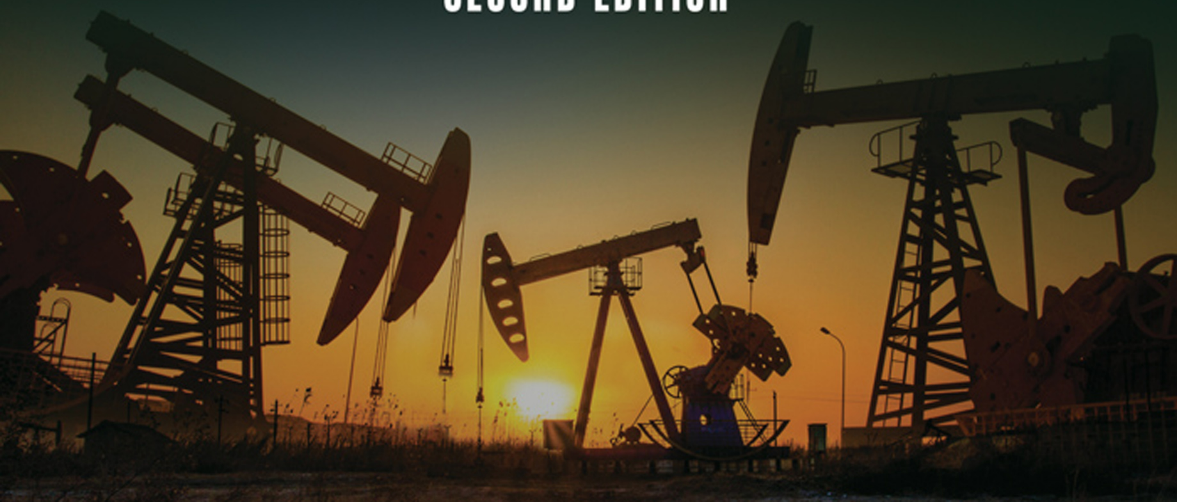
Vaclav Smil

ENERGY TRANSITIONS

Global and National Perspectives

SECOND EDITION



Energy Transitions

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Energy Transitions

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Second Edition

Vaclav Smil

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Preface to the New Edition

The first edition of this book came out in 2010. In that year global energy developments were still affected by the lingering economic crisis that began in 2008. But a rebound was on the way, with world oil price recovering from the lows of 2009, with rising oil and gas production in the United States made possible by a widespread adoption of hydraulic fracturing, and with fairly large additions of new wind and solar electricity generating capacities in the EU, China, and the United States. Six years later—after world oil prices reached new highs (in 2014) followed by a steep fall (finally arrested in the spring of 2016), after further progress in adopting noncarbon energies, and after a new international agreement to reduce carbon emission was reached in Paris in December 2015—worldwide interest in the nature, pace, and prospects of energy transitions is higher than ever, and these concerns are here to stay.

The second edition of the 2010 book thus seemed to be an obvious choice: it is both a thoroughly revised and substantially expanded version of the original book. The basic structure has remained largely the same, but instead of four chapters there are now six, concluding with recapitulations of key conclusions, a kind of an executive summary (Chapter 6) . Sweden was added to the national transition surveys, and a great deal of attention is given to Germany's *Energiewende*. The new text is one-third longer than the original, and there are more than twice as many references bringing the global and national developments to the end of 2015; there are also new appendices and added illustrations.

The aim remains the same: to impart a fairly systematic, historically grounded, and technically accurate understanding of energy transitions by tracing their course in nine major economies (United States, China, Japan, Russia, Germany, UK, France, Netherlands, and Sweden) as well as on the global level, and by offering appraisals of their past progress and realistic assessments of their prospects during the next few decades.

Introduction: The Book's *Raison d'Être*

Generic meaning of transition—a passage from one condition or one action to another—is quite straightforward, 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 transition* needs to be qualified and defined. To begin with, the plural is needed: tracing the changes of a single variable would provide only a partial understanding, and a number of different measures must be used to trace the complexity of *energy transitions*, be it on a national or the global scale.

There is no generally accepted hierarchy of meanings, but the term *energy transition* is used most often to describe the *changing composition (structure) of primary energy supply*. Transition from traditional biomass fuels (wood, charcoal, and crop residues) to fossil fuels (coal and hydrocarbons) has been the most important, and universally experienced, example of this process. Specific inquiries possible within this grand shift include the transition from wood to less-polluting charcoal in heating; shift from coal to more conveniently handled and cleaner-burning oil in households and industries; decline of coal and rise of natural gas in electricity generation; and transition from direct combustion of fossil fuels to their 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. But given the growth of energy supply over time, a close attention also should be 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 and that also create lower environmental impacts. A combination of all of these approaches provides 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 transitions as specific subsets of two more general processes of technical innovation and resource substitution. Modern civilization could not have arisen without the massive combustion of fossil fuels, but that very dependence has been the source of rising atmospheric CO_2 and the leading cause of anthropogenic global warming. That is why the principal concern of the unfolding energy transition is with *decarbonization*, *displacement of fossil fuel combustion by increasing reliance on carbon-free flows of renewable energy.*

I will use all of these approaches in my examination of global and national energy transitions. But there is one commonality that defines all large-scale energy transitions: because of the requisite technical and infrastructural imperatives (what economists call, not quite accurately, lock-in or path dependence) and because of numerous (and often entirely unforeseen) social and economic and environmental implications, energy transitions taking place in large economies and on the global scale are inherently protracted affairs. Small economies endowed with plentiful resources had undergone very rapid transitions (think of the Netherlands or Kuwait)—but decades, not years, are required before a new source of energy, a new conversion, or a new consumption mode becomes the dominant component in a particular category of energy use or before it supplies a substantial share of the world's final primary energy demand.

The greater the degree of reliance on a particular energy source or a prime mover, the more widespread the prevailing uses and conversions, and the more elaborate, costly, and enduring are the associated infrastructures, the longer their substitutions will take. This conclusion seems obvious but it is often ignored: otherwise we would not have those repeatedly failed predictions of imminent triumphs of new energy sources or converters. And inherently gradual nature of large-scale energy transitions is also the key reason why—barring some extraordinary and entirely unprecedented investment and regulatory actions—today's promises for greatly accelerated transition from fossil fuels to renewable energies will remain largely unrealized.

A world without fossil fuel combustion might be 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 unfolding global energy transitions will last for decades, not years, and modern civilization's dependence on fossil fuels will not be shed by a sequence of government-dictated goals. Perhaps nothing is as important for understanding energy prospects of modern civilization as is an informed appreciation of these fundamental realities. This is the book's *raison d'être*; this is its key message.

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CHAPTER ONE

Energy Systems: Their Basic Properties

Every 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 also to increase their individual and collective power and to dominate and kill)—has three fundamental components: natural energy sources, their conversions, and specific uses of energy flows. During the long period of hominin evolution our ancestors relied actively on just two kinds of inherently inefficient energy conversions for their basic precarious subsistence: muscles, energized by digested food, were their only source of kinetic energy, and burning of phytomass (plant biomass, mostly wood) was the only source of thermal energy.

Existence of the earliest hominin foragers resembled that of other scavenging omnivorous mammals as their somatic energy (food converted to growth and muscle power) was just a fraction of naturally cascading energy degradation that began with solar radiation and ended with the dissipation of heat. Their first deliberate use of extrasomatic energy was perhaps as early as 1.9 million years ago, but incontrovertible evidence of controlled fire goes back only to 790,000 years ago, and by the Middle Paleolithic periods (300,000 to 200,000 years ago) the use of fire was common (Bar-Yosef 2002; Goren-Inbar et al. 2004; Karkanas et al. 2007).

In contrast, modern civilization draws energy from numerous natural stores and fluxes, converts them in many ways by using highly sophisticated devices, and uses them in a myriad of ways in order to energize agriculture, resource extraction and manufacturing, to enable mass-scale long-distance transport, and to provide a still expanding array of personal uses and comforts. But the benefits arising from high energy consumption are not evenly distributed as final per capita energy consumption ranges over two orders of magnitude, from the miseries of the sub-Saharan Africa (<10 GJ/capita, most of it as traditional biofuels, and with hundreds of millions having no access to electricity) to the affluent societies of North America, Europe, and Asia where the richest urbanites now consume annually more than 300 GJ, some even more than 500 GJ/capita.

At the same time, unprecedented benefits of high-energy societies also exact considerable costs. Modern energy systems require extensive, elaborate and fairly energy-intensive infrastructures that comprise not only tangible and capital-intensive components (mines, hydrocarbon fields, power plants, transmission lines) but also include increasingly complicated intangible organizational and managerial arrangements needed to extract, trade, and convert fuels and electricity. Energy cost of energy is obviously a critical determinant of the viability of any energy system as only reasonably high energy returns can create affluent societies.

Energy costs of energy are now increasingly expressed in terms of EROI, energy return on investment (more accurately it should be energy return on energy invested). Ratios for individual energy source range widely, from barely positive (1–1.4) for the U.S. corn-based ethanol to more than 100 for the early years of extraction from the world's most productive oilfields (Gupta and Hall 2011). King, Maxwell, and Donovan (2015a) looked at 44 countries whose GDP comprises more than 90% of the world economic product and found that the global ratio for all primary energy declined from 34 in 1980 to 17 in 1986 before remaining between 14 and 16 from 1991 to 2010.

But the prevailing practice is not to measure those expenditures in energy terms but in monies 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). King, Maxwell, and Donovan (2015b) calculated that the global expenditure on primary energy declined from the maximum of 10.3% in 1979 to just 3% in 1998 before reaching a second peak in 2008. Significant fluctuations of oil prices have been the principal reason for these shifts.

Every energy conversion has some undesirable environmental impacts. Deforestation in the Mediterranean and in North China was the first widespread environmental degradation during the antiquity as emerging cities and expanding metal smelting (first copper, then iron) needed more wood and charcoal. Fossil fuel combustion generates emissions of SO_2, NO_x, and volatile organic compounds that caused acid deposition (first in parts of Europe and North America, more recently in East Asia), photochemical smog and higher ground ozone levels (in all megacities), while the emissions of CO_2, CH_4, and N_2O (greenhouse gases) increase tropospheric temperatures (Bashkin and Park 1998; IPCC 2013; Smil 1997).

Some of these damaging externalities have been either eliminated or reduced to tolerable levels: surface extraction did away with health and accident risks of underground coal mining (and produces cheaper fuel); electrostatic precipitators in coal-fired power plants cut particulate emissions by more than 99% (increasing electricity cost by less than 5%); and flue gas desulfurization (typically 95% efficient) has reduced emissions of SO_x to a small fraction of their uncontrolled flows while raising the capital costs of coal-fired plants by about 10% (NREL 2012). Other impacts, most notably the global effects of greenhouse gas emissions, are yet to be factored into the real cost of energy.

As in so many other instances, energy transitions show very different rates of change when contrasting the preindustrial era (variously dated before 1750, 1800, or 1850) with the developments during the height of Western industrialization (1850–1950) and with the most recent decades, now often labeled as the postindustrial period (Fouquet 2008; Kander, Malanima, and Warde 2013; Smil 2008). The preindustrial era, dominated by biomass fuels and animate power, saw only very slow changes in the composition of the primary energy supply as well as in the use of prime movers. In contrast, the last two hundred years have seen a series of remarkable energy transitions that brought wide-ranging economic and social transformations and created modern high-energy societies.

These changes can be traced along several key lines: as shifts in the shares of individual fuels, starting with the transition from wood and charcoal to coal, followed by the rise of crude oil and refined liquid fuels and then by the spreading adoption of natural gas; as the rising importance of electricity, first generated by coal combustion and falling water, later as a combination of nation-specific shares of thermal, hydro, and nuclear generation; as the adoption and diffusion of new prime movers, starting with internal combustion engines and electric motors and proceeding to gas turbines and rocket engines; and as new patterns of final energy consumption, with falling shares (but rising aggregates) required in productive activities (agriculture and industries) and with increasing shares of total flows claimed by transportation and by households for a variety of discretionary private uses (Smil 2008, 2016a)

Resources and Prime Movers

Energies used by human societies can be classified according to their origins either as renewable and nonrenewable or primary and secondary.

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 (phytomass production); geothermal energy and tidal energy complete the list. As with all other energies, it is imperative to distinguish between renewable resources (aggregates of available fluxes) and reserves, their much smaller portions that are economically recoverable with existing extraction or conversion techniques. This distinction applies as much to wind or waste cellulosic phytomass as it does to crude oil or uranium, and those often-cited enormous flows of renewable resources give no 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 generic fractions. For example, dams storing too much water for hydro generation could weaken many environmental services provided by flowing rivers (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.

Magnitude of annual flows (resources) of renewable energies is best appreciated by comparing them to the global extraction of fossil fuel that reached about 475 EJ (15 TW) in 2015. 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 (120 PW), nearly four orders of magnitude greater than the annual fossil fuel consumption, and the total absorbed by land is roughly 790 ZJ (25 PW), still nearly 2,000 times the current fossil fuel extraction. Even after excluding polar and subpolar regions with the weakest insolation, and the areas difficult to access (steep mountains, wetlands), there are still at least 15 PW of potentially usable flux, roughly 1,000 times today's annual fossil fuel consumption.

Two important attributes complicate large-scale development of renewable energy flows: their intermittency and their relatively low power density. Some fluctuations are perfectly predictable (daily availability of solar radiation in cloud-free subtropical settings; time and magnitude of local tides), but most of them are forecast with varying degrees of probability, particularly as far as longer term outlook is concerned (solar radiation in cloudy midlatitudes, timing and frequency of winds, seasonal harvests of phytomass affected by climate variations and pests). There are two solutions for electricity's intermittency: storage and long-distance interconnections.

Where the terrain allows, pumped hydro storage remains the only high-capacity (GW-scale) option while battery storage at multi-MW scale is becoming more common (IRENA 2015a).

Power density—the rate of flow of energy per unit of land area—of solar radiation reaching the continents averages 170 W/m^2, with most of the inhabited regions falling between 100 W/m^2 (Dublin) and 200 W/m^2 (San Antonio); Paris averages about 125 W/m^2, Rome, about 175 W/m^2, but cities in arid and subtropical climates rate above 200 W/m^2 (Los Angeles 225 W/m^2, Cairo 237 W/m^2) and their noon-time maxima are more than 1,100 W/m^2 (Smil 2015a). These high power density fluxes, superior to any widely available renewable flows, mean that even low conversion efficiencies (10%–15%) result in relatively high power densities of solar heat and photovoltaic electricity generation.

Only a very small part of insolation (no more than 2%) energizes the global atmospheric circulation, but the wind power generated by this differential heating is a meaningless aggregate when assessing the exploitable flux because the Earth's most powerful winds are in the jet stream at altitude around 11 km above the surface; moreover, in the northern hemisphere their location shifts with seasons between 30°–70° N. Peixoto and Oort (1992) estimated that about 870 TW of solar radiation is transferred to wind's kinetic energy. Miller, Gans, and Kleidon (2011) put the maximum wind power that could be extracted from the atmosphere's boundary layer above the nonglaciated land at 18–68 TW, resulting in average power densities of as low as 0.15 W/m^2 and no the higher than 0.57 W/m^2. Adams and Keith (2013) demonstrated that wind power production will be limited to no more than about 1 W/m^2 for any large-scale wind farm occupying an area larger than 100 km^2. Power densities for smaller projects in windy locations could have power densities on the order of 10 W/m^2 (Smil 2015a).

Total potential energy of the Earth's stream runoff (nearly 370 EJ or 11.75 TW, equal to about two-thirds of the global commercial energy use of about 550 EJ in 2015) is just of theoretical interest: most of it cannot be tapped because of the limited number of sites suitable for large dams; seasonal fluctuations of water flows and competing water uses for flows supporting natural aquatic ecosystems; and water supplies for drinking, irrigation, fisheries, flood control, and recreation uses. Aggregate of technically exploitable capacity is only about 15% of the theoretical power of river runoff (WEC 2013), and economically exploitable capacity is even lower. Power densities of hydro projects range mostly from less than 1 W/m^2 for smaller stations to more than 3 W/m^2 for large dams, and only the world's largest dams surpass 10 W/m^2 (Smil 2015a).

