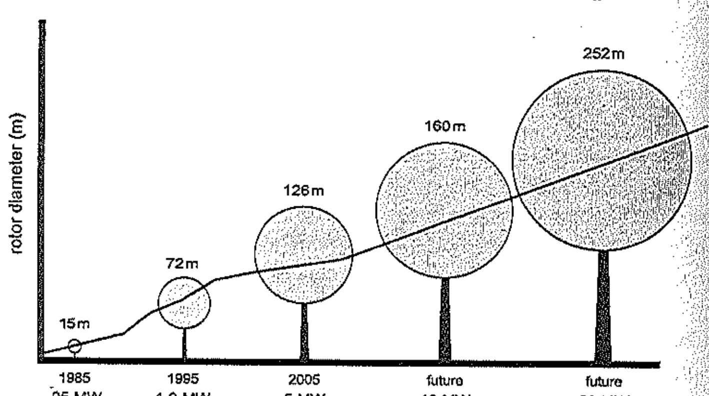
Perhaps the most important case of this technical stasis has been the efficiency of thermal generation, now the source of four-fifths of the world's electricity. Capacity of typical steam turbo-generating units has been stagnant since the early 1970s and both the maximum and average efficiency of fossil-fueled power plants have not improved since the early 1960s (Yeh & Rubin, 2003; EIA, 2009). U.S. statistics show average consumption of 11.1 MJ/kWh in 1970 and 10.9 MJ/kWh in 2000, a tiny 2% gain in three decades. Unfortunately, there are no parallels between rising microchip capacities and improving performance of energy conversions, and the idea of accelerating technical progress does not apply to any fundamental advances in energy harnessing and use.

But should not this conclusion be questioned by pointing out that it has been based on the advances of long-established, and hence obviously mature, techniques and that innovative conversions of renewable energies that are on thresholds of mass markets will behave differently? The best way to appraise their past progress and near-term potential is to focus on the two most promising new energy conversions, on wind-driven and photovoltaic electricity generation. Commercialization of large wind turbines has shown notable capacity advances and engendered high expectation. In 1986 California's Altamont Pass, the first large-scale modern wind farm, whose construction began in the 1981, had average turbine capacity of 94 kW and the largest units rated 330 kW (Smith, 1987). Nearly 20 years later the world's largest turbine rated 6 MW and typical new installations were 1 MW.

This means that the modal capacities of wind turbines have been doubling every 5.5 years (they grew roughly ten-fold in two decades) and that the largest capacities have doubled every 4.4 years (they increased by a factor of 18 in two decades). Even so, these highest unit capacities are two orders of magnitude smaller than the average capacities of steam turbogenerators, the best conversion efficiencies of wind turbines have remained largely unchanged since the late 1980s (at around 35%), and neither they nor the maximum capacities will see several consecutive doublings during the next 10–20 years. The EU's UpWind research project has been considering designs of turbines with capacities between 10 and 20 MW whose rotor diameters would be 160–252 m, the latter dimension being twice the diameter of a 5-MW machine and more than three times the wing span of the jumbo A380 jetliner (UpWind, 2009; Figure 4.4).

Hendriks (2008) argues that building such structures is technically possible, because the Eiffel tower had surpassed 300 m already in 1889 and because we routinely build supertankers and giant container vessels whose length approaches 400 m, and assemble bridges whose individual elements have mass more than 5,000 t. That this comparison is guilty of a categorical mistake (as none of those structures is surmounted by massive moving rotors) is not actually so important: What matters are the economies of such giant turbines and, as Bulder (2009) concluded, those are not at all obvious. This is mainly because the weight stresses are proportional to the turbine radius (making longer blades more susceptible to buckling) and because the turbine's energy yield goes up with the square of its radius while the mass (i.e., the turbine's cost) goes up with the cube of the radius.

Figure 4.4 Increasing rotor diameter of the largest wind turbines (1985–2010) compared with a diameter of a 20-MW machine. Adapted from UpWind (2009).



But even if we were to see a 20-MW machine as early as 2020 this would amount to just a tripling of the maximum capacities in a decade, hardly an unprecedented achievement: For example, average capacities of new steam turbogenerators installed in U.S. thermal stations rose from 175 MW in 1960 to 575 MW in 1970, more than a threefold gain. And it is obvious that no wind turbine can be nearly 100% efficient (as natural gas furnace or large electric motors now routinely are), as that would virtually stop the wind flow, and a truly massive deployment of such super-efficient turbines would drastically change local and regional climate by altering the normal wind patterns. The maximum share of wind's kinetic energy that can be converted into rotary motion occurs when the ratio of wind speed after the passage through the rotor plane and the wind speed impacting the turbine is 1/3 and it amounts to 16/27 or 59% of the wind's total kinetic energy (Betz, 1926). Consequently, it will be impossible even to double today's prevailing wind turbine efficiencies in the future.

And Gore's silicon analogy is no less flawed when applied to PV generation, a technique whose major applications have been actually based on silicon wafers. True, the cost of producing PV cells has declined substantially—from $100/W in 1970 to about $1/W—and this trend has been sufficiently impressive to engender expectations of further cost declines and to foresee an early arrival of grid-parity when the cost of decentralized PV generation will equal the cost of electricity delivered by the existing grid with electricity generated largely from the combustion of fossil fuel. Again, corrective perspectives are in order. While some producers can now turn out their cells at $1/W, the average U.S. retail price of complete PV modules was $4.60/W in 2009, and this price represented just over half of the total retail cost for a residential rooftop PV system (about $8.75/W in 2009), with balance of the system and installation accounting for most of the remainder (Solarbuzz, 2009).

If the cost of complete PV modules were to be halved every 18 months then in just 10 years it would drop to 1% of today's value and the modules selling for close to $5/W would cost less than $0.05/W, and they would be producing the cheapest electricity in history. That is, obviously, quite impossible, and the PV industry's more realistic expectations are to reduce the price of typical modules to $1.5–2/W within 10 years, implying a halving of the cost in seven to eight years. But this does not mean that the cost of actual PV installations will be halved as well, because the costs of other components (inverters and regulators) and the cost of installation may not fall that fast. After all, despite the falling costs of PV cells, the cost of electricity generated by typical residential systems (with capacities of about 2 kW) has hardly changed since the year 2000, when it was close to 40 cents/kWh: During the second half of 2009 it was still between 35 and 36 c/kWh. And even the largest industrial installations (up to 500 kW) were generating electricity in 2009 almost as expensively as in 2000 at 19–20 c/kWh (Solarbuzz, 2009).

Moreover, if there is to be early grid parity for decentralized PV systems then the total installed module cost of $8.75/W in 2009 would have to fall to about $2/W and the overall cost of producing PV cells would have to be just around $1/W. But because in the past each doubling of cumulative production volume reduced the module costs by some 20%, nearly seven doublings (more than 100-fold volume increase) would be needed to bring today's price to that level. And this would not suffice, as we would also have to assume that the non-PV costs would be declining at a comparable rate, a clearly optimistic assumption, especially as far as the cost of installation and maintenance labor is concerned.

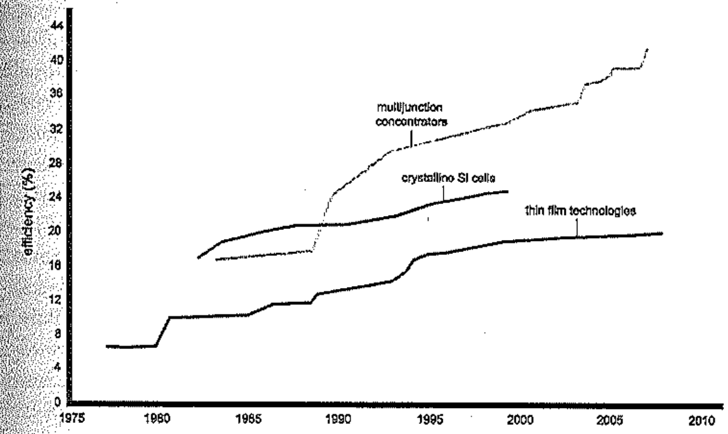
In any case, even the most enthusiastic advocates of PV electricity do not envisage a 100-fold rise in cumulative installations in a matter of years, and slower rates of cost decline would defer the time of grid parity, and hence the real beginning of large-scale diffusion of PV generation, until after 2020 or 2025. However, Yang (2010) uses the history of solar hot water systems to argue that even at that point the diffusion of decentralized rooftop PV installations may be relatively slow. Solar hot water systems have been cost-effective (saving electricity at a cost well below grid parity) in sunny regions for decades, and with nearly 130 GW installed worldwide they are clearly also a mature innovation—and yet less than 1% of all U.S. households have chosen to install them (Davidson, 2005).

The most obvious explanation is that for most consumers the long-term savings are not significant enough to justify a relatively high initial capital investment and to purchase and maintain another energy delivery system that would supplement only one function served by the existing electricity connection. If solar hot water systems are a valid indicator, then the adoption of decentralized PV generation may proceed even slower because its initial capital costs are much higher and because of the necessity to integrate these installations with the existing grid. And even more fundamentally, performance of commercially deployed PV cells has not been soaring, with efficiencies of thin-film cells doubling between 1980 and 1995 (from 8% to 16%) but remaining below 20% by 2009, while the efficiency of multijunction concentrating monocrystalline cells rose from about 30% in 1995 to about 40% by the year 2008 (NREL, 2009; Figure 4.5).

This means that even the best conversions in research laboratories have required 15–20 years to double their efficiency and that another doubling for multijunction and monocrystalline cells is highly unlikely. Similarly, fundamental physical and biochemical limits restrict the performance of other renewable energy conversions, be it the maximum yield of crops grown for fuel or woody biomass or the power to be harnessed from waves or tides: These limits will assert themselves after only relatively modest improvements of today's performance and hence no strings of successive performance doublings are ahead.