Ocean energies have aggregate global fluxes inferior to wind (Hermann 2006), and none of them is easy to harness. 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 (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 is large (about 100 TW), but even in the warmest tropical seas (where the difference between the surface and deep water surpass 20°C) it 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 major commercial projects (IRENA 2014).

Terrestrial photosynthesis (measured as net primary productivity) proceeds at a rate of about 60 TW (power density of no more than 0.5 W/m^2 of ice-free land) and recent phytomass harvests (food and feed crops and their residues; wood for energy, lumber and pulp; grazing by domesticated animals) have been about 10 TW (Smil 2013a). Because of inherently low photosynthetic efficiency, power densities of woody phytomass harvests are low, ranging from just 0.1 W/m^2 for species grown in arid and cold climates to just above 1 W/m^2 for fast-growing tree plantations in warmer climates and in the tropics; the best crops harvest (corn yielding above 10 t/ha, sugar cane yielding above 50 t/ha) produce around 0.5 W/m^2.

Geothermal flux can be considered as renewable because its principal sources—basal cooling of the Earth's primordially hot core and crustal heat-producing isotopes including ^{235}U, ^{238}U, ^{232}Th, and ^{40}K (Murthy, van Westrenen, and Fei 2003)—have a very slow rate of decay. Continental flux of geothermal heat amounts to nearly 9 TW, but most of it is in areas of normal (low, 24°C/km) temperature gradient with average power density of less than 0.1 W/m^2. Available production techniques using hot steam in high-gradient regions could tap up to about 140 GW by the year 2050 (Bertani 2009), and enhanced (engineered) systems (requiring deeper drilling) could eventually contribute to base-load generation (Tester et al. 2006).

Reviewing potentially exploitable maxima of renewable energy flows shows a sobering reality. First—and contrary to common perceptions of renewable cornucopia—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 21st century (and far beyond). Second, only extraordinarily high rates of wind energy capture and of phytomass harvests (both of which may be environmentally undesirable and technically problematic) could provide a significant share of overall future energy demand. Third, exploitable maxima for all other renewable energies fall far short of today's fossil fuel flux: one order of magnitude in the case of hydro energy, ocean waves and geothermal energy; two orders of magnitude for tides; and four orders of magnitude for ocean currents and ocean thermal differences. Fourth, only solar radiation has relatively high power density while most renewable flows can be tapped with densities no higher than a few W/m^2 (Smil 2015a).

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 (predominantly tree phytomass for coals, mostly single-cell phytoplankton and zooplankton for hydrocarbons) buried in sediments and processed by high pressures and temperatures (for 10^6 to 10^8 years), but a significant share of natural gases may be of abiogenic origin (Smil 2008, 2015a). All fossil fuels are largely carbon: the best anthracite coals are nearly 100% C, bituminous coal have between 60%–80% C, ultimate elemental analysis of crude oils shows 83%–87% C, and methane (CH_4) has 75% C.

Most fossil fuels also contain sulfur: a mere trace in some gases, 1%–2% in many crude oils, up to 4% in bituminous coals. Coals also contain variable shares of incombustible ash (5%–10% for bituminous coals, up to 40% for lignites) and moisture (5%–10% in bituminous coals), as well traces of heavy metals (Cd, Cr, Hg, and Pb) that are also present in some crude oils. Natural gases often contain dissolved N_2, H_2O, and H_2S. Energy density of coals ranges from just 8 MJ/kg for poor lignites to about 30 MJ/kg for the best anthracites, with most bituminous (steam) coals between 20–25 MJ/kg. All of these are lower heating values obtained by subtracting the latent heat of vaporization of the water vapor formed during the combustion from higher heating values. Energy densities of crude oils are much more uniform (40–42 MJ/kg), as are those of natural gases (mostly between 35–40 MJ/m^3).

Resources of fossil fuels (their total mass present in the Earth's crust) are enormous. Those of conventional and unconventional crude oils and natural gases are estimated at up to about 64 ZJ (10^{21} J); those of bituminous coal and lignite approach 600 ZJ (IEA 2013). Their reserves (the part of resources in place that is economically recoverable with existing technical means) keep changing as new techniques (such as the recently deployed horizontal drilling and hydraulic fracturing to extract hydrocarbons from shales) lower the cost of extractions and make new production profitable. Recently assessed reserves of fossil fuels (IEA 2013) contain roughly 44 ZJ of energy (nearly 60% in coals), an equivalent of about 80 years of the 2015 global primary commercial energy supply.

Coal is extracted from thick seams of bituminous coal with power densities in excess of 10,000 W/m^2, and the rates are usually above 1,000 W/m^2

for thinner seams. Hydrocarbon fields yield crude oil with power densities of well above 10,000 W/m^2 for the richest Middle Eastern fields and between 1,000–2,000 W/m^2 for typical North American operations, while natural gas production has similar power densities, ranging from 10^3–10^4 W/m^2 (Smil 2015a). Because of the depletion of the richest fossil fuel deposits, average power densities of coal mining and hydrocarbon extraction have been declining. Even after including transportation, processing, conversion, transmission, and distribution needs, coals and hydrocarbons (as well as thermal electricity generated by their combustion) are produced with densities of no less than 10^2 W/m^2, most commonly to the range of 250–500 W/m^2. Typical power densities of fossil fuel energy systems are thus 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.

Inevitable depletion of fossil fuel resources has led to concerns about an early peak of global crude oil production, about the eventual magnitude of natural gas resources, and about the durability of coal deposits. Many analyses published since the year 2000 have been predicting an imminent peak of global oil extraction (Aleklett and Qvennerstdet 2012; Deffeyes 2001, 2006; Goodstein 2005), while the growing supply brought historically low (adjusted for inflation and for oil intensity of the economy) and even temporarily falling prices (Smil 2015b). What is not in doubt is that a large share of fossil fuel resources will never be exploited.

The first reason for this is that extraction of many marginal resources (thin seams of poor-quality coal located at great depths, small hydrocarbon reservoirs, very heavy oils, deeply buried oil sands and shales) would be technically forbidding or exceedingly costly. The second reason is the concern about rising anthropogenic CO_2 emissions. Combustion of fossil fuels remains their largest source, and any serious effort at first moderating their growth, then stabilizing their level, and eventually greatly reducing their generation would leave substantial shares of coals and hydrocarbons untouched. According to McGlade and Ekins (2015) a third of oil reserves, half of gas reserves, and 80% of current coal reserves should remain unused from 2010 to 2050, but real reductions, impossible to predict with any confidence, will be certainly much lower.

Nuclear energy can be released either by fission of the heaviest natural elements (as it is in all nuclear electricity-generating plants) or by fusion of the lightest ones (a process whose commercial realization has been a frustratingly receding mirage). Uranium fission has been used in commercial nuclear stations since 1956. Recoverable resources of uranium amount to nearly 6 Mt, with half of the total in Australia, Kazakhstan, and Russia (WNA 2015a). Much larger quantities are present in very low concentrations (2–5 ppm U) in granite and sedimentary rocks and in seawater (0.003 ppm U), but they will remain largely, or entirely, unexploited. And, after spending some seven decades and tens of billions of dollars, there are still no fusion-based plants and none are even on a distant horizon.

Division of energies into primary and secondary is based on the method of their production. Primary fuels (stored chemical energy) are harvested (wood, crop residues) or extracted from the uppermost strata of the Earth's crust (fossil fuels). Their combustion provides heat (thermal energy) that also can be converted to motion (kinetic 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), 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 (Fig. 1.1).

With all volatile components driven out, the fuel is virtually pure carbon, nearly smokeless, and with high energy density of almost 30 MJ/kg.

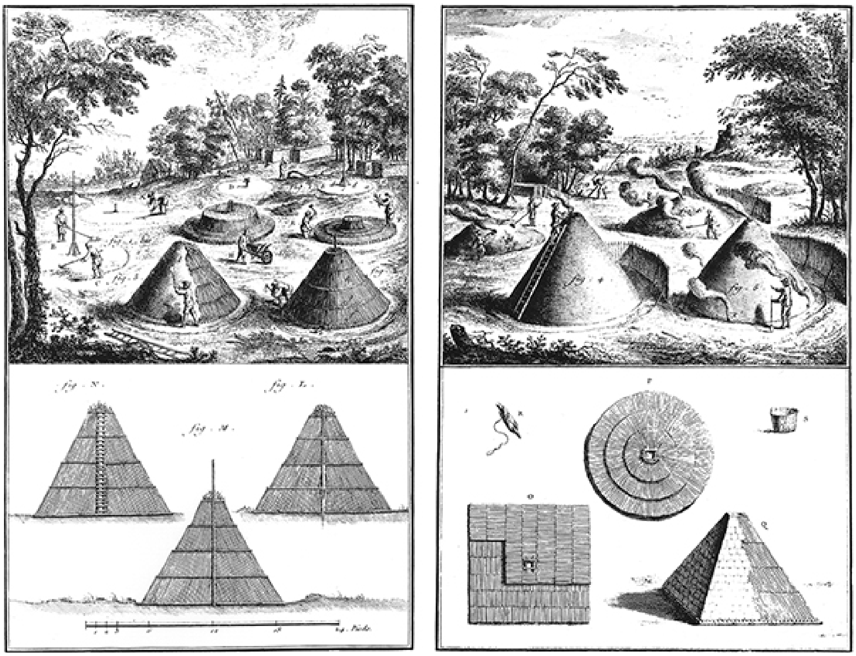

Figure 1.1 Steps in traditional charcoal making illustrated in Diderot and D'Alembert's *L'Encyclopédie* (1769–1772).

Coke, made by high-temperature pyrolysis of coal, was first used in England during the 1640s in malt preparation and in 1709 in iron smelting, but it began to replace charcoal as a fuel in blast furnaces on a large scale only after 1750 (Smil 2016a). Starting in the early 19th century (London in 1812, New York in 1825) another secondary fuel—coal gas (town gas or manufactured gas)—was a common urban illuminant as well as a fuel for cooking; it was eventually displaced by electric lights and natural gas.

Today's most important secondary fuels are liquids produced by the refining of crude oils. Refining began as 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), the two 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 land transport (trucks and railroad locomotives), while the heaviest residual oil powers the marine transportation. Diesel oil and residual fuel oil are also used in stationary generation of electricity.

Commercial electricity generation began in 1882. Primary electricity involves all conversions of natural renewable energy flows. Nuclear electricity is considered to be 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 of coal for steam turbogenerators and of natural gas for gas turbines. Electricity generation began with coal combustion and coal dominated until after World War II, but by the year 2015 a steady process of diversification reduced its global share to about 40%, with 27% coming from hydrocarbons (mostly natural gas), just over 10% from nuclear fission, 16% from water turbines, and the remainder from geothermal energy, wind and solar radiation, and burning phytomass (USEIA 2015a). In some nations a single source is now dominant: leading examples are coal in China (about 75% in 2015), water power in Brazil (about two-thirds in 2015), and nuclear in France (about 75% in 2015).

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 food's chemical energy to motion and to countless manual tasks) until the domestication of cattle and horses provided more powerful prime movers used in fieldwork, other agricultural tasks (notably for irrigation), transportation (most efficiently by using large horses with collar harness), food processing (grain milling), and for some industrial tasks (Smil 2017). Simple sails were the first inanimate prime movers followed, millennia later, by small water wheels, and roughly another millennium afterward by small wind mills.

During the 18th century the steam engine became the first mechanical prime mover powered by the combustion of a fossil fuel. Steam turbine and two key types of internal combustion engines (sparking gasoline-fueled machine and Rudolf Diesel's nonsparking engine fueled by heavier fuels) were invented before the end of the 19th century, and gas turbine became a practical prime mover during the 1930s (Smil 2010a). 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 faciae prime movers, be it steam turbogenerators or gas, water, and wind turbines.

Energy uses, as well as the deployment of prime movers, are classified by their location, temperature of the final use, and by principal economic sectors. Stationary combustion provides space heating as well as hot air and steam for industrial processes. Stationary steam turbogenerators and water turbines produce most of the world's electricity and electric motors and internal combustion engines power most of the modern industrial processes. Heavy horses were the most powerful 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 20th century (Smil 2005).

Steam turbines first powered ships at the beginning of the 20th century, but marine transport became eventually dominated by Diesel's 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, with widespread adoption during the1960s. 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, while modified stationary jet engines are also used for electricity generation (Smil 2010a).

Conversions and Uses

There is no binding classification of the uses that provide individuals, households, cities, and economies with essential energy services, but 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 (that is 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 irreversibly 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.

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 efficiency is the output or transfer of the desired energy divided by the initial energy input. 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 1,200°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 applying that efficiency to many human actions may be irrelevant or inappropriate. For example, one of the most efficient ways to produce animal protein is carp aquaculture (as those cold-blooded herbivorous species have inherently low metabolism), while the most inefficient way to produce animal protein is beef from cattle fed mixture of corn and soybeans in feedlots. But most people with high disposable incomes prefer beef, not carp. Similarly, corn is the most efficient staple grain crop—but unlike gluten-rich hard wheat it cannot be used to bake leavened breads. And a periodic bleeding of cattle by Kenya's Maasai (by piercing the jugular vein) is a vastly more efficient means of converting grasses to food than slaughtering cattle for meat (Smil 2013b)—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: burning of woody phytomass remained the principal means of securing heat and light until the advent of industrialization and today's most affluent societies derive most of their useful energies from the burning of fossil fuels. What has changed, particularly since 1850, 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 up to 30%, while today's most efficient household furnaces convert 94%–97% of energy in natural gas to indoor heat.

The earliest commercial steam engines transferred only about 0.5% of coal's energy into useful reciprocating motion, Watt's more efficient designs converted about 2.5%—while the best compound steam engines of the late 19th century had efficiencies on the order of 20% and steam locomotives never surpassed 10% (Smil 2005; Fig. 1.2). The first internal combustion engines (stationary horizontal machines powered by coal gas during the 1860s) had lower efficiencies than the best contemporary steam engines, and even today's best-performing gasoline-fueled engines do not usually surpass 25%. But in 1897 the first working prototype of Rudolf Diesel's nonsparking engine had surpassed that rate and the largest marine diesel engines now reach, and even slightly surpass, 50%, while today's best gas turbines are about 40% efficient (Smil 2010a; Fig. 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

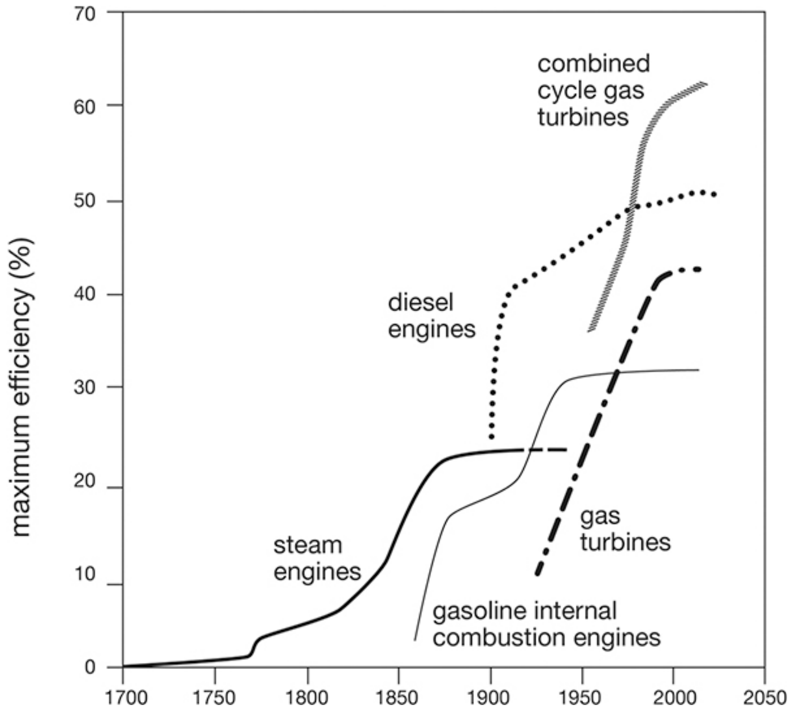

Figure 1.2 Maximum efficiency of prime movers, 1700–2000. There has been an order of magnitude gain for the best performances since 1800, from about 6% for steam engines to just above 60% for the combined cycle gas turbines (Smil 2008).

about 60%, and the maximum efficiency of coal-fired electricity-generating plants is just over 40%.

Because of the rising efficiencies the difference between average per capita energy use in modern and traditional societies is significantly greater when they are compared in useful terms rather than as gross energy consumption. Wood and charcoal consumption was very high in the richly forested United States: about 100 GJ/capita in 1860, compared to about 350 GJ/capita for all fossil and biomass fuel at the beginning of the 21st century (Schurr and Netschert 1960; USEIA 2015b). But with typical 1860 combustion efficiencies only around 10%, the useful energy was merely 10 GJ/capita. Overall efficiency of energy conversion in the U.S. economy is now almost exactly 40% (LLNL 2014), and hence an average American is now served by roughly 150 GJ/year, nearly 15-fold higher than during the height of the wooden era.

Energy uses had undergone some significant changes even during the preindustrial period. Expansion of manufactures and metallurgy led to a greater use of water power, while ore smelting and the preference for smokeless household fuel created higher demand for charcoal. Crop rotations including leguminous food and cover crops improved yields and enabled to divert higher shares of harvests to animal feeding and to deploy larger numbers of more powerful animals for fieldwork. Industrialization brought a radical change in the composition of national energy use. Coal mining, metallurgy, and heavy machinery sectors became the leading consumers of energy, followed by light manufactures (textiles, foodstuffs) and by 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 coal (town) gas, and (starting during the 1880s) as electricity for lighting and soon afterward also for household appliances (Smil 2017). Subsequent energy use has seen a steady relative decline of industrial and agricultural consumption and increasing claims by transportation and households. By 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.

But standard sectoral classification is questionable. Most notably, modern agriculture consumes directly only a few percent of the total energy supply as fuels to operate field machinery and as electricity for heating, cooling, and in 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 (dominated by refrigeration), retailing, cooking, and waste management raise the aggregate cost of the entire U.S. food production/distribution/preparation/disposal system to around 15% of total energy supply (Canning et al. 2010).

Changing sectoral requirements have affected the final uses. In 1890, before the advent of extensive electricity generation, 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. A century later coal ceased to be an important transportation fuel; only in a few countries (most notably in parts of China and Poland) it was 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 required large-scale production of gasoline (Smil 2006). After World War I diffusion of Diesel's efficient engine in trucking and shipping claimed the heaviest fuel oils, and the post–World War II 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 (Smil 2015c). There were also some notable shifts in nonenergy uses of fuels: during the late 19th century coal became an important feedstock for chemical industries, but its use was soon displaced by crude oil and natural gas. Currently about 14% of all extracted oil and slightly more than 5% of all natural gas are used as feedstocks, above all for syntheses of ammonia and plastics.

Another revealing classification 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, heat is often wasted when these needs are supplied by high-temperature combustion of fossil fuels, which also accounts 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.

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 2015a). Industrial facilities, above all steel mills and refineries, have power densities in excess of 500 W/m^2, and high-rise buildings that will house an increasing share of humanity in the 21st century megacities go easily above 1,000 W/m^2.

Infrastructures and Impacts

No infrastructures were needed to collect woody debris and to burn it in open fires, and some early energy infrastructures were simple. For example, in 18th century an unpaved road leading to an outcropping coal seam made it possible to use horse-drawn wagons for bringing in the material necessary for opening a small mine and for hauling the mined coal to the nearest market. But a large 19th-century mine would have to be connected to its markets by a railroad or its coal would have to be shipped by barges, and the mining of deeper seams could not be accomplished without installing adequate steam-powered water pumping and ventilation facilities.

Infrastructural needs reached an entirely new level with large-scale exploitation of hydrocarbons. Drilling rigs and drill pipes are required to discover the hydrocarbon-bearing reservoirs, pipelines carry crude oil and natural gas to markets (or to the nearest coast for overseas exports), and pretreatment (separation of water, petroleum gases, or H_2S) may be required before sending such fuels by a pipeline. When natural gas is used for household heating, it is necessary to have voluminous seasonal storages to meet winter peak demand and crude oil (including its national strategic reserves) must be stored either underground or in large above-ground tanks. Refining converts crude oil into gasoline, kerosene, diesel oil, residual oil, and nonenergy products (lubricants, paving materials).

Electricity generation requires an even greater variety of infrastructural prerequisites: it is necessary to have not only extensive networks of transmission and distribution lines in place before any large-scale generation can take place, and rising numbers of converters (ranging from lights and appliances to electric furnaces and electrochemical processes) determine the installed capacities of electric systems and also constrain the existing (and anticipated) load. For example, the maximum size of turbogenerators in the U.S. thermal stations stopped growing once it had reached 1 GW (Ravenswood unit in 1965), and the average size of such units had actually declined as the demand for electricity weakened during the 1970s.

Exports of liquefied natural gas (LNG) have presented a particularly demanding challenge. Cooling the gas to −162°C reduces its volume to nearly 1/600th of the gaseous state as the density rises from 0.761 g/L at ambient temperature to 428 g/L. LNG exports are predicated either on the proximity of liquefaction plants to natural gas fields able to supply enough gas for the project's duration (at least two decades or more) or on the existence of adequate pipelines bringing the fuel to a coastal location. High costs of liquefaction plants, LNG tankers, and regasification facilities used to limit the minimum size of a delivery system to at least 1 Mt of gas a year, but recent advances in plant and tanker design have made it possible to construct small and mini-LNG facilities with annual capacities of just 0.1–0.5 Mt/year (Linde 2015; Wakamatsu 2013).

Energy systems have also become more interdependent. During the preindustrial era they 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. Modernization began to enlarge their boundaries, first with railway and ship-borne transport of coal, then with increasingly large-scale production of industrial manufactures 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 selling natural gas (by cross-border pipelines or as LNG), and with nearly a dozen major coal importers and a similar number of countries with substantial coal imports.

At least two dozen countries carry on cross-border exchanges of electricity on a GW scale. And there are no national autarkies as far as energy extraction, transportation, and processing is concerned: mining machinery, oil and gas drilling rigs, pipelines, oil and LNG tankers, coal-carrying vessels, and refineries are designed and made by a relatively small number of producers, mostly in just a score of countries (including the United States, Germany, China, South Korea, and Japan among the leading exporters). Design and production of the most powerful prime movers has been even more concentrated. All of the world's marine diesel engines that power virtually all large commercial vessels come from the duopoly of designs by MAN Diesel and Wärtsilä, and they license their engines to a small number of makers in Europe and Asia. 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 set up by these companies (the largest one being CFM International between GE and French Snecma).

Mass-scale burning of fossil fuels, splitting of uranium, and capture of renewable energy flows have many profound economic and environmental consequences but, incredibly, energy has never been a primary, not even a major, concern of modern economic inquiry, and societies began to deal with widespread environmental impacts of energy use only after World War II. Studies of energy-economy links have uncovered some broad commonalities that have marked the path from traditional to industrial and then to postindustrial societies—but they also reveal many peculiarities. Environmental impacts of energy use are often difficult to appraise because there can be no generally acceptable metric for valuing their varied burdens.

Global growth of primary energy consumption has driven the expansion of the world's economic product: during the 20th century a roughly 17-fold expansion of commercial energy use (from about 22 EJ to about 380 EJ/year) produced a 16-fold increase of annual economic output, from about $2 to $32 trillion/year in constant 1990 dollars (Maddison Project 2015; World Bank 2015). And, as already noted, consumption of useful energy has grown much faster. A close relationship between GDP and energy growth rates is also revealed by studying historical statistics of many countries, but comparisons among the countries indicate that a given level of economic development does not require the same, or a similar, level of the total primary energy consumption. Sri Lanka is better off than Swaziland (both have average annual commercial energy supply just around 15 GJ/capita), and France has a much higher standard of living than Russia even though Russia's average per capita supply of primary energy is about 30% higher (World Bank 2015).

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 19th century, the U.S. and Canadian peaks followed six to seven decades later. OPEC's two price rises of the 1970s accelerated the process: by 1985 the average oil-intensity of the U.S. economy was 37% lower than in 1970, and by 2015 it was 62% below the 1970 level (Smil 2017). Japan reached its highest energy intensity in 1970, but between 1980 and 2010 it saw a 25% decline (USEIA 2015c). China's energy intensity continued to rise until the late 1970s, but it fell by almost 75% between 1980 and 2013 (China Energy Group 2014). In contrast, India saw only a 7% drop between 1980 and 2010.

But comparisons of national energy intensities and trends require careful interpretation: they differ due to climate, consumer preferences, composition of primary energy supply, and the structure and efficiency of final conversions. 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 explain why Canada's energy intensity is more than twice as high as that of Italy, and why China's intensity is still more than twice that of Japan.

Technical innovation, economies of scale, and competitive markets have combined to bring 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 UK in 2000 about 160 times more affordable than in 1900. In contrast, inflation-adjusted prices of coal and oil show 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 1900 and the early 1970s, they retreated rapidly after two OPEC-driven price rises of 1973–1974 and 1979–1981, but their recent fluctuations, including sharp declines in 2008–2009 and 2014–2016, make any forecasts questionable.

But most of the time energy prices have not been determined solely by market forces as energy industries have been among the greatest beneficiaries of government subsidies, tax breaks, and special regulations. In 2011 the International Monetary Fund put the total of global energy subsidies at $2 trillion and in 2015 it had increased that estimate to $5.3 trillion or about 6.5% of the world economic product (IMF 2015). Most of these subsidies arise from undercharging for environmental and health burdens and other externalities (including traffic congestion and accidents). China, due to its coal combustion, was the largest subsidizer (about $2.27 trillion in 2015). New subsidies have been used to expand solar and wind electricity generation and to produce liquid biofuels (Alberici et al. 2014; USEIA 2015d).

As already noted, internalization of energy-related externalities has been done adequately in some cases (including electrostatic precipitators, flue gas desulfurization, and three-way catalytic converters in cars), butt pricing of most externalities remains a challenge, above all because health effects (accounting for most of the cost) are notoriously difficult to monetize, as are the long-term ecosystemic effects of photochemical smog, acid deposition, nitrogen enrichment and, most importantly, of climate change. 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 (about 1.8 Gt CO_2) in 1900 to more than 9.6 Gt C (35.3 Gt CO_2) by 2015 (CDIAC 2016; Olivier et al. 2015). Steady rise of tropospheric CO_2 concentrations has been continuously monitored at the Mauna Loa observatory in Hawai'i since 1958: annual global mean rose from estimated 295 ppm in 1900 to 316 ppm in 1959 (the first full year of monitoring), reached 369.5 ppm in the year 2000, and surpassed 400 ppm in 2015 (NOAA 2016; Fig. 1.3). Most of the emissions come from only a dozen countries: 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 was still a nearly three-fold difference in 2015).

Extraction and conversion of energy has many other environmental consequences. Underground coal mining created subsidence, mountains of mine spoils, and localized water pollution (acid runoff). Extraction and transportation of crude oil can cause local water pollution and accidental oil spills. Nuclear electricity generation 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 while some countries (France, Sweden) have had a nearly perfect

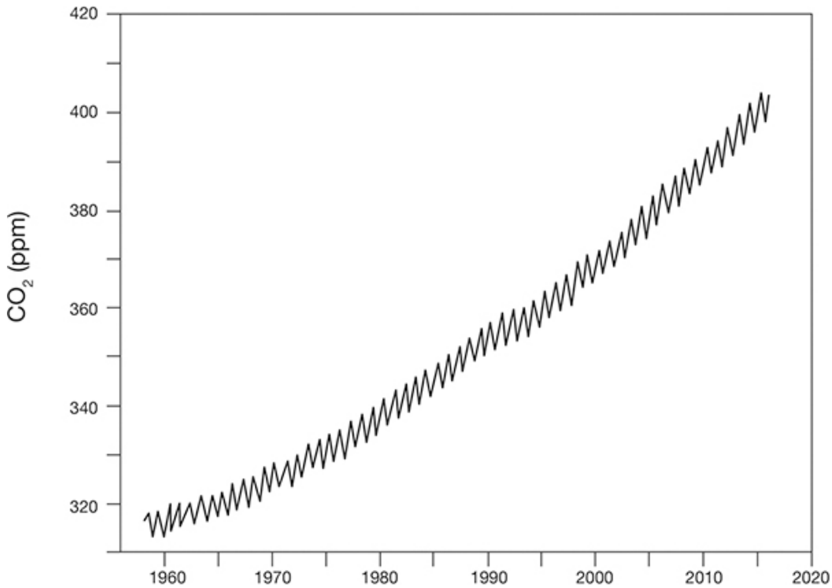

Figure 1.3 Global emissions of CO_2 (in Gt C/year) and tropospheric CO_2 concentrations, 1850–2015. Plotted from emissions data in CDIAC (2016) and from Mauna Loa concentrations data in NOAA (2016).

operation safety record, accidental releases of radiation in Chornobyl (April 1986) and in Fukushima (March 2011) have tested the public acceptance of nuclear generation (Hindmarsh and Priestley 2015; Marples 1988).

And harnessing renewable energy flows brings a multitude of new environmental, and other, concerns. Alterations of water's quality caused by large dams (lower temperature, water aging behind dams), problems with esthetic acceptability of large wind turbine farms, their noise and killing of birds, and fertilizer leaching from large monocultural plantings of biofuel crops and their reduction of biodiversity are perhaps the most common concerns. Expansion of crops for biofuel production (about 40% of the U.S. corn crop has been fermented into ethanol) also raises concerns about the long-term impact on food prices.

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CHAPTER TWO

Energy Transitions: Universal Patterns

Energy systems have many components whose relative importance and technical and economic performances evolve—and hence there are many energy transitions. Not surprisingly, transitions to new energy sources 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. A great deal of attention has been also paid 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 electric 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 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 and at changing patterns of sectoral consumption. Among the most notable examples in the first category is coal losing its transportation markets (steam locomotives and ships) but becoming the world's leading fuel for electricity generation, and the principal uses of refined oil products shifting from illuminants and lubricants to transportation. Diversification of final energy uses has proceeded from the initial pattern dominated by industrial consumption to a combination characterized by the absence of any dominant use: in the United States each of the four key sectors (households, industries, commerce, and transportation) now claims a major share of the final demand, respectively 22%, 31%,19%, and 28% (USEIA 2016).

The most obvious reality that emerges from the study of energy transitions across the entire historical time span is a highly skewed division of their progress. Stasis, stagnation, marginal adjustments, and slowly proceeding innovations marked the preindustrial era—while the process of industrialization and the evolution of postindustrial societies have been marked (indeed formed) by rapid 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 and by exertions of humans and animals to provide most of the needed mechanical energy (sails were the only early exception).

This situation did not change fundamentally even during the early modern era (1500–1800) when the UK (and, to a much lesser extent, some Western European regions) began extracting 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 leading European economies) 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. These transitions evolved from localized phenomena into nationwide developments, and eventually they became truly global. 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 minimal lag, a phenomenon perhaps best illustrated by China's rapid deployment of wind turbines and solar panels.

I will trace these developments by following first the millennia-long dependence on biomass energies that was replaced by now virtually universal dependence on fossil fuels. In the next section I will emphasize the importance of electricity in modern societies and review the development of thermal, hydro, and nuclear generation. Then I will outline a brief history of the other critical transition, from animate to mechanical prime movers, and the chapter will conclude with a quantitative appraisal of these trends on the global scale—and with inevitable caveats regarding the quality of various historical data used for these analyses. But before proceeding with these topics I will make some general observations regarding the process and tempo of energy transitions.

Processes and Paces: Complexities of Energy Transitions

When properly interpreted—that is, in a suggestive manner and not as rigid intellectual templates—analogies offer new perspectives as they enrich our understanding and lead us to think of new implications. I think that two analogies of a widely differing provenience are particularly relevant to a better understanding of energy transitions: the first one is Tolstoy's famous observation about families (made in *Anna Karenina*); the second one refers to the causes of aircraft accidents established by subsequent detailed investigations. Tolstoy noted that "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 has been most evident in small countries (especially those with compact territories) that have either relatively few people or a high density of population. No matter if they were affluent economies or still essentially premodern societies with very low per capita economic product, once they discovered a new rich source of primary energy they had developed it rapidly and ended up with completely transformed energy foundations in less than a single generation. Netherlands is perhaps the most apposite example of an affluent economy following this path after the discovery of its giant Groningen natural gas field in the municipality of Slochteren on July 22, 1959 (NAM 2015), and I will look at its trajectory in some detail in Chapter 3.