Any expectations that the future performance gains of renewable energies in general, and solar PV electricity generation in particular, will resemble the

Figure 4.5 Maximum efficiencies of PV cells achieved in laboratories. Plotted from data in NREL (2009).



post-1971 record of packing transistors on microchips are thus a consequence of succumbing to what I have called Moore's curse, an unfortunate categorical mistake that takes an exceptional performance as a general norm of coming technical innovation. The second key reason why the doubling of microprocessor performance every two years is an entirely inappropriate analogy for assessing the future of renewable energy conversions is that such a comparison completely ignores the need for massive infrastructures to extract, harness, process, transport, and convert energies.

Production of microprocessors is a costly activity, with the fabrication facilities costing at least $2–3 (and future ones up to $10) billion. But given the entirely automated nature of the production process (with microprocessors used to design more advanced fabrication facilities) and a massive annual output of these factories, the entire world can be served by only a small number of chipmaking facilities. Intel, whose share of the global microprocessor market remains close to 80%, has only 15 operating silicon wafer fabrication facilities in nine locations around the world, and two new units under construction (Intel, 2009), and worldwide there are only about 300 plants making high-grade silicon. Such an infrastructural sparsity is the very opposite of the situation prevailing in energy production, delivery, and consumption.

Coal and uranium mines, oil and gas fields, coal trains, pipelines, coal-carrying vessels, oil and LNG tankers, coal treatment plants, refineries, LNG terminals, uranium processing (and reprocessing) facilities, thermal and hydro electricity-generating plants, HV transmission lines and distribution lines, and gasoline and diesel filling stations constitute the world's most extensive, and the most costly, web of infrastructures that now spans the globe. Its individual components number between thousands (large coal mines and large thermal power plants) and tens of thousands of facilities (there are about 50,000 oil fields) and its worldwide networks extend over millions of kilometers: For example, the United States alone has about 300,000 km of oil and 500,000 km of natural gas pipelines as well as some 300,000 km of transmission lines (Smil, 2008).

These infrastructures are present in high densities in all affluent nations, and modernizing countries are building them as rapidly as they can. Certainly the most impressive example is China's coal-based quest for modernity. During the first eight years of the twenty-first century China more than doubled its coal extraction and it added almost 300 GW of new coal-fired electricity-generating capacity, more than the combined thermal-generating capacity installed in the EU's five largest economies (Germany, France, the United Kingdom, Italy, and Spain) by 2006 (EIA, 2008). Even by using a very conservative cost average of $1,000/kW the latter building spree represents an investment on the order of $300 billion and these plants will operate for at least 30–35 years to recover their cost and to make profit.

Could anybody expect that the Chinese will suddenly terminate this brand-new investment and turn to costlier methods of electricity generation that remain relatively unproven and that are not readily available at GW scale? In global terms, could we expect that the world will simply walk away from fossil and nuclear energy infrastructures whose replacement cost is worth at least $15–20 trillion before these investments will be paid for and produce rewarding returns? Negative answers to these questions are obvious. But the infrastructural argument cuts forward as well because new large-scale infrastructures must be put in place before any new modes of electricity generation or new methods of producing and distributing biofuels can begin to make a major difference in modern high-energy economies. Given the scale of national and global energy demand (for large countries 10^{11} W, globally nearly 15 TW in 2010, likely around 20 TW by 2025) and the cost and complexity of the requisite new infrastructures, there can be no advances in the structure and function of energy systems that are even remotely analogical to Moore's progression of transistor packing.

Given these realities it is not at all surprising that the actual advances of renewable conversions have not been exceptionally rapid. In global terms the new renewables—wind, geothermal, solar (both thermal and PV), and modern biofuels—contributed no more than 0.45% of all primary energy in 1990 and by 2008 that share rose to about 0.75%. In relative terms this translates to an annual exponential growth of 2.85%, a much slower expansion than during the early decades of coal mining (more than 5%/year between 1850 and 1870), oil extraction (more than 8%/year between 1880 and 1900), or natural gas production (more than 6%/year between 1920 and 1940). And while in relative terms this was a considerably faster growth rate than those of expanding coal, crude oil, and natural gas production during the same period (their multiples were, respectively, 1.56, 1.48, and 1.24), in absolute terms it amounted to adding an equivalent of about 50 Mtoe in 18 years while during the same period coal production added about 1,080 Mtoe, oil extraction added about 760 Mtoe, and natural gas production increased by nearly 990 Mtoe.

Fossil fuel additions during that period thus amounted to about 2.83 Gtoe and they were roughly 57 times higher than the gain for all new renewables. Jefferson (2008) calls this rightly a very poor performance, but the contrast is not so surprising when the first (already outlined) challenge of the coming transition—the magnitude of the global switch from fossil to renewable energies—is kept in mind. The achievement is, obviously, better as far as electricity is concerned, but even in that case the aggregate share for wind, geothermal, PV, and biomass-fueled generation reached just 3% of the total in 2008, wind generation accounting for half of that fraction, and with solar electricity remaining below 0.05% of the total.

Finally, I must emphasize the relatively slow rates of past and present transitions to new prime movers. This was the case for replacing draft animals by machines even in the United States, where it had taken more than half a century to complete the transition from horses and mules to tractors and combines to internal combustion engines. Less surprisingly, poverty explains why the transition from animate to inanimate prime movers in agriculture is yet to be completed in many low-income nations: There are still some 500 million draft oxen, buffaloes, horses, donkeys, and camels, most of them in Asia and Africa. On national scales their aggregate capacity (roughly 200 GW) has become dwarfed by the power of agricultural machinery tractors and pumps but their work remains indispensable in many rural regions not only for field work but also for local transportation.

Inertial reliance on the first mechanical prime mover is best illustrated by a wartime example. By the time the Japanese attacked Pearl Harbor in December 1941 there could be absolutely no doubt about the superiority of diesel engines in marine propulsion: First small ship engines were installed on river-going vessels in 1903, the first diesel-powered vessel completed its intercontinental voyage in 1911, and by 1940 a quarter of the world's merchant fleet, and practically all newly launched ships, had diesel engines (Smil, 2010b). But when the U.S. military needed the fastest possible delivery of a large number of transport ships the choice was made to go with steam propulsion. Between 1942 and 1945 U.S. and Canadian shipyards built 2,710 *Liberty* (EC2) class ships powered by three-cylinder steam engines (each supplied by two oil-fired boilers) rated at 1.86 MW (Bunker, 1972; Elphick, 2001). The "ships that won the war" thus used the prime mover introduced during the 1770s and perfected during the subsequent 100 years.

As already explained (in chapter 2), the world's currently most numerous fuel-powered prime movers are internal combustion engines, gasoline-fueled sparking engines in passenger cars and light trucks, and diesel engines in cars, heavy trucks, trains, ships, and heavy machinery. By 2010 the aggregate count of these machines reached one billion and their installed capacity surpassed 150 TW. Their remarkable inertia is illustrated by recalling that their first prototypes were deployed in Germany during the mid-1880s (gasoline engines built by Benz, Maybach, and Daimler) and the late 1890s (Diesel's engine), that their commercialization was well underway before World War I, and that their technical maturity was reached shortly after World War II with designs in the United States, Europe, and Japan. The engine's two currently most prominent innovative modifications—a hybrid arrangement that couples it with electric motors, and so-called Dies-Otto engine that combines its standard (sparking) operation with that of a (non-sparking) Diesel machine—do not fundamentally alter its basic design.

The only emerging rival of gasoline and diesel engines is the all-electric drive, but a long history of electric cars and repeated delays of their mass adoption make an imminent demise of the gasoline-fueled internal combustion engine highly unlikely. Technical breakthrough of another alternative, the fuel cell–powered drive, was prematurely touted as imminent during the late 1990s but the probability of near-term large-scale commercial adoption of vehicles powered by hydrogen remains exceedingly low. An even more unlikely event is any early replacement of massive diesel engines that are used in heavy-duty road and rail transport and that almost completely dominate high-volume ocean shipping: There is simply no alternative to the machine, as no existing combustion engine can deliver the same service at a comparable cost and, no less importantly, at a similarly high reliability and durability.

Finally, most people would not think of steam turbines when asked to name the world's most important continuously working prime mover. The machine was invented by Charles Parsons in 1884, it was much improved and widely commercialized before World War I, and it has remained fundamentally unchanged 125 years later: Gradual advances in metallurgy made it simply larger and more efficient, but their pace has slowed significantly since the late 1960s and the early 1970s when it reached its highest unit capacities in excess of 1 GW. The position of steam turbines as the world's most powerful stationary prime mover is solidly entrenched: These machines now generate more than 70% of the world's electricity in fossil-fueled and nuclear stations (the rest comes from gas and water turbines and diesels) and there is simply no alternative technique of a similar capacity, efficiency, and reliability in sight. And there are no prospects for any near-term replacement of gas turbines used in flight: There is simply no alternative to replace these prime movers that have dominated global air transportation since the 1960s.

Without any doubt, our reliance on those indispensable prime movers introduced, respectively, during the 1880s, 1890s, and 1930s is even more inertial than our dependence on primary energies: Transition spans for fuels are measured in decades, while generations (a single generation being a span of 20–30 years) may

be a better choice for the prime movers. As a result the principal impact of renewable energy conversions on transportation will be limited for many decades to producing alternative fuels to be used by internal combustion engines and perhaps also by natural gas turbines in flight. But, as already explained, an even relatively modest contribution by liquid biofuels (up to 20% of today's global demand for gasoline, kerosene, diesel, and residual oils) would have enormous impacts on agroecosystems, on fertilizer and energy demand and costs, and on world food prices.