Kuwait's development of its giant oilfields is an iconic example of a small country making a dash from poverty to riches. Kuwaiti oil development began only in 1934 with the concession given to the Kuwait Oil Company, a joint undertaking of the Anglo-Persian Oil Company (later British Petroleum) and Gulf Oil. The concessionary agreement was signed after an expert hired to evaluate the country's oil prospects concluded 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, 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 empty interior with a small number of desert nomads; export of pearls (harvested by diving) was declining and trading of horses, spices, and coffee was the only notable economic activity.

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, and it turned out to be the world's second largest accumulation of oil, following the Saudi al-Ghawār (Howard 2008; Stegner 2007). In 1946, when it began its oil exports, Kuwait produced about 800,000 t of oil, annual output surpassed 50 Mt by 1955 and 100 Mt by 1965 when the country was 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, coal, and kerosene to an oil superpower in a single generation.

In contrast, large economies, particularly those with relatively high per capita energy demand and with extensive infrastructures serving a well-established fuel demand, cannot accomplish the substitutions so rapidly. Comparing the Dutch and the British experience is particularly revealing, 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 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: natural gas supplied a bit less than 5% of the primary energy in 1970, and it peaked only 30 years later at about 39%.

Five principal reasons explain the difference: a much higher total needed to provide an identical share of the primary energy (by 1970 the UK's primary energy supply was nearly four times larger than in the Netherlands (about 9.25 EJ compared to 2.5 EJ/year); UK's traditionally high dependence on coal-fired electricity generation; the country's pioneering dependence on nuclear generation (precluding costly shut downs of new stations and their replacement by gas-fired plants); higher costs and longer lead times to develop offshore resources (particularly in such an inhospitable environment as the North Sea); and also a larger size of the country necessitating longer trunk and distribution pipelines.

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. They started in 1969 with *Polar Alaska* and *Arctic Tokyo*, each with a capacity of 71,500 m^3 to carry gas from Alaska, and were replaced in 1993 by *Polar Eagle* and *Arctic Sun* (Marine Exchange of Alaska 2016). At that time Japan was the global leader in advanced shipbuilding, but a slow pace of substitution comes as no surprise given the size of Japan's economy (at that time the world's second largest) and its nearly total dependence on fossil fuel imports. Given these realities, Japan's LNG progress could be actually seen as rather impressive as the country had increased the share of natural gas in its primary energy supply from 5% in 1979 to about 22% in 2015.

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 caused by a number of factors and that the final outcome is a result of a specific sequence of errors (wrong actions or inactions) taken by a crew in response to a sudden event, be it a faulty instrument reading, collision with a bird, or a 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. In the next section I will show that this is the case even with perhaps the most commonly cited example that portrays worsening wood shortages as the decisive factor forcing England's early transition to coal.

As with the aircraft accidents, a careful investigation of energy transitions always reveals that their progress requires a specific sequence of events including key conceptional breakthroughs, technical innovations, and organizational actions taken in specific economic, political, and strategic circumstances: missing a single component in such a sequence, or delaying its introduction because of some unforeseen events, results in very different outcomes and often in considerably lengthier transition periods. An excellent example illustrating this necessity of a specific sequence, and of assorted events delaying a transition's progress, is provided by the recent emergence of LNG as a fuel traded competitively on the global scale.

A long road toward this accomplishment had to include at least four key developments: invention and commercialization of gas liquefaction; establishment of LNG supply chain (liquefaction, tanker-borne transport, regasification); increase of liquefaction and LNG tankers capacities in order to lower unit costs of the delivered gas; and a greater number of importing countries in order to justify the construction and expansion of larger terminals and 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. The latter category has included 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 and, most recently, emergence of an entirely unforeseen combination of inexpensive shale gas extraction and sharply lower crude oil prices.

The long road toward global LNG industry began in 1852 when the pioneering work done by Thomas 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, and the gas eventually liquefies. Practical designs for commercial liquefaction of oxygen and nitrogen followed during the last three decades of the 19th century, with the most important contribution made by Carl von Linde (1842–1934) whose patented process (in 1895) combined Thomson-Joule effect with what Linde termed counter-current cooling with compressed air expanded through a nozzle at the bottom of an insulated chamber used to precool the incoming compressed air (Linde 1916).

Because the United States was the only notable consumer of natural gas before World War II, there was no commercial need for LNG: that is why handling and transporting of liquid natural gas patented by Godfrey Cabot in 1915 had no practical consequences (Cabot 1915). 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 the Cleveland tanks failed and the ignited vaporized gas killed 128 people. This accident did not prove that LNG industry was very risky: the investigation report concluded that the mishap was caused by a poor tank design and that when properly done the gas liquefaction and storage are not exceptionally dangerous (USBM 1946).

Post–World War II surfeit of cheap Middle Eastern crude oil and rapid expansion of North American gas extraction had postponed the beginning of 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 World War II Liberty class freighter). The first methane liquefaction plant was completed in Arzew, Algeria, in 1964, and LNG exports to the UK began in the same year with two specifically designed tankers, *Methane Princess* and *Methane Progress*, each with capacity of 27,400 m^3 (Corkhill 1975).

They were followed by the Japanese imports from Alaska in 1969 (*Polar Alaska* and *Arctic Tokyo,* each with capacity of about 70,000 m^3) and the French imports from Arzew and Spanish and Italian imports from Libya's Marsa al-Brega in 1970. But by then the Groningen gas and the North Sea gas made the LNG imports to Western Europe uneconomical, and when the Arzew-Canvey contract expired in 1979 it was not renewed. Prospects for further LNG imports to European countries were weakened in 1984 with the completion of a high-capacity Urengoy-Uzhgorod pipeline (and its extensions to Western Europe) exporting the Soviet (Siberian) natural gas.

The situation was different in the United States where the combination of slower growth of natural gas extraction and rising industrial and household demand led to the decision to build four regasification terminals for the imports of Algerian gas. The first one opened in Everett, MA, in 1971 on the northern shore of the Mystic River less than 4 km from Boston's downtown. But this shift was short-lived as two terminals were shut down and two reduced their imports once the availability of domestic natural gas increased with the post-1993 wellhead price deregulation. This left Japan as the world's leading importer of LNG. New long-term import contracts were concluded with Abu Dhabi and Indonesia (in 1977), Malaysia (1983), and Australia (1989). By 1984 Japanese imports accounted for 75% of the world's LNG trade, and by 1999 they were still 66% of the total. And while Taiwan (in 1990) and South Korea (in 1991) became new Asian importers, the LNG trade remained confined by long-term contracts served by dedicated plants and tankers on inflexible routes.

These realities impeded technical advances. Between the late 1960s and the late 1990s typical capacities of LNG trains (liquefaction units) grew very slowly as the aggregate outputs of entire plants rose from the 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. Although the largest ship capacities increased fairly rapidly during the first decade of LNG trade—from 27,400 m^3 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 (one in 1964, six by 1980, 12 by 2000) and LNG tankers (fewer than 60 vessels until 1984, 100 by 1997), the total LNG trade surpassed 50 Mt/year only by 1991 and only in 1999 it carried more than 5% of all exported gas (Castle 2007). The industry began to change rapidly at the century's turn. Qatar began exporting 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); and Nigeria and Oman began shipping LNG in 2000. New exporters were added in 2004 (Egypt), 2007 (Equatorial Guinea and Norway), 2009 (Russia from Sakhalin fields to Japan, and Yemen), 2010 (Peru), 2013 (Angola) and 2014 (Papua New Guinea), and Cheniere Energy began the first U.S. LNG export from the Sabine Pass terminal in February 2016. Ranks of LNG importers were enlarged by Portugal and Dominican Republic (2003), India (2004), Mexico and China (2006) and Lithuania (2014), with Jordan, Poland, and Pakistan joining in 2015.

Increasing train size (average from less than 1 Mt/y in 1975 to nearly 5 Mt/year since 2010) and decreasing costs of train and tanker construction resulted in rapid capacity increases and bold plans for further expansion. Total exports rose from 100 Mt in the year 2000 to nearly 250 Mt in 2015. 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 wasted storage space and steel spheres increased 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, the average size of ships ordered in 2015 was about 160,000 m^{3}, and Qatargas had a growing fleet of large tankers of Q-Flex (210,000 m^3) and Q-Max (266,000 m^3) class (Qatargas 2015).

This means that after decades of stagnation or slow growth the largest LNG tankers now have capacities comparable to those of standard large crude oil tankers, but they are still more expensive to build. Moreover, because of crude oil's higher energy density (roughly 36 MJ/L vs. 24 MJ/L for LNG) the largest oil tankers (>300,000 deadweight tons) carry more than twice as much energy per vessel as do the largest LNG carriers. By the beginning of 2015 there were 373 LNG tankers with the total capacity of 55 Mm^3, and the global LNG trade carried about 32% of all internationally traded natural gas (BP 2016). LNG was imported by 29 countries on four continents, and its trade has been finally elevated from a marginal endeavor to an important component of global energy supply. This has become true in terms of total exports (about 30% of all natural gas sold abroad), number of countries involved (now more than 30 exporters and importers) as well as the flexibility of transactions (with traditional long-term contracts alongside spot market purchases).

This brief recounting of LNG history is an excellent illustration of decades-long spans that are required to convert innovative theoretical concepts into technical possibilities and then to adapt these technical advances, lower their costs, and diffuse them to create new energy industries (Fig. 2.1). 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). In global terms it had remained so until the 1960s when its cleanliness and flexibility began to justify high price of its

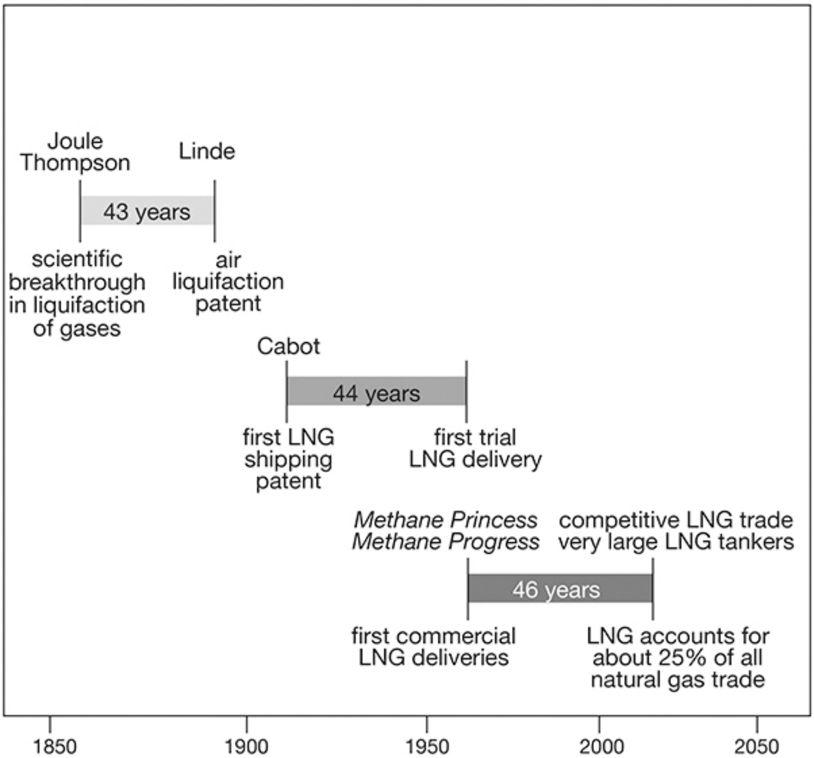

Figure 2.1 History of LNG shipments illustrates often very long time spans required for the maturation and diffusion of innovations in energy extraction, transport, and conversion.

ship-borne imports. 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 existing pipelines that could be used to sell the imported gas to households and enterprises (UK, France).

The industry's subsequent growth was affected by a combination of events that could not have been predicted during the 1960s. During the 1970s came the two oil price crises, the collapse of the Iranian monarchy in 1979, and the establishment of *shi'i* theocracy. During the 1980s, the United States deregulated natural gas prices (with the consequent boost of the domestic extraction), and the world oil prices collapsed in 1985. The 1990s saw the end of the Soviet state and America's unexpectedly strong economic performance. As a result, many plans were postponed or canceled. In 1975 it was expected that by 1981 Nigeria would begin its

LNG to Europe and that Iran would be selling its gas to Europe, the United States, and Japan (Faridany 1975). In reality, 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 when it became an important earner for a few major exporters (Algeria, Indonesia, Brunei) and a significant source of energy for Japan, South Korea, and Taiwan, but still could not qualify as a key ingredient of the global energy supply. More upheavals came during the first decade of the 21st century, most notably the great success of horizontal drilling and hydraulic fracturing in the United States, the main driver of natural gas extraction rising by a third between the end of 2009 and the end of 2015. In the early 2000s the United States was expected to become a large LNG importer—but now it is a growing LNG exporter.

If we take 1999, when the worldwide LNG exports surpassed 5% of all natural gas sales, as the onset of LNG's global importance then it had taken 35 years to reach that point from the time of the first commercial shipment (1964), more than a century since we have 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. How soon will LNG exports account for half of the global natural gas market; will they ever supply most of it? In 2015 it seemed that stagnating economies, unconventional gas resources, falling energy prices, and canceled LNG projects promised, once again, a slower progress. In any case, LNG history is a perfect illustration of complexities and vagaries inherent in major energy transitions.

Grand Fuel Sequence: From Biomass to Coal and Hydrocarbons

All preindustrial societies had a simple and persistent pattern of fuel use as they derived all of their limited heat requirements from burning biomass. Fuelwood (firewood) was the dominant source of primary energy, but woody phytomass would be a better term: the earliest users did not have any saws and axes to cut and split tree trunks, and those tools remained beyond the reach of the poorest peasants even during the early modern era. Any woody phytomass was used, including branches fallen to the ground or broken off small trees, twigs, and small shrubs. In parts of the sub-Saharan Africa and in many regions of Asia and Latin America this woody phytomass, collected mostly by women and children, continues to be the only accessible and affordable form of fuel for cooking, and water and (in seasonally cold climates) house heating for the poorest rural families.

Moreover, in some environments large shares of all woody matter were always gathered by families outside forests from small tree clumps and bushes, from the litter fall under plantation tree crops (rubber, coconut) or from roadside, backyard, or living fence trees and shrubs. This reliance on nonforest woody phytomass continues today in many tropical and subtropical countries. In less hospitable, arid, or deforested environments, children and women collected any available nonwoody cellulosic phytomass, fallen leaves (they were commonly raked in North China's groves, leaving the barren, dusty ground), dry grasses, and plant roots. For hundreds of millions of Asians and Africans, and for smaller numbers of people in Latin America, the grand energy transition traced in this chapter is yet to fully unfold: they continue to live largely in the wooden era.

Another usage that has been around for millennia is the burning of crop residues (mostly cereal and leguminous straws, but also corn or cotton stalks) and food-processing wastes (ranging from almond shells to date kernels). And on the lowest rung of the reliance on biomass fuels was (and is) dry dung, gathered by those with no access to other fuels (be it the westward moving settlers of the United States during the 19th century collecting buffalo dung or the poorest segments of rural population in today's India) or whose environment (grasslands or high mountain regions) provides no suitable phytomass to collect (Tibetan and Andean plateaus, subtropical deserts of the Old World where, respectively, yak, llama, and camel dung can be collected).

But there also have been important changes in wood use and production. Charcoal was widely used in the antiquity, and it eventually became a preferred source of heat for those who could afford its higher price and valued its smokeless combustion. Remarkably, the British House of Commons was heated by charcoal until 1791, long after (as I will soon explain) everybody in the country's cities, including the royal family, switched to coal. Charcoal was also the best choice for many small manufactures, particularly for metal-working. But this cleaner fuel was produced so inefficiently that in mass terms up to 15 units of wood were needed for a unit of charcoal, and even a typical preindustrial mean of 5:1 meant this conversion entailed (assuming that air-dry wood has about 15 GJ/t and density of 0.65 t/m^3 while charcoal's energy density is about 30 GJ/t) about 60% loss of initially charged energy content (Smil 2013a).

In households, open-hearths were eventually replaced by wood stoves with proper chimneys. These stoves were a surprisingly late innovation, beginning with tiled *Kachelofen* (common in Central Europe by the 16th century), and with various iron stove designs introduced during the 18th century, including the famous but misleadingly named Franklin stove in 1742: it was actually just an iron-lined fireplace (Edgerton 1990). At the same time, industries introduced more efficient, larger furnaces, and boilers and iron makers began to convert wood to charcoal on a massive scale needed for blast furnaces. Growing cities, expanding manufactures, and increasing iron production led to regional deforestation, and availability of wood or charcoal supplies became a key factor limiting the size of preindustrial cities and the level of iron output, restrictions that some early modern economies (notably the UK and the Netherlands) circumvented by importing both wood and iron.

There are no reliable records of ancient or medieval household biomass fuel consumption, and even for the early modern era (1500–1800), and for the 19th-century annual reconstructions are available for a small number of European countries: in 1800 per capita fuelwood use averaged only about 7 GJ in Germany and 9 GJ in France, but it was more than 35 GJ in Sweden (Kander, Malanima, and Warde 2013). Reconstructions for the United States start in 1850 when the average for all uses was much higher than in Europe, about 95 GJ/capita (Schurr and Netschert 1960). In some regions wood combustion by households was easily equaled or surpassed by industrial demand of ironmaking or glassmaking or for salt production. German medieval glassmaking was particularly wood-intensive with as much as 2.4 t of wood (97% of it burned to obtain potassium rather than energy) used per kg of glass, an equivalent of 90 MJ/kg (Sieferle 2001). Salt works using large heated pans to evaporate brines produced 15–100 kg of salt/m^3 wood or as much as 500–600 MJ/kg.

And reliable information about English iron smelting indicates that during the Middle Ages up to 20 kg (almost 600 MJ) of charcoal were used to produce 1 kg of hot metal; by the end of the 18th century it was about 8 kg (240 MJ)/kg (Smil 2016a). Ensuing deforestation undercut not only the viability of charcoal-using establishments but also threatened the very existence of nearby villages and cities that needed wood as timber for their houses and as raw material for making nearly all of their machines and utensils. A more predictable supply of wood was secured in some regions by deliberate planting of trees in backyards, on roadsides, on uncultivated slope land, or in fuelwood groves to supply nearby farms or villages.

Gradual shift from fuelwood and charcoal to increasing uses of coal, well known from developments in the UK, Germany, or the United States, has not been a universal phenomenon. There was an interesting early exception when the Golden Age of the Dutch Republic (1608–1672) was energized by peat, aided considerably by a widespread use of wind power (de Zeeuw 1978; Unger 1984), and during the 20th century many Asian and African countries with abundant hydrocarbon resources but with either no or poor domestic coal deposits moved from the biofuel era directly to the use of hydrocarbons. Moreover, some Middle Eastern desert countries went from very low per capita consumption of biomass fuels to becoming some of the world's highest energy consumers in just two generations. But, without exception, all of the world's major economies—United States, UK, Germany, France, Russia, Japan, China, and India—had followed the classical sequence from biofuels to coal.

During the earliest stage of small-scale local coal extraction there was no need to discover the fuel and to develop elaborate mines: the first coal seams to be tapped were those outcropping to the surface or those under only a shallow overburden and hence easily accessible by open pits or short shafts. In some places and at different times—ranging from the Roman Britain of the first two centuries of the CE to Arizona Hopis of the 13th century—coal was used locally for heating, and its first metallurgical uses were during the Han dynasty (Needham 1964). The oldest European extraction is documented in Belgium in 1113, and London received its first coal deliveries in 1228, but, as Nef (1932) noted, until the 16th century the fuel was regularly burned only by the poor who could not afford to buy wood and who lived close to coal outcrops.

Genesis of the growing British reliance on coal offers some valuable lessons with a wider validity. Thanks to Nef's (1932) influential work, a national wood crisis has been commonly seen as the key reason for the expansion of English coal mining between 1550 and 1680. But other historians could not support this claim, pointing to the persistence of large wooded areas in the country, seeing such shortages as largely local and criticizing unwarranted generalization based on the worst-case urban situations (Coleman 1977). This was undoubtedly true but not entirely relevant as transportation constraints would not allow the emergence of a national fuelwood market and local and regional wood scarcities were real.

At the same time, the best available reconstruction of energy prices in the southeast of England shows that (in real terms) fuelwood prices were actually fairly stable between 1550 and 1650 and that it was a steady decline in coal prices that primed the expanding fuel extraction (Fouquet 2008). By 1600 coal prices were about half of the wood prices per unit of gross energy, and by the time wood prices began to rise during the latter half of the 17th century (driven also by expanded shipbuilding) coal was the dominant source of energy for nearly all British industries as well as for household heating (Hatcher 1993). Coal production was greatly boosted with the invention of the steam engine and with the replacement of charcoal by coke in iron smelting (Smil 2017).

Neither of these innovations was immediately successful. Thomas Newcomen's highly inefficient (0.7%) steam engine was introduced in 1712, but even its improved version by John Smeaton was used only by coal mines, and it was only the machine's radical redesign patented in 1769 by James Watt that gained wider commercial acceptance during the last three decades of the 18th century (Fig. 2.2; for more detail see the third section of this chapter). Expanded coal extraction created its own positive production

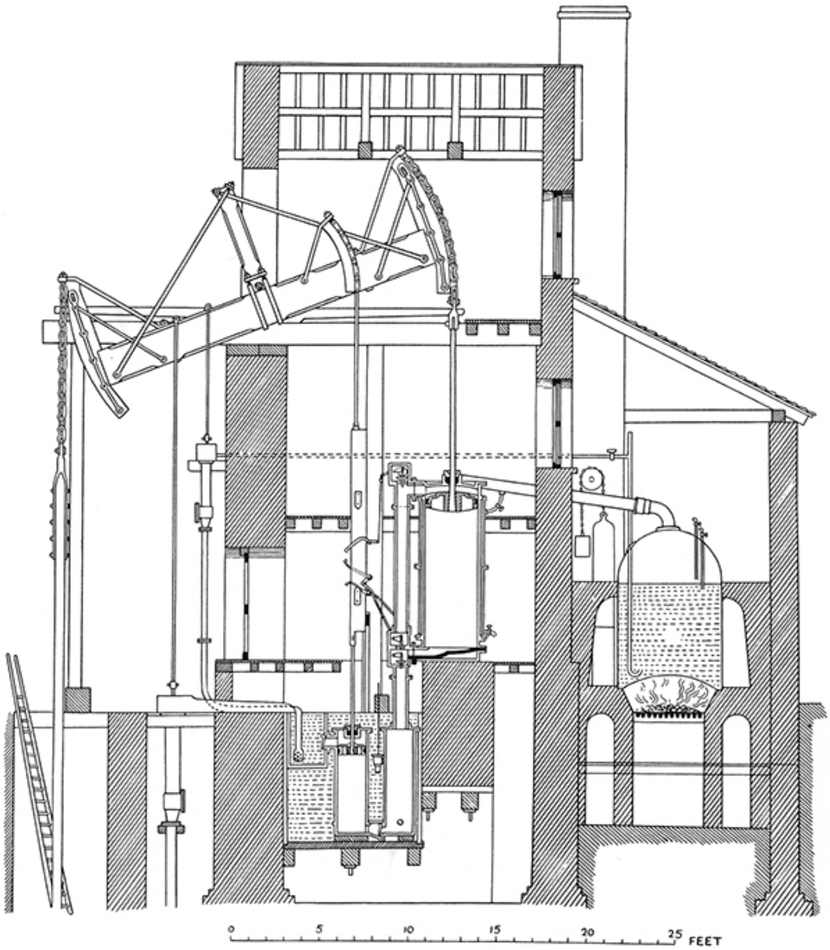

Figure 2.2 Cross-section of Watt's engine. Reproduced from Farey (1827).

feedbacks as deeper shafts required more water pumping and as larger mines also needed more energy for ventilation and for hoisting of the fuel.

Unlike in forested Sweden or Russia, wood availability for charcoaling was a limiting factor for the English iron industry. Maximum harvest of wood for charcoal in England and Wales was about 1 Mt/year, but that rate was never reached. In 1720 the annual output of 17,000 t of pig iron required about 680,000 t of charcoaling wood and further 150,000 t wood were consumed by forges: 830,000 t of wood, mostly from coppice growth, required nearly 1,700 km^2 of trees. Charcoal supply remained adequate because less iron was smelted in England and Wales during the first four decades of the 18th century than between 1600 and 1640, and the country became a major importer of Swedish and Russian iron (Hammersley 1973; King 2005).

Coke was first used during the early 1640s for drying malt, but its metallurgical use began only in 1709 with Abraham Darby (1678–17171) as the lone pioneer. Why his iron works remained an exception until the early 1750s, and why the output of charcoal-smelted iron actually rose by nearly a third between 1720 and 1755, is yet another fine illustration of many complexities of energy transitions. Darby's innovation remained isolated not because of any trade secrets, poor quality of early coke, or higher capital or operating costs of new furnaces. Darby's works made the early coke-based smelting profitable "*in spite of higher costs of the new process* because they received higher than average revenues from a new by-product of coke pig iron—thin-walled castings" (Hyde 1977, 40). This technique, patented in 1707, profited from higher fluidity of Si-rich coke-smelted iron that could be used to make lighter pots with thinner walls with fewer defects.

Hyde (1977) also concluded that bar iron made by using coke was more expensive, but this was challenged by King (2011) who examined business records of Darby's works and found that the small and poorly run enterprise had, until the late 1720s, excessive coke consumption. The prospect did not immediately improve even with more efficient use of coke:

> Whatever technical difficulties existed in the use of coke pig iron in forges in the early 1720s, these were evidently overcome by the end of that decade, but the depressed state of the iron trade discouraged the introduction to the market of coke-smelted forge pig iron, until the industry benefited from an economic upturn in the 1750s. That upturn can in part be attributed to the Swedish limitation on their iron production, which began a few years earlier. (King 2011, 154)

The proximate cause of England's subsequently rapid conversion to coke was a decline in imports—and the response was impressive: between 1750 and 1770 the country built nearly 30 new coke-based furnaces, and their share of total output rose from just 10% to 46% (King 2005). This was an epochal shift as a renewable source of energy was replaced by a nonrenewable fuel whose production could be expanded much more easily by increasing coal extraction than by improving productivity of existing forests or plantings or extending their areas. And although the English move was not primarily driven by actual shortages of charcoal, such deficits would have rapidly arisen in England and in other less-forested industrializing countries as their ironmaking was expanding during the 19th century. For example, Madureira (2012) calculated that in 1820 slightly more than half of Belgium's forested area was already used to produce metallurgical charcoal, and taking into account other requirements for wood that left little room for further expansion.

Coke was readily adopted because it was a superior metallurgical ingredient: it has the same energy density as charcoal (30 MJ/kg), but it is much less friable and can withstand heavier burdens; its compressive strength is nearly four times that of charcoal (Emmerich and Luengo 1996; Haapakangas et al. 2011). Supporting the burden (consisting of iron ore, limestone) and creating permeable volume in order to permit the ascent of heat and reducing gases and the descent of slag and metal is, of course, the fuel's second key function in a blast furnace besides generating heat and CO gas required for the reduction of iron oxides. Charcoal would be crushed under heavier loads (in furnaces taller than 8 m), and the collapse of charged material would make iron smelting impossible (Smil 2016a).

Charcoal-fueled furnaces still produced about a third of English and Welsh iron in 1810, but their subsequent demise in the UK and in coal-mining countries of Western Europe was fairly rapid. The U.S. iron industry took a different course. In its early stages it experienced no shortages of wood, and its post-1836 expansion in Pennsylvania was driven by direct use of high-quality anthracite, virtually pure carbon with good mechanical properties (Bone 1928). Yet another notable American difference was a lingering production of coke in traditional inefficient beehive ovens rather than by-product coking batteries introduced in Europe during the 1880s: by 1918 beehives produced more than half of the country's metallurgical coke, and their diminishing use persisted into the early 1960s (Hoffmann 1953; Sexton 1897; Washlaski 2008).

By 1800 Britain's coal extraction was far ahead of any of its future competitors: at about 9 Mt/year of coal it was an order of magnitude larger than the American output, most of it coming from Pennsylvania, with smaller contributions from Virginia, West Virginia, and eastern Kentucky (Milici 2003). Before 1800 major coal-mining regions also emerged in continental

Europe in northern France, around Liege in Belgium, in Bohemia, and in Silesia, Saxony, and the Ruhr region of Germany. German transition to coal is a notable example of the fact that the shift from wood to coal did not have to be primed by growing shortages of fuelwood (Sieferle 2001). Large parts of the country were always well forested, and even by 1800 it was possible to secure enough fuelwood at acceptable prices. German wood crisis was above all a timber crisis, but it is also clear that the country's wood supply could not have eventually supported economic growth associated with industrialization.

Wood shortages did not precipitate the German transition to coal, but only coal could sustain the country's rapid post-1870 industrialization. Timber shortage could be best eased by improved forestry practices and by reserving more wood harvests for timber. These measures led to state-promoted, even state-subsidized switch to coal in some German states (the unification came only in 1871), first in some state-owned industries and later in households. And it was only because of this switch that, as Sieferle (2001, 180) put it, "the limits of the agrarian solar energy system were burst in the transition to fossil energy system. Precisely this constituted the solution that formed the energy basis for the industrial transformation and marked it as a unique epochal discontinuity." This conclusion has a universal validity.

Because both good-quality bituminous coals and poorer lignites are widely distributed worldwide, it was not long before many other countries joined the United States, UK, Belgium, France, Germany, and Austrian Empire (Austro-Hungarian since 1867) and began producing solid fuels on an increasing scale. In Europe minor production began in Sweden, Greece, and Spain, and major expansion took place in Russia; Asia, China, India, Japan, and Turkey became the leading producers. Extraction also increased in Canada (where coal was mined first in 1638 in New Brunswick, and since 1720 in Cape Breton in Nova Scotia), Mexico, Peru, Australia, and New Zealand. Britain maintained its coal-mining lead almost until the end of the 19th century. In 1800 the country produced more than 80% of the global output, by 1870 its share was still 50%, but by 1899 it was surpassed by the U.S. extraction and Germany's production was not far behind.

By 1900 coal became firmly established as the most important primary fuel, having surpassed the global contribution of traditional phytomass fuels sometime during the late 1890s. Three grand trends marked the global coal production of the 20th century: continuous decline of its relative importance, continuous growth of its absolute contribution to the primary energy supply, and the transformation from a highly labor-intensive to a highly mechanized industry. In 1900 hydrocarbons were still marginal (only 4% of all modern energy supply), and by 2000 they had far surpassed coal's contribution, accounting for nearly 64% of the total. In 1900 the worldwide extraction of coals was about 800 Mt, a century later it was about 4.5 Gt, a roughly 5.6-fold increase in mass terms—but because of the declining quality it was only a fourfold increase in energy terms.

Coal energized the rise of modern industries and infrastructures in all European countries as well as in North America, Australia, and Japan during the first half of the 20th century, and the fuel remains important because of its continuing prominence in electricity generation and iron smelting. Contrary to common perceptions, the 19th century belonged, in global terms, to the wooden era—and the 20th century was not dominated by crude oil but by coal. My integration of the best available supply estimates (for the 19th century) and fairly reliable output statistics (for the 20th century) shows that between 1801 and 1900 the world consumed about 2.4 ZJ of wood and close to 500 EJ of coal, while between 1901 and the year 2000 coal contributed 5.5 ZJ and crude oil supplied 5.3 ZJ. But during the second half of the 20th century energy from crude oil was roughly a third higher than from coal (Smil 2008).