NATIONAL ASPIRATIONS: GOALS AND REALITIES

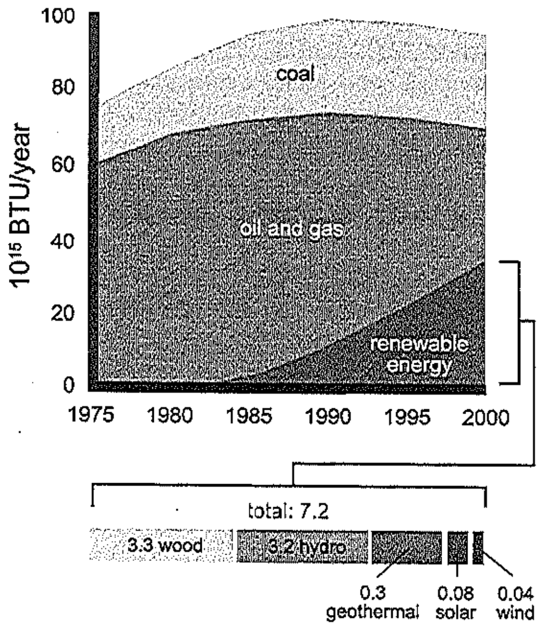
Substitution goals are usually stated as shares of a particular energy supply to be provided by specified new energy conversions in future years (typically ending in zero or five) and are accepted by governments, although not necessarily as binding targets. Aspirations and perceived potentials are expressed in formal and informal forecasts, proposals, and scenarios produced by governments, industrial associations, nongovernmental organizations, and universities, and by frequent promises of campaigning politicians. Most of these goals and aspirations share a basic property, namely that they do not dwell on all those sobering, limiting, and complicating realities that were explained in the first two sections of this chapter.

Robust optimism (or, less charitably, naïve expectations) and a remarkable unwillingness to err on the side of caution is an unmistakable commonality shared by an overwhelming majority of those goals, promises, and aspirations. This, of course, is nothing new. Recent anticipations of a fairly rapid and comfortingly smooth transition to renewable energies had a notable precedent during the aftermath of the first two energy "crises" (1973–1974 and 1979–1981) when those large, OPEC-driven increases in oil prices convinced many people that the end of the hydrocarbon era was imminent and that a grand transition to renewable was about to begin.

Among many failed forecasts from that era is the InterTechnology Corporation's (1977) conclusion that by the year 2000 solar energy could provide 36% of U.S. industrial process heat; Sørensen's (1980) disaggregation that put the share of U.S. renewable energy in 2005 at 49%, with biogas and wind each at 5%; and Lovins's forecast of more than 30% renewables in 2000. Actual share of all renewables in the U.S. 2000 primary energy supply was about 7%, with biogas supplying less than 0.001%, wind 0.04%, photovoltaics less than 0.1%, and there was no use of solar energy for industrial heat supply (Figure 4.6).

But the boldest shift toward renewable energies in the wake of the oil price shocks of the 1970s was to be made in Sweden: By 2015 the country was to derive half of its energy from tree plantations that were to cover 6–7% of the country's large territory (Johansson & Steen, 1978). Moreover, the country's

Figure 4.6 In 1976 Lovins forecast a 33% share of renewable energies in the U.S. primary energy supply: The actual share of 7.2% was composed mostly of water power and wood, with the new renewable (wind, solar, geothermal) providing only 0.42% of the total. Based on Lovins (1976) and data in EIA (2009).



reedlands were to become an important source of pelleted phytomass (Björk & Granéli, 1978). Those visions fell apart as rapidly as their U.S. counterparts, but a large-scale Swedish quest for biomass energy was reincarnated during the 1990s in the form of new plans for massive willow (*Salix viminalis*) plantations to be harvested four to six years after planting and then in three to four year intervals for at least another 20 years (Helby, Rosenqvist, & Roos, 2006). The principal use of the wood was to be combustion for district heating and in combined heat and power generation plants.

New operations received government subsidies of 10,000 SEK/ha at planting and in 1998 the Swedish Environmental Protection Agency envisaged more than 100,000 ha of energy willows in production by 2005 and nearly 400,000 ha by 2020. Here are the prosaic realities of 2009. Sweden has no large-scale cultivation of reeds for energy and no mass-production of pelletized reed phytomass. There has been a massive retreat from willow plantings: After a linear ascent to about 14,000 ha between 1989 and 1996 the further expansion of willow plantings had stopped—leaving the area at about 10% of the extent where it should have been by now—and some 40% of farmers have either retreated from willow cultivation or are regretting that they ever turned to that kind of silviculture.

And the country's energy balances show that in 2008 all combustible renewable and wastes (dominated by wood) supplied less than 2% of all primary energy. And so it appears that this attempt to energize a modern society by coppiced willows (an image that invokes medieval landscapes of severely pruned trees) is not turning into a harbinger of things to come.

Given this history it is only fair to ask: Are today's forecasts of anticipated, planned, or mandated shares of renewable energies as unrealistic as those of three decades ago? Jefferson (2008, p. 4116) gave a reasoned answer that covers all the major points: "Targets are usually too short term and clearly unrealistic . . . subsidy systems often promote renewable energy schemes that are misdirected and buoyed up by grossly exaggerated claims. One or two mature energy technologies are pushed nationally with insufficient regard for their costs, contribution to electricity generation, transportation fuels' needs, or carbon emission avoidance."

I will illustrate these general observations by a number of prominent examples. Two of the eight countries whose energy transitions were traced in this book's previous chapter—oil-rich Saudi Arabia and hydrocarbon- and coal-rich Russia—have no (formal or informal) goals for using more renewable energy for domestic consumption. There is an academic project of renewable scenarios for Saudi Arabia (Al-Saleh, Upham, & Malik, 2008)—but the country's oil minister warns against any rapid shift to renewables (because it may result in energy shortages once the global economy recovers) even as he expresses his hope that Saudi Arabia will become "the world's largest exporter of clean electric energy produced from our abundant sunlight"—but not for another 30 to 50 years (Patel, 2009).

In contrast, Europe is the leader of renewable promises. The EU's *Second Strategic Energy Review* set "the ambitious objective of raising the share of renewable energy sources in its final energy consumption from around 8.5% in 2005 to 20% in 2020" as "a necessary contribution to the fight against climate change and the effort to diversify our energy mix" (CEC, 2008, p. 20). Because most of today's renewable share consists of hydroelectricity, those member countries with minimal water power will find that target extremely challenging as they would have to add new renewable capacities only in wind and solar electricity generation and in biofuels. But if the biofuel target will also include all aviation fuel, then it will be challenging for every EU state: The vision of every fifth jetliner powered by bio-kerosene by 2020 is surely a heady one! No matter, "green" activists are urging to aim far higher: For example, a report prepared by Friends of the Earth Scotland and WWF Scotland concluded that renewables (hydro, wind, waves, and geothermal) can supply 60% of the Scotland's electricity by 2020 and 143% of the demand by 2030 (FOE Scotland, 2009).

Sweden is at it again, and in an official manner: In June 2006 the governmental Commission on Oil Independence issued its report boldly entitled *Making Sweden an OIL-FREE Society* (COI, 2006). That would be a stunning accomplishment particularly as it is to be done without any reliance on nuclear generation (the existing plants are to be closed). Achieving that goal would take more than rejuvenating the moribund willow plantings, the Swedes would also have to give up all flights to Thailand, and refuse to eat Spanish produce: I would rate the likelihood of reaching the goal at less than 0.3%, a 3σ event. But reading beyond the report's catchy title reveals more realistic goals, beginning with a 20% increase in overall efficiency of energy use, and reducing gasoline and diesel use in transportation by 40–50% and cutting the use of refined fuels in industry by 25–40%. "Oil-free" would apply only to heating residential and commercial buildings: "by 2020 in principle no oil should be used" by those sectors, with biofuels and renewable electricity filling the need.

Japan, not too long ago considered as a leader in solar heat and PV conversions, has only a minimalist renewable energy target of 1.6% of the total supply by 2014 compared to 1.3% in 2009. In contrast, China, now the world's largest user of coal and the leading emitter of CO_2, has set a very ambitious target of 15% of all primary energy supply coming from renewables by 2020, but some Chinese policymakers believe that with the accelerated development of wind and solar generation the actual share will be at least 18% and perhaps even 20%, matching the EU goal (*China Daily*, 2009). I would classify the probability of meeting the last target as another notable 3σ event.

But, and despite the country's weakening economic and strategic power, it will be the U.S. achievements that will prove or disprove the possibilities of an accelerated shift toward renewable conversions. Although the country has no formal government-mandated target for future renewable energy shares, it has no shortage of goals and proposals. The Utility Solar Assessment Study offered what it called "a comprehensive roadmap for utilities, solar companies, and regulators" to produce 10% of U.S. electricity by PV generation by 2025, a goal predicated on costs below $3 per peak watt by 2018 and by substantial grid expansion (USA, 2008).

Because wind-powered electricity generation is technically the most mature choice it is hardly surprising that most specific production targets refer to its future shares of electricity generation. The U.S. Department of Energy projected 20% of U.S. electricity generated by wind turbines by 2030, a goal requiring about 250 GW of new capacity on land and roughly 55 GW offshore (USDOE, 2008). For comparison, the European Wind Energy Technology Platform, launched in 2006, is relatively slightly more ambitious, calling for 180 GW (including 40 GW offshore) by 2020 and 300 GW (half offshore), or about 25% of the EU's electricity consumption, by 2030 (TPWind, 2008). But by far the most ambitious energy transition challenge for the United States was presented by the country's former vice president.

Gore's fundamental premise is that the country's three major challenges—the economic, environmental, and national security crisis—had a common denominator in "our dangerous over-reliance on carbon-based fuels." And Gore is confident that he has an effective solution (Gore, 2008, p. 4):

> But if we grab hold of that common thread and pull it hard, all of these complex problems begin to unravel and we will find that we're holding the answer to all of them right in our hand. The answer is to end our reliance on carbon-based fuels . . . We have such fuels. Scientists have confirmed that enough solar energy falls on the surface of the earth every 40 minutes to meet 100 percent of the entire world's energy needs for a full year. Tapping just a small portion of this solar energy could provide all of the electricity America uses. And enough wind power blows through the Midwest corridor every day to also meet 100 percent of US electricity demand. Geothermal energy, similarly, is capable of providing enormous supplies of electricity for America. The quickest, cheapest and best way to start using all this renewable energy is in the production of electricity. In fact, we can start right now using solar power, wind power and geothermal power to make electricity for our homes and businesses.

Gore's bold goal called for "a strategic initiative designed to free us from the crises that are holding us down and to regain control of our own destiny": He challenged the nation "to commit to producing 100 percent of our electricity from renewable energy and truly clean carbon-free sources within 10 years" and he thought that goal to be challenging but "achievable, affordable and transformative." His confidence was based on his expectation that "as the demand for renewable energy grows, the costs will continue to fall" and then he used the silicon analogy to explain the anticipated cost declines. I have already explained the completely misleading and entirely inappropriate choice of this analogy in the preceding section.