Expanded coal extraction would not have been possible without mechanization of underground mining and without the rising share of surface (open-cast) production that, in its basic techniques and reliance on outsize machinery, differs little from other mass-scale extractive enterprises. Since the 1950s high levels of mechanized underground mining have been the norm everywhere except in many of China's small mines. U.S. data show continued post-1950 productivity growth, from the national mean of about 0.65 t per employee hour in 1950 to 3.75 t in the year 2000 (USEIA 2012). Much greater productivities (and much higher safety) have been achieved by surface mining: averages in the U.S. West have been 18–20 t/employee-hour, with the best mines going above 30 t/hour.

Coal industry at the beginning of the 21st century also had a profoundly changed spatial distribution. The most notable national trends have included a long decline ending in a complete demise of the British underground extraction; ascent of the Soviet, and then the retreat of the Russian, output; continuing high levels of American production that began to weaken only since 2012; rise and then unprecedented increase of China's extraction that now appears close to plateauing; and the emergence of Australia, Indonesia, and Colombia as new large coal exporters. The British output peaked in 1913 (287 Mt from more than 3,000 mines), and it was still above 200 Mt during the 1950s (Hicks and Allen 1999; Fig. 2.3).

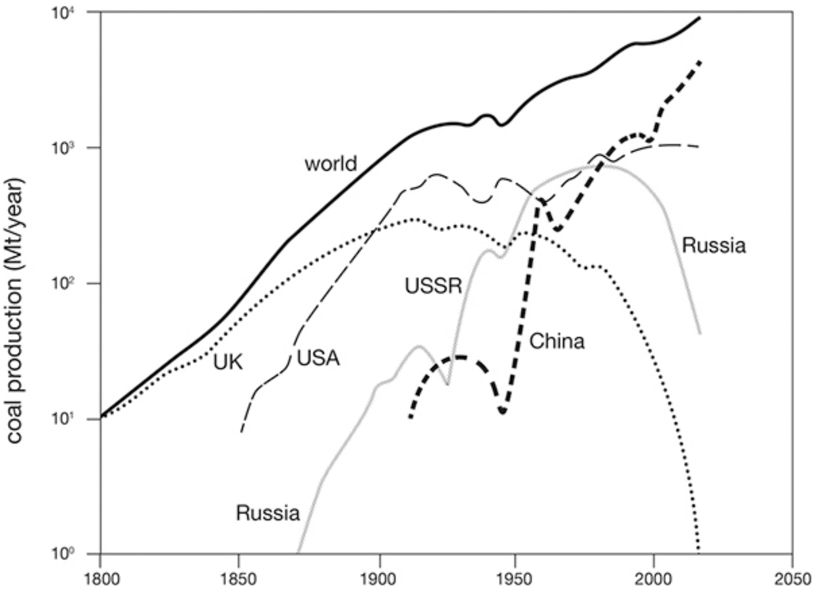

Figure 2.3 Coal production, 1800–2015. Plotted from data in UNO (1956, 1976), Etemad et al. (1991), and BP (2016).

Subsequent oil imports and then the domestic production of crude oil and natural gas from the North Sea reduced it to less than 100 Mt during the 1980s. By 2000 the UK was extracting less than 20 Mt/year, and it was importing coal, mostly from Australia, Indonesia, South Africa, Colombia, Russia, and the United States. By the end of 2014 there were still 10 deep mines whose output was just 4 Mt compared to imports of 42 Mt (DECC 2015), but on December 18, 2015, the last deep British mine, Kellingley pit in North Yorkshire, ended its production, letting go its 450 miners and closing more than a 500-year-long history of English coal mining (Moss 2015).

After the United States surpassed the UK's coal extraction, its 1900 output doubled by 1913, and it reached the pre–World War II peak of nearly 600 Mt in 1923; that total was surpassed only in 1944, and after another postwar pullback the industry became the prime energizer of rapidly expanding electricity generation, a period that lasted until the early 1970s. By that time the USSR was the world's second largest producer, with China rising fast. The United States yielded to China only in 1991, the year that ended with the dissolution of the USSR and that was followed by a decade of Russian economic stagnation. American annul output remained little changed (at close to 1 Gt), Russian production kept slowly declining, while China's extraordinarily rapid post-1990 economic growth was energized predominantly by coal. In 1990 the country produced 1.08 Gt (almost 23% of the global total), but in 2013, when its production peaked at 3.97 Gt, it extracted 48% of global production (BP 2016; Fig. 2.3).

As any liquid under pressure, crude oil has the propensity to seep to the surface along fracture zones and to form black lakes or tar or bitumen pools and, when under high pressure and mixed with natural gas, to create periodically reappearing burning pillars. These occurrences were fairly common not only in parts of the Middle East but also in some regions in North America, although few people know that a "burning spring" in the Kanawha River valley of West Virginia was listed in the Schedule of Property appended to George Washington's will. He took the land "on account of a bituminous spring which it contains, of so inflammable a nature as to burn as freely as spirits, and is nearly as difficult to extinguish" (Upham 1851, 385).

Oil was used in small amounts, often for nonenergy applications, since the antiquity. In ancient Mesopotamia asphalts and bitumens were used in floor and wall mosaics and as protective coatings, and lighter oils were burned in fire pans for illumination. Such uses were copied by the Greeks and the Romans, and later they were perpetuated by the inhabitants of the medieval Middle East (Forbes 1964). Oil from natural seeps in western Pennsylvania was collected during the late 18th century and bottled to be sold as a medicinal(!) "Seneca oil." Crude oil was also known in preindustrial Europe in the form of oil sands in Merkwiller-Pechelbronn in Alsace where the first shallow (less than 10 m) pit was dug in 1745, the first refinery was built in 1857, water injection began in 1879, and small-scale production continued until 1970 (Walther 2007).

There was only one locality in the preindustrial world where active steps were taken to collect liquid crude oil—the Absheron peninsula of the Baku region on the Caspian Sea in Azerbaijan. Baku's oil pools and wells were described by medieval Arabic travelers and historians, and in 1593 an inscription was affixed near a 35-m deep well that was dug manually in Balakhani (Mir-Babaev 2004). By the time the Czarist Russia took over Baku (in 1806) the Absheron region had many shallow wells from which lighter oil was collected in order to produce kerosene (by thermal distillation) used for local lighting as well as for export by camels (in skins) and in wooden barrels on small ships. In 1837 Russians built the first commercial oil-distilling factory in Balakhani, and nine years later they sank the world's first (21 m deep) exploratory oil well in Bibi-Heybat and thus opened up what was later classified as the world's first giant oilfield (that is, one having at least 500 million barrels of recoverable crude oil). Baku was thus the place where the modern oil era began in 1846.

North American developments followed soon afterwards, spurred by the search for an alternative source of lighting to replace whale oil (Brantly 1971). In 1858 Charles Tripp and James Miller Williams financed America's first (manually dug) oil well near Black Creek (Lambton County in southwestern Ontario), and a year later, amidst the world's first oil boom, the hamlet was renamed Oil Springs. And 1859 was also the year of the first commercial U.S. oil discovery as Edwin Drake (employed by George Bissell who started the Pennsylvania Rock Oil Company) supervised the drilling of a shallow well at an oil seep site at Oil Creek near Titusville, Pennsylvania. The well (whose drilling used an ancient Chinese percussion method but was powered by the steam engine) struck oil at the depth of 21 m on August 27, 1859, the date the Americans use as the beginning of the modern oil era (AOHGS 2016).

During the early 1860s crude oil thus began to contribute to primary energy consumption in Russia, Canada, and the United States. Canada soon fell out of the new oil league: another Oil Springs boom began in 1862 with the world's first gusher, and in 1865 oil was discovered also in nearby Petrolea, but the pressure in Ontario's small reservoirs soon declined, steam pumps were used to produce diminishing oil volumes, and by the 1890s a shrinking industry could not compete with much cheaper American oil. Canada's second oil era began only with the post–World War II discoveries in Alberta, and what might be termed the third era commenced (at a low level) during the late 1960s with the first extraction of oil from northern Alberta oil sands.

Russian oil extraction progressed swiftly thanks to substantial foreign investment (above all by Ludwig and Robert Nobel who launched Nobel Brothers Petroleum Company in 1875, and Rothschild brothers who established the Caspian and Black Sea Oil Industry and Trade Society in 1883) and to new major discoveries at the giant Bibi-Heybat field in 1878 (Fig. 2.4). Other notable pre-1900 crude oil developments took place in Romania, Indonesia, and Burma. In Romania pools and shallow wells were known for centuries, the first commercial refinery was opened in Ploieşti (60 km north of Bucharest) in 1857, and the country's only giant oilfield was discovered in 1900.

Oil was discovered in northern Sumatra in 1883, Burmese production began in 1887, and most of the oil was shipped to Europe. The first major oil discovery in the Middle East came on May 26, 1908, at Masjid-e-Soleiman in Iran, and Venezuela's giant Mene Grande field on the Lake Maracaibo's coast began producing in 1914. With the exception of pre–World War I

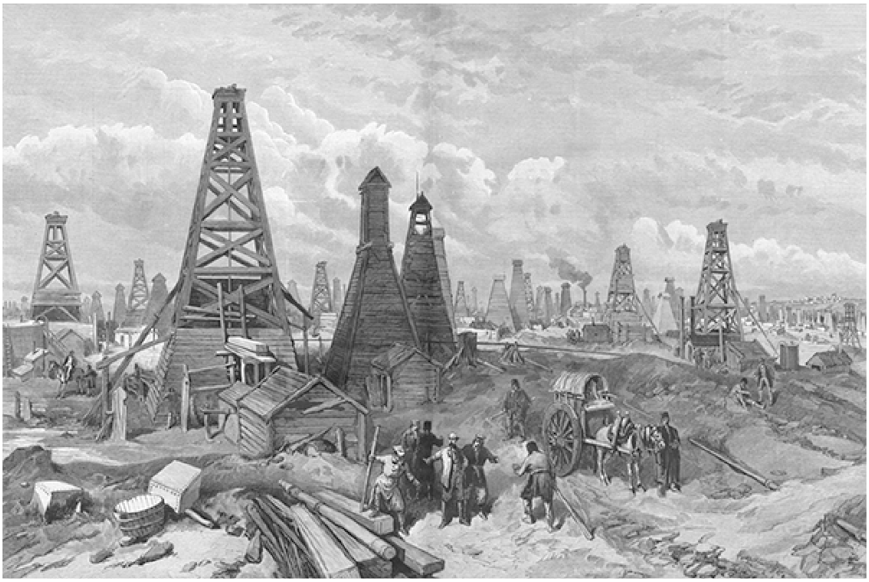

Figure 2.4 Baku oil wells. Reproduced from *The Illustrated London News*, June 19, 1886.

discoveries in Iran, all major finds in the Persian Gulf region came only between the late 1920s and the early 1960s. Iraqi Kirkuk was first (discovered in 1927, producing since 1934), followed by Iranian Gachsaran and Haft Kel in 1928, Naft-i-Said in 1935, Pazaran in 1937, and Agha Jari in 1938 (Howard 2008; Nehring 1978).

In that year came also the first large discovery in Kuwait, and in Saudi Arabia (Dammam on the western shore of the Persian Gulf near Dhahrān), followed by Abqaiq and Abu Hadrīya in 1940, Qatīf in 1945, and in 1948 al-Ghawār (southwest of Dhahrān) that was confirmed by 1956 to be by far the world's largest reservoir of crude oil. Canada also rejoined the ranks of major oil producers with the discoveries of giant oilfields in Alberta (Leduc-Woodland in 1947 and Redwater in 1948), and the Soviet center of oil production shifted from Baku to the Volga-Ural region where the first strike in 1937 (giant Tuymazy) was followed by two more giants, Mukhanovo and Romashkino, in, respectively, 1945 and 1948 (Peterson and Clarke 1983).

Postwar economic recovery in Europe, USSR, and Japan, and America's baby boom–driven growth stimulated demand for oil through rising car ownership, shift to suburbs, widespread use of plastics and synthetic fertilizers and, starting in 1957, the jet-powered air travel made more affordable by the first wide-body plane (Boeing 747) in 1969. Increasing networks of large-diameter pipelines and construction of massive crude oil supertankers made it possible to export the fuel cheaply, and adoption of efficient catalytic cracking enabled to produce larger volumes of the most valuable transportation fuels, gasoline, kerosene, and diesel oil (Smil 2006).

Future of this increased supply seemed to be secure, as the 1950s and 1960s were the two record decades for the discovery of giant oilfields (Li 2011; Nehring 1978). These finds included giants in Saudi Arabia (Safānīya-Khafjī, Manīfa, Berri, Shayba), Iraq (Rumaila), Iran (Ahwaz, Marun, Fereidūn), and Abu Dhabi's (Bū Hasa, Zākūm, Asab), as well as in Canada (Pembina, Weyburn-Midale, Swan Hills) and the United States (the Prudhoe Bay on the North Slope of Alaska in 1968) and the largest Soviet supergiant in Western Siberia (Samotlor in 1965). Discoveries in Algeria, Libya, and Nigeria made Africa into a major new supplier, and a supergiant Daqing oilfield in Heilongjiang (discovered in 1959) finally changed China's previously meager oil fortunes.

Size of the Middle Eastern oilfields and readily available requisite investments brought rapid extraction increases: for example, the Saudi output (all of it managed by the Arabian American Oil Company) tripled between 1960 and 1970 (from 62 to 192 Mt/year), while the Kuwaiti output went from less than 1 Mt in 1945 to more than 80 Mt by 1960. Dissatisfaction with low oil prices led to the establishment of the Organization of Petroleum Exporting Countries (OPEC) in 1960 (OPEC 2016). As the oil demand continued to grow and the U.S. production began to fall in 1971 (it remained the world's largest until 1975), OPEC began rising its prices. Its first round of large increases (from $2.70/barrel in early 1973 to $10.50/barrel in early 1975) was followed by the second round in 1979–1980 (from $12.80/barrel in 1978 to $35.50/barrel in 1980) that was precipitated by the overthrow of the Iranian monarchy.

Concerns arose about the adequacy of the future supply but OPEC overplayed its hand, and as the oil price rose to nearly $40/bbl the global demand (and with it the worries about an imminent peak oil production, as well as new drilling) receded. Global oil production peaked at just over 3.2 Gt in 1979, and it did not surpass that level until 1994 (Fig. 2.5). Prices remained fairly stable until the century's end and new major discoveries of the 1990s came from Mexico, Iran, Brazil, and from the U.S. offshore waters in the Gulf of Mexico. Meanwhile another major change took place, as the USSR, the world's largest oil producer since 1975, fell apart and the aggregate oil extraction of its former states declined by nearly a third between 1991 and 1996, making Saudi Arabia a new leader starting in 1993.

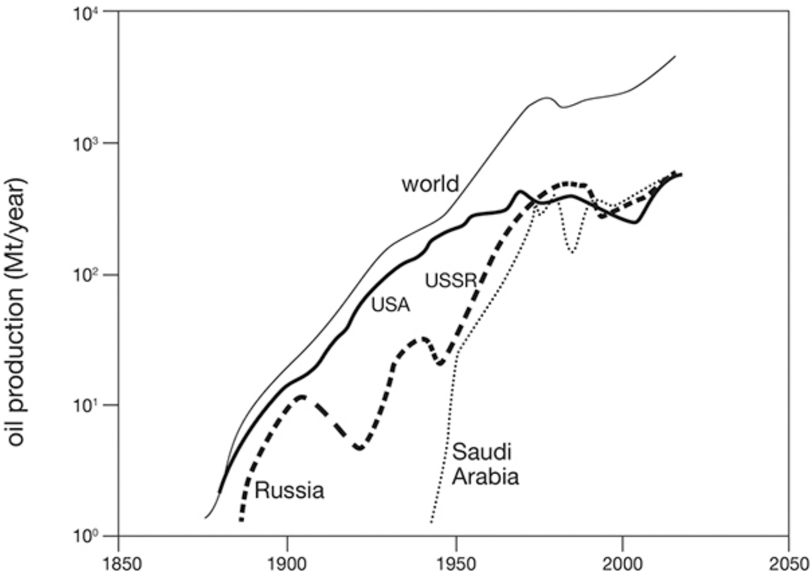

Figure 2.5 Crude oil production, 1850–2010. Plotted from data in UNO (1956, 1976), Etemad et al. (1991), and BP (2016).