Here I will focus on another critical matter, on Gore's unrealistic appraisal of technical and infrastructural possibilities. In 2008 the United States generated about 4 PWh of electricity with almost exactly one half coming from coal-fired stations, 20% from nuclear fission, only a bit over 6% from hydro stations, and just 2.3% came from "new" renewables, that is, wind, geothermal, and solar (EIA, 2009). Because Gore wants to eliminate carbon-based electricity this would mean replacing 71% of the current generation originating in the combustion of fossil fuels. But if the country were to end up only with "renewable" means of electricity generation then the repowering should also affect the nuclear stations, whose operation emits no carbon but whose source of energy (fissionable isotopes) is obviously not renewable: Then the country would have to replace just over 90% of its current generation.

In 2007 the net summer capacity of the U.S. fossil-fueled stations was about 740 GW and they generated 2.88 PWh of electricity, which means that the load factor (number of hours they were generating in a year) was about 44% (with averages of 73% for base-load coal-fired stations but only 25% for predominantly peak-load natural gas-fired generation). In 2007 wind and solar electricity contributed just 35 TWh (less than 0.9% of the total), and with installed capacity of 17 GW its load factor was just 23%. This means (assuming a high degree of HV interconnections to distribute the concentrated wind generation) that two units of generating capacity in wind and solar would be needed to replace one unit of capacity currently installed in coal- and gas-fired plants—and the country would have to build about 1,480 GW of new wind and solar capacity in a single decade, or roughly 1.65 times as much as it had added between 1950 and 2007!

Annual capacity additions would have to average nearly 150 GW or, if they would start lower and then accelerate, they would have to reach more than 200 or 250 GW during the decade's last few years: This compares to the average net additions of less than 15 GW/year of all generating capacity during the two decades between 1987 and 2007, and to the record wind capacity addition of 8.5 GW in 2008 (AWEA, 2009). These contrasts alone—most notably the fact that annual additions would have to average 20 times as much as the record 2008 rate—should suffice to demonstrate the impossibility of the task. Moreover, that impossible feat would also require writing off in a decade the entire fossil-fueled electricity generation industry and the associated production and transportation infrastructure, an enterprise whose replacement value is at least \$2 trillion—while concurrently spending no less than \$2.5 trillion (assuming, conservatively, \$1,500/kW) to build the new renewable generation capacity.

But those new capacities would be concentrated in the Great Plains (with wind power densities being the highest in their northern part) and in the Southwest (with southern California, Nevada, Arizona, and New Mexico having the highest average insolation), and these regions have currently either only weak connections with the rest of the country or, for the most part, no major HV transmission links to major load centers on the East and West Coast at all. Repowering of the United States would thus have to be preceded by considerable rewiring, by creation of new, high-capacity, long-distance transmission links. This limited transmission capacity to move electricity from the new power centers in the Southwest, Texas (Texas has its own grid weakly connected to the rest of the country), and the Midwest has been already delaying new wind projects even as wind generates less than 2% of all U.S. electricity. The United States now has about 265,000 km of HV lines, and at least 65,000 km of new high-capacity lines would be needed to rewire the nation, at an aggregate cost surpassing \$100 billion.

Once again, this is a very conservative estimate (assuming about \$2 million/km), as the costs are bound to escalate. A key factor in this matter, besides the usual uncertainties concerning future inflation rate and rises in the cost of materials, is a lengthy regulatory approval process that takes many years even before a new line construction can begin. Installing in 10 years wind- and solar-generating capacity more than twice as large as that of all fossil-fueled stations operating today while concurrently incurring write-off and building costs on the order of \$4–5 trillion and reducing regulatory approval of generation and transmission megaprojects from many years to mere months would be neither achievable nor affordable at the best of times: At a time when the nation has been adding to its massive national debt at a rate approaching \$2 trillion a year, it is nothing but a grand delusion (to say nothing of the fact that solar generation is far from ready to be deployed on a GW scale).

Gore's repowering plan was actually preceded by a more modest, but still very ambitious, plan advanced during the summer of 2008 by T. Boone Pickens, a Texas oilman, billionaire, and former corporate raider. His 10-year energy plan for United States had what I called an appealing "cascading simplicity" (Smil, 2008). Pickens wanted to fill the Great Plains ("the Saudi Arabia of wind power") with wind turbines; this new wind power would replace all the electricity currently produced by burning natural gas. This natural gas freed by wind-powered generation would be used to run efficient and clean natural gas vehicles. And this substitution would create new, massive, domestic aerospace-like industry (providing good jobs and bringing economic revival to the depopulating Great Plains) while cutting U.S. oil imports by more than one third and helping to put the country on a better fiscal foundation.

Pickens outlined the plan to the Congress and promoted it with a \$58 million advertising blitz to rally public support (www.pickensplan.com). There is no arguing about the key reason behind the plan: Pickens rightly saw the U.S. addiction to oil, especially with the high prices of the summer 2008, as a threat to "our economy, our environment and our national security" that "ties our hands as a nation and a people." But his plan would require building more than 100,000 wind turbines, connecting them to large cities with at least 65,000 km of transmission lines, and converting tens of millions of cars to natural gas fuel, a daunting task for a single decade. The plan proposed roughly \$1 trillion in private investment to build the large wind farms and (conservatively estimated) another \$200 billion in order to construct the requisite high-voltage transmission lines that would connect those giant wind farms to densely populated coastal regions.

Al Gore has not withdrawn or substantially modified his plan and his organization (wecansolveit.org) went on to publish pathetic prayer-like advertisements imploring "our leaders" to "free us from our addiction to oil . . . Save us from this climate crisis . . . Give us 100% clean electricity within 10 years." Pickens first acknowledged that his grandiose plan has little chance to be realized anytime soon due to inadequate transmission links, late in 2008 he switched his vehicular gas proposal from passenger cars to trucks (because only about 1% of America's filling stations are equipped to sell compressed natural gas), and by July 2009 the economic downturn led him to delay it: "I didn't cancel it. Financing is tough right now and so it's going to be delayed a year or two" (Rascoe & O'Grady, 2009, p. 1). Even his own project, that was planned to be the world's largest, 4-GW wind farm near Pampa in Texas, was set aside because the \$4.9 billion worth of the needed transmission lines will not pass all regulatory requirements before 2013.

The Grand Energy Transition (GET) plan proposed by Robert Hefner, a lifelong natural gas explorer and producer, amounts basically to the second part of the Pickens Plan, but with some other questionable provisos (Hefner, 2009).

Hefner believes not only that U.S., and global, natural gas resources are larger than those of crude oil (a view shared by others) but that U.S. attainable gas reserves are as large or perhaps even larger than the country's remaining minable coal deposits. Although the last claim may be too optimistic, the latest assessment by the Potential Gas Committee (2009) boosted the estimate of the U.S. gas resources by 39% compared to the 2006 total.

In any case, Hefner's plan calls for retrofitting and converting half of the U.S. vehicle fleet to natural gas by the year 2020. He also believes that this would not be a difficult conversion because a natural gas grid already extends to most of today's urban gasoline filling stations as well as to some 63 million homes where more than 130 million vehicles could be filled with a convenient home-fueling appliance. According to Hefner this conversion would cut the oil imports by about 250 Mt/year (in 2008 the country imported nearly 640 Mt), save trillions of dollars of foreign payments, trigger some $100 billion of private investment due to higher natural gas demand, and add some 100,000 new jobs. Actually the most important part of the GET plan that would unleash these massive changes is the elimination of taxes on labor and capital and their replacement with a "green" consumption tax to be levied initially on coal and oil products. Even if gas resources were superabundant, an obvious question to ask concerns the likelihood of the U.S. Congress acting to eliminate all taxes on labor and capital.

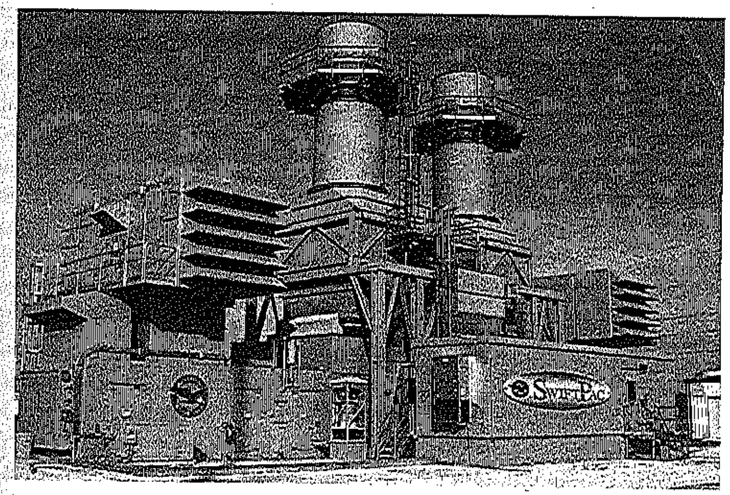
I will note just one more of several recently issued sweeping proposals for reducing U.S. dependence on fossil fuels, Google's plan to repower the United States that was released in October 2008, shortly after Gore's challenge. Google's *Clean Energy 2030* called for "weaning the U.S. off of coal and oil for electricity generation by 2030 (with some remaining use of natural gas as well as nuclear), and cutting oil use for cars by 44%" (Google, 2008). This rapid energy transition rests on three key steps. First, cutting the fossil fuel–based electricity generation by 88%. Second, deploying aggressive end-use electrical energy efficiency in order to cut the anticipated 2030 demand by 33% and hence keep the overall demand flat at the 2008 level. And, finally, by raising the sales of plug-in vehicles (hybrids and pure electrics) to 90% of all new car sales by 2030 and boosting the conventional vehicle efficiency to 45 mpg by 2030.

Based on the past experience and on the current baselines I conclude that keeping the nationwide electricity demand flat at the 2008 level by 2030 and raising the average car performance to 45 mpg are technically eminently doable goals. Having plug-in vehicles taking over in just two decades is an entirely different challenge, and eliminating nearly 90% of all fossil-fueled electricity generation is a goal whose achievement is based on some unrealistic assumptions. The Google plan proposes to do that by eliminating all electricity produced by burning coal and liquid fuels and about half of all electricity originating in gas-fired stations: Their generation amounted to about 2.5 PWh in 2007 and they are to be replaced by 380 GW of new wind, 250 GW of new solar, and 80 GW of new geothermal capacity.

Google's plan points out (correctly) that such rapid build-ups of electricity-generating capacity are not without precedent: Most notably, more than 200 GW of natural gas-fired capacity were added between 1998 and 2006, including 60 GW in a single year (in 2002); and during the 15-year period between 1972 and 1987 more than 85 GW of new nuclear generation capacity were put in place (with peak addition of almost 10 GW/year) raising the share of nuclear electricity generation from about 3% to 18%. Unfortunately, both comparisons are categorical errors, and the second one should not be invoked to demonstrate possibilities of rapid capacity growth because the history of U.S. nuclear expansion is actually the best possible example of perils inherent in forecasting the transition toward new energy conversions.

In 2008 the average capacity of newly installed U.S. wind turbines was about 1.7 MW, with the largest units between 3 and 5 MW, and today's large-scale industrial-size PV units remain below 1 MW—while gas turbines larger than 100 MW have been available since 1976, units around 200 MW are common and in 2008 Siemens completed the world's largest gas turbine, rated at 340 MW (Siemens, 2009). Moreover, it is usually quite easy to accommodate those units at the existing power plant sites (they need very little space) and they can be ready to generate in a few months; indeed, some gas turbines, such as P&W's SwiftPac available in 30-MW and 60-MW sizes, can be ordered fully assembled and packaged in multi-trailer modules and are able to generate electricity in less than a month after arriving at their location (Figure 4.7).

Figure 4.7 Pratt & Whitney's SwiftPac series of gas turbines (30–60 MW) used to generate electricity requires less than a month to install. Copyright (C) 2008 United Technologies Corporation. All rights reserved.



And turbogenerators in nuclear stations were added in unit capacities ranging from 300 MW to more than 1 GW!

In contrast, before large wind farms are assembled from hundreds of massive units their siting is subject to lengthy selection, environmental assessment, and approval process, and their completion (as Pickens so quickly discovered) *must be preceded* by the construction of requisite high-voltage transmission lines, a process that demands even lengthier route selection and regulatory approval. No less importantly, in order to generate 2.5 PWh of electricity, Google's renewable conversions would have to achieve average load factors of 35% for both wind and solar and 80% for geothermal generation. The last rate is realistic; the first two are impossibly high as national means rather than as exceptional ratings.

Years of experience with European wind power give a clear long-term answer: Average load factor for the European Union between 2003 and 2007 was just 20.8%, with the high of 29.3% for Ireland and Greece and the low of 18.3% for Denmark (Boccard, 2009). Similarly, solar PV capacity factors average below 25% even in such sunny places as Arizona, and studies show that (because of the limited flexibility of base-load units) increasingly large amounts of unusable PV generation would be produced when PV capacities would reach 10–20% of a system's total capability (Denholm & Margolis, 2007). And, to mention only one additional notable complication, the single largest item in Google's appraisal of net savings accruing from this rapid forced transition are carbon credits for CO_2 not emitted, rated initially at $20/ton of CO_2 and doubling by 2030—but no such mechanism is in place and nobody knows when, indeed even if, it will be enacted by the Congress.

Uncertainty regarding this key profit-making assumption underscores a major failing of all of explicit transition plans or bold aspirations: Their goals might have a fair probability of success only if a concatenation of extraordinarily advantageous circumstances and radical departures from prevailing modes of action (most often a strong government intervention) and resource valuation (be it the proposed carbon credits or life cycle assessment pricing) takes place. But the history of energy transitions makes it clear that many unexpected discontinuities have strongly affected the economic viability, public acceptance, and governmental support of new fuels and new conversion techniques and that they had changed, or even reversed, their adoption or diffusion rates.

The most prominent examples of this kind that have been encountered in the past three decades are listed here in order that does not imply any ranking: unpredictable shifts in energy prices; relatively sudden arrival of major new consumers to the global market; loss of faith in approaches that were initially touted as effective and rewarding solutions, a process that begins with a sudden embrace and ends with an equally sudden abandonment of problematic or immature techniques; effects of long-term environmental implications of energy use; unprecedented economic crises; fiscal mismanagement whose painful effects can be postponed but not averted; and recurrent eagerness of governments to support fashionable solutions whose long-term impact turns out to be limited or nonexistent.

Here are some essential expansions of these seven prominent examples. Unprecedented rise of world crude oil prices between 1973 and 1981 (from around $2/bbl to as high as $38/bbl in monies of the day) followed by their precipitous fall (monthly mean as low as $11/bbl in July 1986) were the main reasons for the fact that the 1979 peak level of global oil consumption was not surpassed until 1994, and that the new exploratory drilling, overall investment in the sector and new oil discoveries entered a long period of post-1985 slump, and that the oil stocks were the least profitable stock market play of the entire 1990s.

As for the arrival of new major and rapidly growing consumers of energy whose entry into the global market for fuels has had a strong effect on prices, China is the top example, with India a distant second. Who would have said in 1980, four years after Mao's death, or in 1990, a year after the Tian'anmen killings when China continued to be a significant oil exporter with a relatively limited manufacturing base, that at the beginning of a new century the country will become a major oil importer, a veritable factory for the world, the planet's second-largest energy user and the first emitter of greenhouse gases? Looking ahead, India (whose population will surpass that of China in about three decades) has a no smaller potential to alter the global energy market, especially given the fact that its per capita consumption of primary energy is still so much lower than in China (in 2010 just short of 20 GJ/capita in India vs. nearly 65 GJ/capita in China).

Nuclear electricity generation is not the only prominent example of a rather sudden loss of faith in a new technique that was seen, for years or even decades, to offer an ultimate (or nearly so) solution before its sudden retreat. At the height of the second oil price crisis in the late 1970s it was the oil production from shales that was to save the United States, and that was supported by a huge commitment of federal monies: the Energy Security Act of 1980 budgeted $17 billion (with a further $68 billion to follow) in order to set a massive new industry producing two million barrels of oil from the Rocky Mountain shales by 1992, but the projected fizzled out rapidly and was completely abandoned in 1985 after the oil prices collapsed.

Two decades later we were assured that within 10 years fuel cells will be the standard energizers of our road vehicles. Market value of Ballard Power Systems of Burnaby, BC, a principal developer of hydrogen-powered fuel cells, topped C$300/share in early 2000—but by the end of 2008 it stood at C$3/share and the company had abandoned any further development of hydrogen-fueled propulsion and survives by selling fuel cells for forklifts and stationary units used for backup electricity generation.

In 1980 acid deposition (a problem largely eliminated by the combination of flue gas desulfurization and switch to low-sulfur fuels, above all to natural gas) was the dominant environmental worry for the Western energy industries.

That concern hardly registers now, with the worries about global warming dwarfing all other environmental impacts of modern energy use.

Little has to be said about the impact of sudden, massive (indeed global) economic dislocations. The global economic downturn that began in 2008 has been, undoubtedly, the worst event of its kind since World War II and the ensuing drop in demand, sharply declined availability of credit, and enormous deficit spending on assorted bailout plans has made many energy targets excessively ambitious. Moreover, nobody knows how deep and how protracted its eventual impact will be. Fiscal mismanagement whose extent and depth eventually comes to limit the actions governments and consumers can make is frighteningly illustrated by the state of U.S. finances, with a grand total of debts (including uncovered future federal and state obligations) now surpassing $60 trillion, roughly five times the country's annual GDP. And the ways in which governments subsidize energy industries and new conversions have ranged from unjustifiable persistence (with tens of billions poured into fusion research during the past 50 years and with nuclear research receiving more monies than all other forms of energy combined) to unpredictable fickleness (credits for wind-powered generation).

The abrupt cessation of U.S. nuclear expansion is perhaps the best illustration of how exaggerated aspirations can end in outcomes that are a fraction of original goals (Smil, 2003). Expectations during the early 1970s were for annual capacity additions exceeding 50 GW in light water reactors beginning during the mid-1980s; at that time the first liquid metal fast breeder reactors (LMFBR) were to make their commercial entry and by 1995 they, too, were expected to add 50 GW/year of new capacity, a combination that was to eliminate all fossil-fueled electricity generation before 1990. In reality, no new nuclear stations were ordered in the United States after 1978 and there is not a single operational LMFBR.

Given all of these uncertainties it is not surprising that the past performance of renewable conversions cannot be used to prime quantitative models of their future advances. The key problem with this approach is that there is not a single growth curve to follow. Growth and diffusion of most phenomena—including energy resource substitutions and adoption of new fuel and electricity conversion techniques—is a process that almost inevitably follows a progression that is distinguished with its slow initial advances followed by a rapid rise, an eventual inflection point, and rapidly declining increments towards saturation. However, when complete or nearly complete substitution or diffusion processes are studied retroactively, some of them are found to conform to a logistic equation while others are best fitted with its variants including, most notably, Gompertz, Weibull, and hyperlogistic distribution (Banks, 1994).