Oil prices during the 1990s remained low and fairly steady (fluctuating mostly between just $18–23/barrel) and the global extraction increased modestly during the first five years of the new millennium. Subsequent combination of a weaker U.S. dollar (international oil trade is denominated in U.S. dollars), speculation in commodity futures and rising demand in China pushed oil prices to new nominal (and demand-destroying) highs of more than $140/barrel in July 2008. As the world's worst post–World War II economic crisis set in the prices fell to less than $35 by the year's end but then rose once again to more than $100 by March 2011. That recovery was short-lived as a new output-depressing combination of trends (significant slow-down of Chinese economic growth, poor performance of affluent economies and weakening energy demand by their aging populations, reemergence of the United States as the world's largest oil producer thanks to horizontal drilling and hydraulic fracturing of shales) began to weigh once the OPEC decided not to cut its output but rather defend its market share.

Once again, this created a supply surplus and the price for the West Texas Intermediate oil fell from the average of about $98/barrel in 2013 to $59 by the end of 2014 and to just $36.50 by the end of 2015 and then even below $30 in early 2016 before it had partially recovered. China's rising coal production lowered crude oil's share of the global primary fuel supply (from nearly 35% in 2010 to 32% in 2015), but shares of natural gas have been also rising.

Natural gas is a mixture of light combustible hydrocarbons, with methane dominant but with up to a fifth of the volume made up of ethane, propane, and butane; other gases commonly present include CO_2, H_2S, N_2, and water vapor. The first well-documented use dates to the Han dynasty (200 BCE) when wells were drilled with percussion tools and the gas was led through bamboo tubing to burn under large iron pans and evaporate brines to produce salt in the landlocked Sichuan (Needham 1964). Americans were the industry's modern pioneers, with the first shallow natural gas well dug in 1821 in Fredonia, New York, by William Hart. Rising volumes of the gas became available with the expanding crude oil production (as gas associated with the liquid fuel), but in the absence of long-distance pipelines most of the fuel was wasted by flaring (Smil 2015c).

In cities natural gas faced competition from town (coal) gas, first used in London in 1812, and in the United States in Baltimore in 1816; by the 1880s gas lights began to be replaced by new electric lights. Three innovations had to take place before natural gas could become a major household and industrial fuel: adoption of a safe burner mixing the gas and air in correct proportion to produce controllable flame for cooking and heating; introduction of large-diameter, high-pressure pipelines that could carry greater volumes of the gas over longer distances; and efficient compressors to propel the gas through pipes. The first advance began with Robert Bunsen's burner in 1885, and it was perfected by temperature-regulating thermostats that could be used to monitor and regulate the flame temperature.

Better pipes and more efficient pipeline construction methods began to diffuse during the 1930s, but it was only after World War II when metallurgical advances and better welding and pipe-laying techniques brought a pipeline construction boom (with trunk lines having diameters up to 120 cm), first in the United States, and by the 1960s also in Europe and parts of Asia. Another important post–World War II advance was the replacement of reciprocating engines or electric motors used to power the compressors that pressurize the transported gas (in stations spaced in intervals of 60–160 km along the pipeline) by more efficient gas turbines fueled by a small amount of the transported gas. Natural gas extraction rose to more than 10% of all U.S. fuel production by 1940, but the gas industry became an important global presence only after World War II.

Clean combustion and flexible use made natural gas a much sought-after fuel used not only for space heating and cooking but also in numerous industrial processes and electricity generation (both by producing steam in boilers and by powering gas turbines). Natural gas is also an excellent feedstock for production of ammonia and a wide variety of synthetic materials. Global extraction expanded rapidly, from about 200 Gm^3 in 1950 to 1.2 Tm^3 by 1975 and 2.4 Tm^3 in 2000, a 12-fold rise in 50 years; by 2015 the output was up to about 3.5 Tm^3, a 45% rise in 15 years (Fig. 2.6). The United States remained the world's largest natural gas producer since the industry's conception until 1982 when it was surpassed by the USSR, with Russia inheriting the top ranking in 1991 thanks to the supergiant fields in Western Siberia.

Except for a few years (1997 and 1998, 2000–2001), when it fell to the second place, Russia kept its primacy until 2009 when the United States regained the lead thanks to the rising production of tight gas from shales

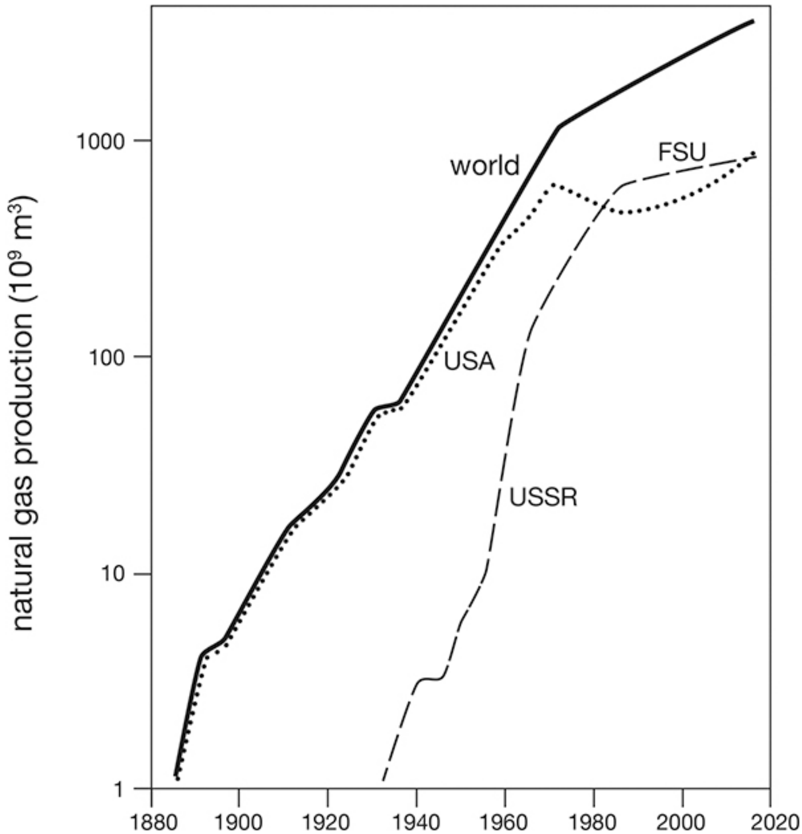

Figure 2.6 Natural gas production, 1900–2015. Plotted from data in UNO (1956, 1976), BP (2016).

(Smil 2017). Canada has been the world's third largest producer since the late 1950s, but it was surpassed slightly by Iran and Qatar in 2011. North Sea discoveries made the UK temporarily the fourth largest producer, but by 2015 it was not even among the top 15. China, Saudi Arabia, Norway, Algeria, and Indonesia made up the rest of the global top ten in 2015. Technical advances, environmental concerns, and growing LNG trade reduced the volume of wasted gas, but flaring is still unacceptably high with major sites seen on the night-time satellite images as the brightest spots on the Earth. The first detailed global inventory found 165 Gm^3 flared in 1970 (with Iran in the lead with about 30 Gm^3). In 2010, despite the intervening rise in output, the total was down to 134 Gm^3 (most of it coming from giant Western Siberian fields, and from Nigeria and Iran), an equivalent of nearly 20% of the U.S. consumption (GGFR 2016).

A New Quality: Generation of Electricity

There are many reasons why electricity has become the preferred form of energy and why it is absolutely essential for the functioning of modern civilization. Electricity brings economic benefits unsurpassed by any fuel as it offers superior conversion efficiencies, unmatched productivity, and unequaled flexibility for uses ranging from lighting to space heating, and with essential roles in industries ranging from steel and aluminum making to food processing. Only in transportation electricity is not ready to claim all key sectors, and some of them may remain beyond its reach. All high-speed trains and many freight trains are powered by electricity, as are all subways, and there is, obviously, an enormous potential for electric cars. But our storage capabilities still preclude the use of electricity-powered heavy trucks, barges, ocean-going ships and, most obviously, of airplanes able to carry hundreds of passengers on intercontinental flights. I will return to this lasting and fundamental limitation when assessing the prospects of the noncarbon world in this book's final Chapter 6.

Electricity's use offers many other advantages. No other source of energy enables such precise control of delivery across such a range of power (ranging from less than 1 watt for the most efficient microchips to multigigawatt flows in large national or regional grids); such focused applications on any conceivable scale (from micromachining to powering the world's largest excavators and the world's fastest trains); and, of course, no need for storage (instant supply on demand), incomparable ease of using (flipping a switch, pushing a button, now also just waving a hand or focusing a look), noiseless operation (creating new accidental risks for electric vehicles) and, at the point of use, cleanliness of conversion to other energies.

And with the now universal reliance on electronic monitoring and automation (ranging from incubators to nuclear reactors) electricity's role as the controller, regulator, and enabler of material and information flows has become even more fundamental: only a small share of its generation energizes these controls, but their cessation would have profound effects on modern societies. But that share has been growing due to rising demands for electronic communication and data and image transfers. U.S. data centers doubled their electricity use between 2000 and 2005, but during the next five years (due to the 2008–2009 recession) they needed about 56% more, and the U.S. requirements rose by only 36% (Koomey 2011). But NRDC (2014) found that the U.S. centers do not operate very efficiently, and it is estimated that in 2020 they will need 53% more electricity than in 2013 (almost140 TWh), an equivalent of annual generation by about 20 1-GW stations with 70% capacity factor.

Most of the world's electricity is now generated from fossil fuels: in 2015 that share was almost exactly two-thirds, with coal accounting for about 60% of the latter fraction, or roughly 40% of the global total (IEA 2015a). Hydroelectricity came next with about 16%, followed by nuclear electricity (about 11%); despite their recent rapid expansion, all forms of new renewable electricity generation (wind, solar, geothermal, biofuels) supplied only about 6% of the 2015 total, with half of it coming from wind turbines. Photovoltaic generation is still marginal, supplying less than 1% of the world's electricity. Moving away from the reliance on fossil fuels in general (and from coal combustion in particular) will reshape the industry, and I will address this in some detail in Chapters 5 and 6 of this book. In the remainder of this section I will review the rise of the modern electricity industry.

Experimental foundations of electric industry were laid before 1850, that is, before we came to understand the demands and the limitations of internal combustion whose mastery led eventually to cars and airplanes. Alessandro Volta (1745–1827) built the first electricity-storing battery in 1800 (the unit of electromotive force bears his name); Hans Christian Ørsted (1777–1851) discovered the magnetic effect of electric currents in 1819 (the unit of magnetizing field is named after him); André Marie Ampère (1775–1836) formulated the concept of a complete circuit and quantified the magnetic effects of electric currents (the unit of electric current has his name); and in 1831 Michael Faraday (1791–1867) discovered the induction of electric current in a moving magnetic field, the finding that was eventually translated into large-scale conversion of mechanical energy into electricity (farad is the unit of electrical capacitance).

But it was only during the 1880s when this new form of energy became commercially available, with the first electricity-generating plants serving only areas encompassing a few city blocks. Remarkably, electricity's commercial introduction was not an outcome of a gradual accumulation of diverse developments but a matter of deliberate creation of an entire new energy system by a boldly thinking individual (Smil 2005). Edison's epochal designs and the first practical applications of a complete electricity system—including generation, transmission, distribution, and final conversion—took place shortly after his invention of the first practical lightbulb patented in 1879. Pearl Street Station in New York, opened in September 1882, had four coal-fired Babcock & Wilcox boilers (about 180 kW each) located on the ground floor, and six Porter-Allen steam engines (94 kW) directly connected to Jumbo dynamos on the reinforced second floor, and by the end of the year it was supplying electricity for 5,000 lightbulbs (Martin 1922; Fig. 2.7).

Generation of primary electricity, that is, production of electric current without any fuel combustion, began at the same time. Edison's first American hydroelectric station, with just 25 kW of installed power produced by two small dynamos placed in a wooden shed, was energized by water rotating a small (107-cm diameter) wheel on the Fox River in Appleton, Wisconsin. The station was built for H. F. Rogers, a paper manufacturer,

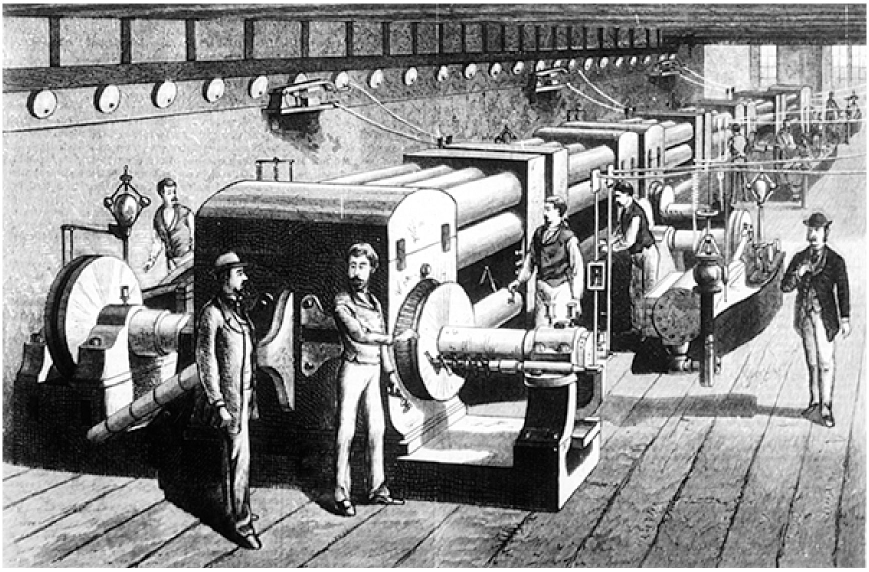

Figure 2.7 Dynamo room of Edison's first American electricity-generating station in New York's Pearl Street. Reproduced from *Scientific American*, August 26, 1882.

it powered 280 weak lightbulbs, and it was in operation for seven years (Dyer and Martin 1929). Those pioneering projects (and their contemporary smaller English counterparts, steam-powered Holborn Viaduct and water-powered Godalming) launched an industry whose expansion has now continued for more than 130 years.

Thermal generation represents perhaps the most consequential shift in modern energy use as increasingly larger shares of fossil fuels have not been used directly to provide heat, light, and motion but to produce electricity. In 1900 electricity generation claimed less than 1% of the world's and less than 2% of the U.S. fossil fuel consumption; those shares rose to about 10% by 1950 and, respectively, to 30% and 34% by the year 2000, and their increase has been an excellent indicator of economic modernization. In 1950 China used 10% of its coal (at that time its only fossil fuel) to generate electricity—but by the year 2000 the country burned 30% of all fuel energy in power plants, a share nearly as high as in the United States (Fridley 2004; Smil 1976). For comparison, the Japanese share was 40% in 2015.

The second transition has seen the primary electricity claiming a growing share of the total primary energy supply. Until the late 1950s almost all of that generation was done by the kinetic energy of water, and since that time primary electricity has come from the combination of water and nuclear fission (with a minuscule share of geothermal power) joined (since the 1980s) by rising contributions from wind turbines and, most recently, also by photovoltaic conversions. There is also small, but increasing, generation based on burning woody phytomass. These different modes of electricity generation have had very different histories, and they also face very different prospects.

There are at least three major reasons why thermal electricity generation took off so swiftly and has continued to expand so vigorously. The first one is an undoubtedly brilliant Edisonian design of an entirely new energy system. Between 1880 and 1882 Edison obtained (in addition to nearly 90 patents for improved incandescent lights) 60 patents for electric dynamos and their regulation, 14 patents for electric lighting systems, 12 patents for electricity transmission, and 10 patents for electric meters and motors (The Thomas A. Edison Papers 2015). The second reason is that since 1882 every key component of Edison's system has been improved by a remarkable concatenation of technical advances that have made the electricity generation more efficient, more affordable, and more reliable.