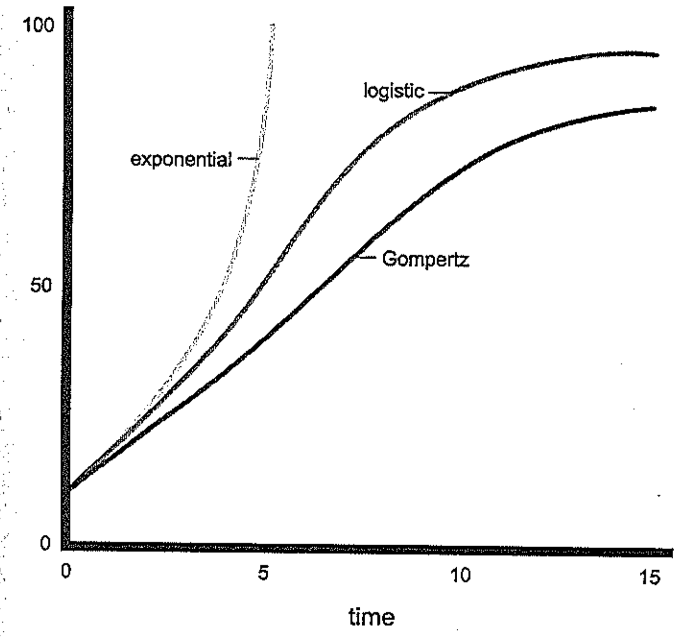
Kramer and Haigh (2009) tried to translate this well-known progression into what they called "the laws of energy-technology deployment." The first law dictates a few decades of exponential growth for new conversions (amounting to an order of magnitude increase in a decade), the second one describes linear gains

after reaching "materiality," that is around 1% of world energy mix. This is nothing else but an alternative description of a ubiquitous growth process—but, as always, the specifics will vary, and saying that the deployment curves of different innovations are remarkably similar is correct only in the sense that the progress must resemble a variant of a growth curve.

Actual growth pattern of any particular innovation cannot be selected *a priori* with a high degree of confidence and the best fit (with some inevitable scatter) can be accurately ascertained only *ex post*. For example, a forecast based on a logistic curve rather than on a Gompertz distribution would end with the same outcome but the former trajectory has a much stronger (nearly exponential) initial growth phase and a much higher inflection point than the latter, but choosing the former on the basis of an early steep growth may turn out to be a major error due to common delays and disruptions of those growth processes that are subject to vagaries of public acceptance and that depend on continuous high flow of governmental subsidies or private investment (Figure 4.8).

A sudden end of the United States' first exponential wind power growth of the 1980s is an excellent example. Between 1980 and 1986 the installed capacity grew at an annual rate of 84%, rising from just 8 MW to 1.265 GW; even if the subsequent growth rate would have been halved, the total capacity would have

Figure 4.8 Comparison of logistic, Gompertz, and exponential growth curves.



reached about 84 GW by 1996, or about 66 times the 1986 total—but in reality (once the subsidies stopped) the annual growth rate fell to just 2.3% and the 1996 total was just 1.614 GW, less than 30% above the 1986 level. Consequently, we have to wait until after most of the growth or adoption process will have been completed before we can get on a firmer quantitative forecasting ground—and given the fact that most new renewable energy conversions have, so far, claimed only very small fractions of their respective markets (wind in several EU countries being the most notable exception), we cannot deploy any particular distribution in confident forecasting.

But some things we can affirm with a great deal of confidence. Even if the boldest national goals for a relatively rapid transition to the new renewables were met, the global primary energy supply in 2025 or 2030 will be still overwhelmingly dominated by fossil fuels and it is highly unlikely that the combined share of coals and hydrocarbons will fall below 50% of the aggregate energy demand by 2050. A world without fossil fuel combustion may be highly desirable, and eventually it will be inevitable, and our collective determination could accelerate its arrival—but making it a reality will demand great determination, extraordinary commitment, substantial expense, and uncommon patience as the process of a new epochal energy transition unfolds across decades.

Cautious Anticipations: Trends and Possibilities

This book had several independent goals. In its first chapter I wanted to make sure that a reader (and particularly anybody whose interest in energy matters has come about because of the recent preoccupation with such concerns as the end of oil or catastrophic global warming) appreciates the basic properties and complexities of modern energy systems, their major resources, conversions, uses, infrastructures, and impacts. This is important because, contrary to a standard view that reduces the process of energy transitions to changes of fuel base (oil replacing coal) or shifts in generating electricity (wind power replacing electricity produced by burning coal), those components, fundamental as they are, form only a partially predictable dynamic whole and all of them keep changing, some fairly rapidly while others display relatively long periods of surprising inertia. As a result, some of the long-established, gradually progressing energy transitions will continue even as the composition of primary energy supply changes.

Secular gains in energy efficiency—expressed most generally as the declining energy intensity of national economies (with less energy needed per unit of GDP) and evident in sectoral improvements (most notably in lower energy use in industrial production and transport) and in less wasteful performance of all major converters (be they fridges or jet engines)—will continue and, given the still ubiquitous opportunities for further improvements, the pace of their advances should not be any slower during the coming two or three decades than it has been during the past generation. For example, a detailed assessment of U.S. energy use estimated that improved efficiency could cut the country's overall energy use 23% by the year 2020 (Granade et al., 2009). The only major uncertainty regards the household energy use in high-income countries, which has been up since 1990 not only in North America but also in Japan and in the European Union where it rose by more than 10% (EEA, 2008): Will it finally stabilize and begin to decline?

There are three major reasons why the gradual trend of global energy supply decarbonization should actually accelerate: Larger volumes of natural gas are becoming available due to increased global LNG trade; technical advances in extracting U.S. shale gas has led to a substantial upward revision of the country's natural gas reserves and this will lead to the fuel's wider use; and new wind-driven and PV electricity generation will have no direct carbon emissions. The third long-term energy transition that will continue its progress is the rising share of electricity in the final energy supply, and if many national goals for relatively high shares of electricity from new renewable conversions are met, or approached, it should also accelerate.

The second chapter offered a truly long-term historical perspective by surveying the grand energy transitions from biomass to fossil fuels and from animate power to mechanical prime movers and the rise of electricity, the most flexible form of all energies. Availability of reasonably good statistics of global energy use augmented by serviceable estimates of preindustrial performance made it possible to conclude the chapter with revealing quantifications of these long-term shifts in resources and prime movers. The record on the global scale is unequivocal: All of the past shifts to new sources of primary energy have been gradual, prolonged affairs, with new sources taking decades from the beginning of production to become more than insignificant contributors, and then another two to three decades before capturing a quarter or a third of their respective markets.

And the record is also unequivocal as far as the notion of any mechanistically preordained primary energy transitions is concerned: As in so many other cases, complex and nuanced reality does not fit any simplistic deterministic models that are supposed to capture the past and reveal the future. Because of the capital mobilization and technical advances required for any large-scale resource extraction and conversion, and because of extensive infrastructures needed to bring the modern energies to their global markets, it is inevitable that primary energy transitions must have a number of generic, underlying properties that constrain the rise of individual fuels or modes of electricity generation, the pace of their maturation, and their eventual retreat. But these broad commonalities leave a great deal of room for exceptions and departures from generally expected norms, and unpredictable changes of the overall economic, social, and political environment can affect even what appeared to be the strongest trends.

The gradual nature of energy transitions can be also traced on the global scale as far as the two important ways of primary electricity generation, water and nuclear power, are concerned. And, again, the development of both of these resources offers excellent illustrations of unpredictable shifts. Who would have said in the mid-1970s, the peak decade of worldwide dam construction, that 20 years later people would be asking if there is such a thing as a good dam and the World Bank would be reluctant to lend money for new hydro projects in low-income countries? And there was also nobody who predicted that in less than two decades that nuclear generation—in 1965 a highly promising technique on the verge of large-scale expansion and one expected to take over most, if not all, electricity generation by the century's end—would come to be seen, at best, as a dubious proposition, at worst as a regrettable past error and completely undesirable future choice.

And surveying the rise of the currently dominant prime movers reveals, yet again, incremental ascents with decades elapsing between the first technical breakthroughs and the conquest of significant shares of respective markets. In addition, the record of modern prime mover development suggests a remarkably high degree of persistence as the machines that have been with us for more than 100 years (gasoline- and diesel-fueled internal combustion engines, steam turbines, electric motors) or for three generations (gas turbines) not only continue the dominance of their respective niches but do not appear to be threatened by any new techniques promising their rapid displacement.

The third chapter focused on eight specific national examples of long-term energy transitions that were selected on the basis of historical importance, overall representativeness or, for the very opposite reason, because they illustrate notable idiosyncrasies of some substitution processes. To say that at a national level anything is possible would be an impermissible exaggeration, but the record displays a remarkable scope of developments, ranging from the centuries-long dominance of English coal to an almost instant demise of the Dutch coal mining, from a highly idiosyncratic and swiftly changing evolution of Japan's energy use to the U.S. orderly sequence of fuels during the first half of the twentieth century followed by a surprising post-1960 near-stasis of the primary energy make-up.

These national examinations offer a few obvious lessons. Small, resource-rich, or affluent, countries can do what large, resource-poor and low-income nations cannot replicate (Dutch and Kuwaiti experience holds no lessons for India and Ethiopia). National commitment to a large-scale technical transformation can make a real difference (French nuclear power is perhaps the best testimony to that). Coal, particularly as the fuel for base-load electricity generation, has shown not only a remarkable staying power but, in Asia, also a phenomenal resurgence (China's and India's rising extraction, Indonesia's growing exports). Refined liquid fuels that are used to energize all modern transportation (electric trains being the only notable exception) cannot be easily and rapidly replaced by alternatives. At the same time, these resource-specific lessons may have little or no relevance for the coming transition to a non-fossil energy system.

In the first three sections of this closing chapter I have addressed the recent expectations concerning the unfolding transition from the combustion of fossil fuels to the harnessing of a variety of renewable energies. In order to map out the possibilities and limits of this complex process I had first assessed the potential contributions of all major renewable resources and the status of their commercial or experimental conversions and then I took a closer look at some key factors that will influence the pace of the coming transitions and, finally, I gave some notable examples of actual national energy transition targets and briefly deconstructed a few plans that presented the boldest scenarios for the new epochal shift from fossil to renewable energies.

Among the new renewable conversions, wind-powered electricity generation stands out due to its recent rapid technical maturation, declining cost and rising unit capacities (MW-sized turbines), annual additions (GW-sized), and overall system capabilities (tens of GW in several countries). Wind-powered electricity generation is thus at the forefront of the unfolding energy transition and there is no doubt that countries with particularly windy climates can generate not just 20% but 30% of their electricity using large wind turbines (Zubi, Bernal-Augustín, & Marín, 2009)—particularly if they are relatively small and are already well connected to grids of adequate capacity or if the construction of new links precedes the commitment to higher rates of wind-driven generation. Denmark—where wind generated almost 20% of all electricity in 2007 and where large offshore projects are to raise the share to 50% by 2025—is a foremost example of this combination: It has a relatively small market (total generating capacity is less than 10 GW) and excellent interconnections with the hydro-rich Scandinavia to the north and with large thermal systems in Germany and beyond to the south.

But the challenge is different in large countries whose wind resources are concentrated far from major load centers (North Dakota is 2,600 km from New York, in European terms more than the distance between Paris and Moscow) and where extensive, and expensive, up-front investment in new high-voltage transmission links will be needed if the shares of wind electricity are to surpass 15% or 20%. Load factors will have to get better than the recent worldwide mean of only about 20% and typical national means of less than 25%—but the best way to raise them, by setting up large wind farms offshore, has its own problems, ranging from high construction costs to increased maintenance and lower durability of components set in extreme environments.

There can be no long-term future for renewable electricity without a mass-scale commercial success of PV generation, but despite some remarkable progress in lowering the cost of producing and installing the PV modules and increasing their maximum unit capacities, this conversion is considerably less mature than the harnessing of wind power: In 2007 the world added about 94 GW of wind turbines but only about 4 GW of peak PV power. Solar enthusiasts will say otherwise (and have been saying so for many years), but I would argue that it is not at all certain if we are just years from the formation of a

J-bend on the technique's growth/adoption logistic curve—or if that take-off point is far from being so imminent. Material and infrastructure constraints are even more important than for wind-driven generation. Rare metals (cadmium, gallium, selenium and tellurium) are required to make the cells, and even cost-competitive modules could not displace fossil-fueled electricity generation in less sunny climates without what are still only visionary mega-transmission links from the Algerian Sahara to Europe or from Arizona to the Atlantic coast.

And as with all technical innovations, a definite judgment regarding long-term capability and reliability of wind-driven or PV generation is still many years ahead. Decades of cumulative experience are needed to assess properly all of the risks and benefits entailed in large-scale operation of these new systems and to quantify satisfactorily their probabilities of catastrophic failures and their true lifetime costs. This means that we will be able to offer it only after very large numbers of large-capacity units will have accumulated at least two decades of operating experience in a wide variety of conditions. This ultimate test of long-term dependence and productivity will be particularly critical for massive offshore wind farms or for extensive PV fields in harsh desert environment.

Future levels of production and adoption of renewably produced fuels have no less uncertain prospects. The best Brazilian sugar cane–based practices aside, the current ways of relatively large-scale ethanol crop–based production cannot be—due to the combination of high energy costs, serious environmental impacts, and major effects on food prices—a basis for an industry producing liquid transportation fuels at scales that would cut the demand for refined fuels by substantial (at least 20–25%) shares. What has been achieved so far (ethanol and biodiesel) has come about as a result of very large and very questionable subsidies (Steenblik, 2007). And all of those repeatedly extolled options based on waste cellulosic substrates (crop and forest residues) or on large-scale cultivation of high-yielding species (switchgrass, miscanthus, jatropha) has yet to reach even the minimal threshold of large-scale commercial viability and hence they should not be seen as imminent and reliable providers of alternative fuels.

And in all cases the renewable energy enthusiasts do not sufficiently recognize the challenge of converting the existing (and basically a century old) system based on centralized extraction and conversion of energies with very high power densities to a system based on harnessing low power density flows to be used in relatively high power density urban areas. Decentralized energy provision, a holy grail of true green believers, is fine for a farmstead or a small town, not for the large cities that already house most of the world's humanity and even less so for megacities (such as today's Tokyo, Shanghai, or Mumbai) where most of the world's population will live by 2050.

An even greater (and curiously rarely noted) challenge will be the replacement of fossil fuels used as key industrial feedstocks. Unique properties of coke made from coal have made it the reduction agent of choice for smelting iron from ore. Charcoal is an excellent form of metallurgical carbon, but its fragility precludes its use in modern massive blast furnaces, and at the rate it would be needed for a complete replacement of coke in today's pig iron smelting (roughly 900 Mt/year, or about 3.5 Gt of dry wood), tree plantations for its production would take over some 350 Mha, an equivalent of almost two thirds of Brazil's forest—a most unlikely proposition. Nor do we have any plant-based substitutes for hydrocarbon feedstocks used in making plastics or synthesizing ammonia (production of fertilizer ammonia now needs more than 100 Gm^3 of natural gas a year).

Because I have always preferred unruly realities to neat simplifications I have always had my doubts about the efficacy of supposedly revelatory models and, as I have demonstrated, the record of past energy transitions justifies this skepticism. And the economics of the entire energy supply offers no firm guidance either. After more than a century of coal-fired electricity generation we have internalized some of its key externalities (from enhanced mining safety to flue gas desulfurization) but we still have not accounted for the long-term cost of its NO_x and above all CO_2 emissions. After more than half a century of living with nuclear power we still dispute its real cost (including the near-perpetual guardianship of long-lived wastes), and this uncertainty is a key reason why most of today's visions of non-fossil futures do not feature mass-scale nuclear generation.

Consequently, all cost comparison and all claims of imminent investment or price parities or advantages should not be mistaken for decisive guides. And the situation is, if anything, even shakier with the claims of future competitive costs of wind-generated or PV electricity, or capital estimates for future wave or ocean thermal energy conversion (OTEC) stations or algal megaflows: All those claims and counterclaims depend on concatenated assumptions whose true details are often impossible to ascertain, on uncertain choices of amortization periods and discount rates, and all of them are contaminated by (past, present, and tacitly expected) tax breaks, government subsidies, and simplistic, mechanistic assumptions regarding the future decline of unit costs. One might think that repeated cost overruns and chronically unmet forecasts of capital or operating costs should have had some effect, but they have done little to stop the recitals of new dubious numbers.

That a lengthy process of maturation, perfection, diffusion, and widespread commercial adoption of new renewable conversions will require government interventions is not at all surprising, as none of the other innovations in the recent history of energy advances has done without it. But the very necessity of such interventions—particularly if they were to become excessively concentrated in one or two areas, or if a panicky assessment were to lead to unusually large "crisis" investment—raises the obvious questions regarding the continuity of policies under different governments, resilience of official policies during the period of highly fluctuating or precipitously declining prices, and the capacity to sustain high levels of investment/subsidies/tax preferences during the period of severe and prolonged economic crises.

Historical record of major energy transitions is one of slowly unfolding incremental gains and regularities—as well as one of surprising accelerations, retreats, discontinuities, and periods of stasis. Undoubtedly, some of these lessons will be applicable to the unfolding energy transition to renewable energies; other new trends will be idiosyncratic, molded by new economic and strategic realities. Evidence of the past transitions would suggest that a shift away from fossil fuels has to be a generations-long process and that the inertia of existing massive and expensive energy infrastructures and prime movers and the time and capital investment needed for putting in place new converters and new networks make it inevitable that the primary energy supply of most modern nations will contain a significant component of fossil fuels for decades to come.

Moreover, inherent constraints and complications accompanying large-scale commercial harnessing of renewable energies would only tend to make this new epochal transition an even more challenging and very likely a much more protracted affair than is commonly assumed. Unfortunately, common expectations of energy futures—shared not only by poorly informed enthusiasts and careless politicians but, inexplicably, by too many uncritical professionals—have been, for decades, resembling more science fiction than unbiased engineering, economic, and environmental appraisals. The list of seriously espoused energy "solutions" has run from that ultimate *fata morgana* of nuclear fusion to an irrepressible (and always commencing in a decade or so) hydrogen economy, and its prominent entries have included everything from liquid metal fast breeder reactors to squeezing 5% of oil from the Rocky Mountain shales.

And so (yet again) *nihil novi sub sole*, as today's renewable list contains such "solutions" as mass deployment of bobbing wave converters in coastal waters, flexible PV films enveloping houses (and even people), enormous solar panels unfolded from satellites in stationary orbits, algae disgorging high-octane gasoline by hundreds of millions of liters a year, or (one of the latest favorites) ingenious harnessing of jet streams' ferocious winds 12 km above the ground (Archer & Caldeira, 2009; Vance, 2009). Those readers of this book who are no older than their early forties will have an excellent chance to see how many of these energy salvations will become commercial ubiquities by 2050.

As always, I will abstain from any long-term quantitative forecasts, but looking a generation or two ahead I can envisage circumstances whose concatenation could speed up, rather that retard, the unfolding energy transition. Undeniable acceleration of global warming attributable to carbon emissions would be a powerful impetus for a faster change, as would be chronically high prices of crude oil and hopeless instability in the Middle East. The epochal transition from biomass to fossil fuels has been the very essence of modernization: Ours is an overwhelmingly fossil-fueled society, our way of life has been largely created by the combustion of photosynthetically converted and fossilized sunlight—and there can be no doubt that the transition to fossil fuels, beset as it was with the miseries of industrialization and rapid urbanization, created a world where more people enjoy a higher quality of life than at any time in previous history.

This grand solar subsidy, this still-intensifying depletion of an energy stock whose beginnings go back hundreds of millions of years, cannot last, and the transition to a non-fossil future is an imperative process of self-preservation for modern high-energy civilization. While I am skeptical about many exaggerated, unwarranted claims regarding the pace and the near-term exploits of new renewable conversions, I remain hopeful in the long run. The first grand energy transition, the mastery of fire, has been one of the great accomplishments that set the hominins irretrievably apart from the rest of the mammalian kingdom. The second grand energy transition, from foraging to sedentary cropping and domestication of animals, gave us eventually high cultures and led to historical consciousness and, millennia later, to the doorstep of the modern world.

The third energy transition, from biomass fuels and animate power to fossil fuels and inanimate prime movers, had created the modern world and the first truly global civilization. The forthcoming fourth energy transition is both desirable (above all on environmental and strategic grounds) and inevitable—but neither its pace nor its compositional and operational details are yet clear. Trying to predict them would be like trying to predict specific energy conversions, particular prime movers and their performances, and typical sectoral consumption levels of the late twentieth century fossil-fueled society in 1900.

At that time all three major kinds of fossil fuels were being extracted by increasingly efficient methods, electricity generation was spreading light and mechanical power in large cities, and most major components of the modern energy system (including large mines, drilling rigs, refineries, pipelines, tankers, and power plants) were in place. But the industrial practices, household and transportation energy uses, and the behavior of the entire energy system in 1900 would have been poor predictors of future accomplishments: there was no gasoline and no mass ownership of cars, there was electricity but barely any household appliances, there was energy-intensive chemical industry but no synthesis of ammonia, now (when compared on a molar basis) the single most important synthetic product and a key reason why the planet can feed seven billion people. And, of course, there was no flight, no gas turbines, no nuclear generation, and not a single item of consumer electronics.

Trying to envisage in some detail the global energy system of 2100, or even that of 2050, is an exercise bound to mislead as the past record is of little help. Fear is always an option. Perelman, writing in 1981, at the end of OPEC's second wave of rapid oil price rise, when an early shift away from fossil fuels was widely expected, concluded that "the degree of social stress and conflict during the coming transition period has sufficiently great destructive potential to constitute a serious problem" and he saw such conflicts and disorders as imminent during "the perennial energy supply problems of the 1980s and 1990s" (Perelman, 1981, pp. 195, 197). But during those two decades energy supply was abundant and after 1985 prices were relatively low: As always, informed concerns are highly advisable, exaggerated fears are counterproductive.

And while we cannot outline complex outcomes of the unfolding transition, we can learn a great deal from the general features of process that got us through the past energy transitions. Inevitably, all past energy transitions have stimulated technical advances and provided unprecedented opportunities for our inventiveness. All of them posed, inevitably, enormous challenges for both producers and consumers of new forms of energy; all of them required the abandonment of old components, habits, and activities; all of them necessitated the rise of new infrastructures and reorganization of existing ways of production and transportation; all of them were costly and protracted; and all of them caused major socioeconomic dislocations.

All of them had also eventually created more productive and richer economies and improved the overall quality of life—and this experience should be eventually replicated by the coming energy transition. There has been a widespread agreement that the new transition must be accompanied, indeed made less taxing, by higher efficiency of energy use. No doubt, a more vigorous pursuit of higher energy efficiency for common converters should be an essential accompaniment of the unfolding energy transition, and it should consist of an organic mixture of adopting proven superior techniques and promoting bold innovations that would result in major efficiency gains throughout the economy. Fortunately, possibilities of such gains remain no less promising today than they appeared two generations ago: This energy transition toward more rational energy use can continue for decades to come.

But *better conversion efficiencies alone are not enough*, they will just keep confirming a lasting truth of Jevons's venerable paradox that "it is wholly a confusion of ideas to suppose that the economical use of fuel is equivalent to a diminished consumption. The very contrary is the truth" (Jevons, 1865, p. 140). The second precondition of a successful new transition in all affluent nations must be to *avoid consuming more energy more efficiently*, and this means that by far the most important step that those countries should take are gradual but *significant overall reductions of energy use*. High-income economies now account for less than 20% of humanity but they claim half of all commercial energy; the United States alone, with about 4.5% of all people, consumes just over 20% of the world's fossil fuels and primary electricity. In per capita terms Americans now consume more than twice as much energy as do the citizens of the largest European economies (Germany and France) or Japan (8.5 vs. about 4.2 toe per capita).

Adjustments for territorial and climatic differences reduce this large gap disparity but the disparity remains large, especially given the extent of U.S. deindustrialization compared to still vigorous energy-intensive manufacturing in Germany or Japan. What has the United States got in return? Its average quality of life (regardless if it is compared in per capita GDP, life expectancy, or happiness terms, or by using the UNDP's Human Development Index) is not double

that of the European Union or Japan, and not a few socioeconomic indicators are actually lagging the EU's or Japan's means. Maintaining this exceptionally high energy consumption level in a global economy where modernizing nations, led by China and India, are trying to improve their quality of life by raising their still low energy use (averaging 1.6 toe in China and less than 0.5 toe in India) is both untenable and highly undesirable—while the goal of reduced energy use is actually less forbidding than it might appear, particularly in the United States.

U.S. energy consumption is not only much higher than in any other affluent economy (a reality that would make it easier to reduce it without compromising the prevailing quality of life), but the country's average per capita use of primary energy in 2010 (8.2 toe) was about 5% lower than in 1980 and no higher than in 1970! Given this reality, it is obvious that if more responsible residential zoning regulations and more demanding automotive efficiency standards had been in place the United States could have prevented the emergence of energy-expensive exurbia and the fuel wasted due to the worsening car performance, and the average per capita energy consumption could have been gradually declining. And Europe, despite its lower per capita consumption, could have also done better: Germany's per capita energy use has remained flat for a generation, but the British rate has been marginally up and the French use in 2010 was nearly 20% higher than in 1980.

Deliberate pursuit of gradual reductions of per capita energy consumption use is both desirable and achievable but it will have to be a gradual process lasting for decades and it could not succeed without redefining many entrenched practices used to measure and to judge fundamental energy realities and policies. One of its most important preconditions would be to discard the misleadingly incomplete ways of valuing goods and services without appraising their real costs (including environmental as well as strategic and health burdens) and without judging their benefit by using life cycle analyses. Although none of these ideas guides today's economic thinking, substantial intellectual foundation for such more comprehensive valuations is already in place.

And if a rapidly changing climate were to force an accelerated transition to renewable energies, then a substantial reduction of per capita energy use may be simply a key unavoidable component of such a transformation. Tellingly, an assessment of a 100% renewable energy system in Denmark concluded that even in that small and energy-efficient country (its current per capita annual energy use of 3.1 toe is about 15% below the EU mean) that goal could be achieved by 2050 only if space heating demand in buildings were reduced by half, if industrial fuel consumption declined by 30%, and if electricity demand were cut by 50% in households and by 30% in industry (Lund & Mathiesen, 2009). Similarly, MacKay (2009, pp. 212–213) ended his presentation of five plans for Britain energized by noting that "there is something unpalatable about every one of them" and that "perhaps you will conclude that a viable plan has to involve less power consumption per capita. I might agree with that, but it's a difficult policy to sell."

Difficult as it would be, reducing the energy use would be much more rewarding than deploying dubious energy conversions operating with marginal energy returns (fermentation of liquids from energy crops being an excellent example), sequestering the emissions of CO_2 (now seen as the best future choice by some industries), and making exaggerated claims for non-fossil electricity production (both in terms of their near-term contributions and eventual market shares), or hoping for an early success of highly unconventional renewable conversions (jet stream winds, ocean thermal differences, deep geothermal). After all, a dedicated but entirely realistic pursuit of this goal could result in reductions on the order of 10% of the total primary energy consumption in a single generation, an achievement whose multiple benefits could not be matched by the opposite effort to increase the overall energy use.

Affluent countries should thus replace their traditional pursuit of higher energy output and increased conversion efficiency with a new approach that would combine aggressively improved efficiency of energy conversion with decreasing rates of per capita energy use. This combination would be the best enabler of the unfolding energy transition. Until we get such history-changing conversions as reliable, inexpensive PV cells generating electricity with 50% efficiency or genetically engineered bacteria exuding billions of liters of kerosene, it is the best way to ensure that the new renewables will come as close to displacing fossil fuels as is economically advantageous and environmentally acceptable.

I believe that having in mind an ultimate goal—one that cannot be reached in one or even two generations but that would serve as a long-term inspiration—would be helpful. There is no doubt that all important quality-of-life variables (ranging from infant mortality to average longevity and from good income to ready access to education) are related to average per capita energy use in a distinctly nonlinear manner. Global data plots display unmistakable inflection zones at around 1.5 toe/capita with diminishing returns afterwards, and with hardly any further gains as average per capita consumption approaches 3 toe/capita. So perhaps the last rate could be a great long-term inspirational goal for rational, reasonably equitable, and decently prosperous societies of the future. Lower rates could be technically conceivable later in this century. Several years ago I set 60 GJ /capita, or roughly 1.5 toe and approximately the global mean of commercial energy consumption, as an ultimate goal.

Similarly, a European initiative led by the Swiss *Eidgenössische Technische Hochschule* had formulated a nearly identical goal of a 2,000-W society (Jochem et al., 2002): Annual per capita use of 60 GJ equals the power of 1,900 W. But the 3-toe economy (roughly 120 GJ/capita) is a practical goal that could be achieved by the majority of high-income countries in two to three generations. And it would be a success, and an enormous help to the unfolding shift away from fossil fuels, even if most of the affluent consumers got only halfway there. Any move in that desirable direction would have multiple, and mutually reinforcing, benefits as it would simultaneously promote the capacity to innovate, strengthen the fuel-importing economies by improving their trade balances, and reduce the burden on the Earth's environment.

Today's excessive energy use has the opposite effect—and it cannot be defended by claiming that, at least, it has made the citizens of affluent economies commensurably more satisfied with their lives. There is no evidence of this: Most notably, U.S. record shows virtually no gain in personal happiness since 1947 when the first nationwide polling was done and when the per capita energy use was nearly 50% below the current level; and, as Easterlin (2003) showed, life events in the nonpecuniary domain (marriage, divorce, and disability) are more important for the state of mind. I know that a call for reduced energy use would be widely seen as undesirable and politically unacceptable, and that its rejection would be shared across most of the modern political spectrum. This must be expected. Replacing entrenched precepts is never easy, but today's combination of major (i.e., economic, environmental, and strategic) concerns provides a nearly perfect opportunity for radical departures.

Energy transitions have been, and will continue to be, inherently prolonged affairs, particularly so in large nations whose high levels of per capita energy use and whose massive and expensive infrastructures make it impossible to greatly accelerate their progress even if we were to resort to some highly effective interventions. The overall composition of primary energy supply and the principal modes of energy conversions will closely resemble today's arrangements five or ten years from now—but how far we will advance into the post-fossil future in three or four decades will not be determined only by the commitment to innovation but also by our willingness to moderate our energy expectations and to have our energy uses following a more sensible direction, one that would combine reduced demand with a difficult, but eventually rewarding, quest for a civilization powered by renewable energy flows.