Remarkable progress was achieved during the first 25 years following Edison's pioneering projects (Smil 2005). Most notably, steam engines in power plants were displaced by steam turbines, direct current (DC) transmission gave way to alternating current (AC), and lights became much more efficient and longer-lasting. The steam engine, used by all early power plants, was an inferior energy converter when compared to the steam turbine patented by Charles A. Parsons in 1884 and then rapidly scaled up to become the world's most powerful, and a very efficient, prime mover. Parsons's first 1884 machine, rated at just 7.5 kW and at 1.6% its efficiency, was inferior to Edison's Pearl Street station that converted less than 2.5% of chemical energy in coal to electric current sent to the financial district light (Parsons 1936). By 1891 the largest steam turbine rated 100 kW, the first 1-MW unit was built in 1899 (Fig. 2.8), and by 1907 Parsons put into operation a 5-MW turbine that converted coal to electricity with about 22% efficiency (Parsons 1911).

Direct current, used by Edison to transmit electricity to his first customers, was replaced by AC transmission, a switch made possible by the introduction of efficient transformers; many inventors contributed to their perfection, but William Stanley introduced the prototype of modern current converters in 1885. AC was used already in some of the first small electric systems completed during the late 1880s, but Edison had clung to his original DC choice for a while (not so much because of his famous stubbornness but because of his vested commercial interests), but by 1890 the so-called "battle of systems" was over with AC triumphant. And Edison's carbon-filament lights gave way to incandescent metallic filaments (osmium in 1898, tantalum in 1901, and, finally, tungsten in 1912).

Maximum capacity of American steam turbines rose swiftly from 1 MW in 1900 to more than 200 MW by the early 1930s—but the latter size was not surpassed until the late 1950s. Exponential growth then pushed the

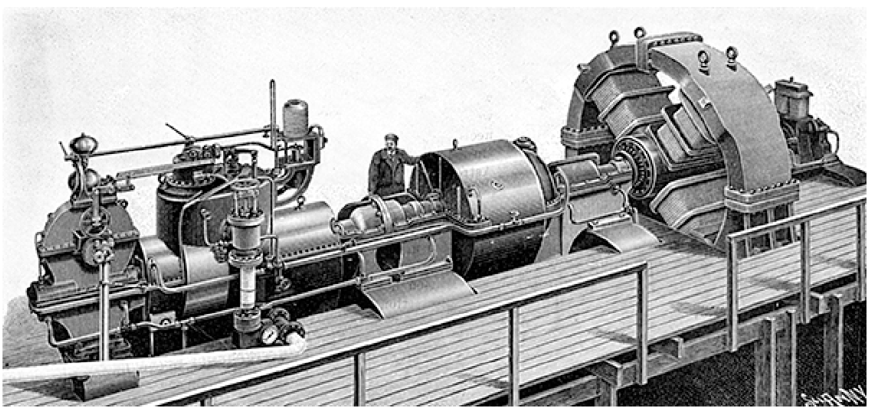

Figure 2.8 The world's first 1-MW steam turbogenerator was installed in 1900 at Elberfeld plant in Germany. Reproduced from *Scientific American*, April 27, 1901.

maximum unit capacity to 1,000 MW (1 GW) by 1967, and at that time it was widely anticipated that turbogenerators of 2 GW and larger would be installed before 1980. But by the year 2000 the largest units reached only about 1.5 GW, and a reverse trend had actually led to smaller units in new thermal power plants. But the new units, using steam at higher temperature and higher pressure (the former rose from less than 200°C in the early 20th-century plants to just over 600°C by 1960, while the latter rose from less than 1 MPa to more than 20 MPa during the same period) generated thermal electricity with higher efficiency, and new gas turbines, used to produce electricity during peak demand periods, were even more efficient.

U.S. statistics show average coal-to-electricity conversion efficiencies (for net plant output) rising from less than 4% in 1900 to nearly 14% in 1925, to 24% by 1950 (Schurr and Netschert 1960), to just over 30% by 1960, and by 1975 the performance of the best stations topped for the first time at 40%. Subsequently the average heating rate had leveled off, and it was still no more than 34% in 2013 (USEIA 2015a). A significant step in the deployment of large turbogenerators was taken in 2010 with the construction of the world's first 1.75-GW Arabelle machine for the third unit of EDF's nuclear station at Flamanville (Alstom 2012): it weighs 1,100 t, its rotating part (1,500 rpm) is 70 m long, and it has an overall efficiency of 38%.

The third reason for the rapid takeoff of thermal electricity generation was the invention and prompt commercialization of a device that was introduced just six years after Edison designed his first electricity-generating stations: in 1888 Nikola Tesla patented his electric induction motor that made it possible to convert electricity into mechanical energy with high efficiency and with precise control (Smil 2005). Within a few decades electric motors became the dominant prime movers in all industries, and they had also revolutionized household work by powering washing machines (first on sale in the United States in 1907), vacuum cleaners (available since 1908), and household refrigerators (since 1912): in the United States these machines had diffused widely before World War II, and in Europe and Japan their ownership became common only after 1945.

The fourth factor enabling a rapid progress of thermal electricity generation was the ability to harness the economies of scale by building stations of increasingly greater capacity and by transmitting the current by high-voltage (HV) lines. Larger stations were typically constructed by using multiple turbogenerators sharing large boilers. As a result, capacity of the largest U.S. thermal station rose from about 40 MW in 1900 to nearly 400 MW by the late 1930s, and it surpassed 4 GW by the late 1970s; the growth of average station capacities paralleled that rate by going from about 20 MW in 1930 to nearly 100 MW by 1960 and 400 MW by 1980 (Smil 2008).

Subsequent lower growth rates of electricity demand have largely ended further unit or maximum plant capacity expansion, but wind turbines, the most successful generators of the new forms of renewable electricity, have followed the same double-trend of growing unit sizes and growing total wind farm capacities.

Because transmission voltages are a direct function of overall electricity-generating capacities, they experienced a similar exponential growth, albeit interrupted by the Great Depression and World War II. American HV lines reached maxima of 110 kV just before 1910 and 230 kV by 1923, (the single exception of Hoover Dam–Los Angeles 287.5-kV line, completed in 1936, aside) but their exponential rate of growth resumed only in 1954 with the introduction of 345-kV links; 500-kV lines followed during the early 1960s, and a new maximum was reached by 1965 when the first 1,100-km long 765-kV line was installed by Hydro-Québec to transmit electricity from Churchill Falls in Labrador to Montréal (Smil 2008). China has been developing the world's most extensive HV grid, including a number of ultra-high-voltage lines (1,000 kV AC, ±800 kV DC), two of the latter (Xiangjiaba-Shanghai and Hami-Zhengzhou) more than 2,000 km long.

Grids were eventually extended to conduct international electricity trade. Interconnection capacities still limit its overall magnitude, but a fully integrated electricity market now encompasses most of the member states of the EU. Long-standing directions include the exports of Scandinavian hydroelectricity, exports of French nuclear power, and the use of Swiss water reservoirs as temporary capacity storages. The latest developments include substantial sales of German wind and solar electricity: by 2015 exports were 2.5 times higher than imports. Electricity trade in North America took off with the completion of HV direct current lines carrying Canadian hydroelectricity to American markets, with interconnections from Québec, Manitoba, and British Columbia to supply, respectively, in the Northeast, Midwest, and the West Coast. But there are no nationwide grids either in Canada or in the United States, although the United States may finally get one soon (Kumagai 2016). International electricity trade has not increased appreciably for the past two decades, and in 2015 it amounted to only about 3.5% of all generation, leaving a great potential for further growth.

Thermal generation became the leading mode of electricity production, but hydrogenation has retained its importance in some large economies and in many small countries. By the end of the 19th century increasingly higher concrete dams were built in the Alps, but the largest hydroelectric project was the Niagara Falls station completed in 1895, and after enlargement in 1904 its installed capacity (78.2 MW) reached 20% of the total

U.S. generation (MacLaren 1943). Another of its record-breaking aspects was the use of long-distance transmission of 5-kV and 25-Hz three-phase 11-kV current to Buffalo for municipal uses and for new industrial plants attracted to the area by inexpensive electricity.

Early hydrogeneration was able to expand thanks to two new turbine designs. The first successful reaction water turbines were built by Benoit Fourneyron during the late 1820s and the 1830s (Smith 1980), and the machine that came to be known as the Francis turbine—although it was a product of many inventors, including Samuel B. Howd (1838 patent) and James B. Francis (improved design of 1848)—was commercialized by the 1860s (Hunter 1979). An entirely new design for high water heads, an impulse turbine driven by water jets discharged into peripheral buckets, was introduced during the 1880s by Lester Allen Pelton, and in 1913 Viktor Kaplan patented his reaction turbine whose adjustable vertical-flow propellers have become a standard choice for low water heads.

More than 500 low-capacity hydro stations for local supply were completed before World War I. The world's first large hydro stations were built by governmental programs in the United States and in the USSR during the 1930s. America's largest projects included a multi-station development directed by the Tennessee Valley Authority (a total of 29 dams) and the two dams of unprecedented size in Colorado (Hoover Dam) and Columbia (Grand Coulee). But the most intensive period of large-scale hydro construction came only after World War II: between 1945 and 2000 more than 150 hydro stations with capacities greater than 1 GW were completed in more than 30 countries (ICOLD 1998).

The most important post-2000 additions have been in China, the country with the world's largest hydrogenation potential. Completed giant dams have included Sanxia (Three Gorges), by far the world's most powerful hydro installation (22.5 GW in 23×700 MW and 2×50 MW turbines completed in 2012), Xiluodu (13.9 GW since 2014), Xiangjiaba (7.75 GW since 2012), and Longtan (6.3 GW since 2009), with a 14-GW project (Baihetan) and a 10.2-GW station (Wudonge) under construction (IHA 2015). While many new stations are planned in Asia and Africa, some older small and midsize dams were removed not because of their structural problems but in order to reverse undesirable environmental impact and to improve migration of anadromous fish. So far the largest removal has been the 31-m tall Elwha dam (Olympic Peninsula in Washington) that stored water for a 14.8-MW plant (USGS 2015).

Nuclear electricity advanced from the basic scientific concept to the first commercial station in just 23 years. Milestones of this development have been described by its creators and by many historians of technical advances.

Neutron's discovery in February 1932 (Chadwick 1932) made it possible to think about the fissioning of suitable isotopes of the heaviest natural elements in order to release energy. Little more than half a year after Chadwick's announcement Leo Szilard formulated, and promptly patented, the basic idea of nuclear chain reaction. Fission's first experimental laboratory demonstration was made public in February 1939 (Meitner and Frisch 1939), and Enrico Fermi directed the experiment that produced the first sustained chain reaction in a graphite reactor built under the bleachers of the University of Chicago stadium: it went critical on December 2, 1942 (Atkins 2000).

The first demonstrations of nuclear power were the explosions of the two atomic bombs over Hiroshima and Nagasaki, and soon after the war's end Hyman Rickover began to develop nuclear reactor propulsion to submarines (Rockwell 1992). *Nautilus*, the first nuclear-powered vessel, was launched in January 1955, and the same reactor design (General Electric's pressurized water reactor, PWR) was rapidly adopted under Rickover's direction for the first U.S. electricity-generating station completed in Shippingport, Pennsylvania, by December 1957 (Fig. 2.9). But the first commercial nuclear electricity generation took place more than a year

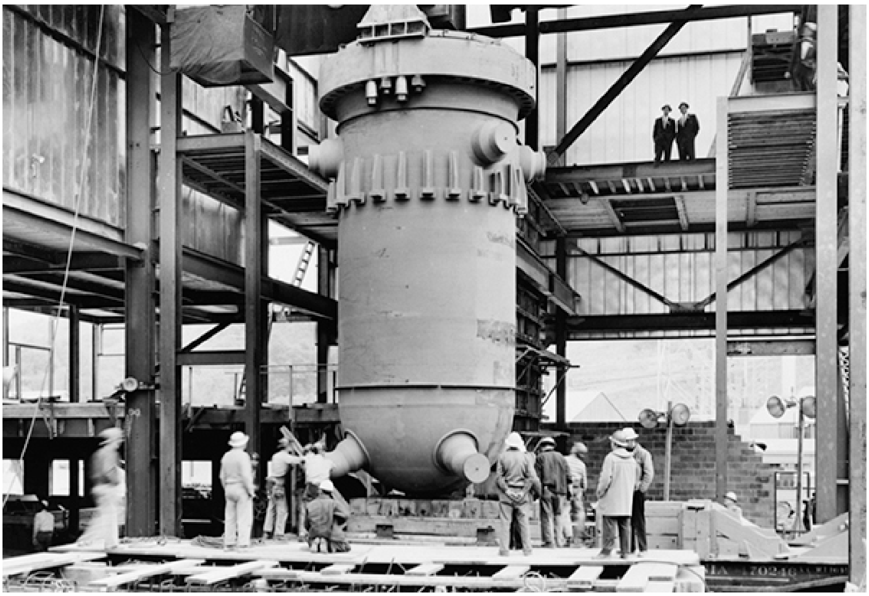

Figure 2.9 Delivery of the reactor vessel for the Shippingport nuclear power station: the vessel's small size betrays the reactor's origin in submarine propulsion. Photograph available from the Library of Congress.

earlier, in October 1956, when the UK's Atomic Energy Agency commissioned Calder Hall station (4 × 23 MW, shut down in 2003, demolished in 2007).

This was followed by a decade of very slow progress and then by a wave of new nuclear power plant orders during the late 1960s and the early 1970s led by the U.S. utilities. This expansion wave was brief: oil price rises of 1973–1974 did not, as might have been expected, provide a greater stimulus for the development of new nuclear capacities. Instead, the U.S. nuclear industry had to deal with constantly changing safety regulations, construction delays, and falling electricity demand. As a result, a typical American nuclear plant was completed only after great delays and at a much higher cost than originally anticipated, and new orders began to decline. And although an accident at the Three Mile Island plant in Pennsylvania in March 1979 did not leak any radiation outside the containment structure, no new nuclear plants were ordered in the United States during the remainder of the 20th century (Smil 2003).

The UK continued with a scaled-down expansion, the USSR and Japan became other major builders, but France embarked on the boldest national nuclear program. Its core was an American (Westinghouse pressurized water) reactor but its execution rested on building a large series of standardized plants (59, distributed around the country) and getting the benefits of cumulative experience and economies of scale. As a result, no other major economy was able to derive as much electricity from nuclear fission as France (in 2015 about 77%). New capacities (almost solely in Asia) brought the total power installed in 440 reactors to 384 GW by March 2016, and increasing load factors (for the best stations more than 90%) raised the aggregate generation to about 2.4 PWh (WNA 2016a). Besides France, the countries with the highest nuclear electricity share in 2015 were Slovak Republic (about 57%), Hungary (54%), Belgium (48%), and Sweden (42%); Japan's pre-Fukushima (2010) share was about 29%, and in 2015 both the United States and Russia were a bit below 20% and China at less than 3%.

Before the recent rapid expansion of wind and solar electricity, geothermal generation was the second most important way to produce primary electricity from a renewable source other than moving water. Italy's Larderello was the first commercial plant in 1902, New Zealand's Wairakei came on line in 1958, and the first American plant was the Geysers north of San Francisco (now with rated capacity of 35 MW) in 1960 (Smil 2015a). All of these pioneering projects are based in high-temperature vapor fields. Subsequent developments have added stations of mostly small- to medium-size in Mexico, the Philippines, Indonesia, and China.

France's La Rance (with 240-MW capacity, completed in 1966) remained the 20th century's only small commercial tidal power plant, and designs for wave-driven converters did not progress beyond theoretical proposals and a few small, temporary demonstration devices. And before 2000 neither wind generation nor PV conversion made any significant global contributions. Installed capacity of wind turbines reached 18 GW in 2000, no more than 2% of the global total, but given their low average capacity factor (on the order of 20%–25% for these early machines) wind-powered generation remained below 1% of the world total. And PV remained completely marginal, with peak capacity of just over 1 GW by 2000. Both of these realities have changed in the new century but, as I will detail in Chapter 4, renewables have a very long way to go before they will become leading sources of electricity generation, and they face even greater challenge in order to emerge as the leading suppliers of primary energy.

History of Prime Movers: From Muscles to Machines

Much as the biofuels had dominated the provision of energy needed for heat and light during the preindustrial period, so did animate energies of human and animal muscles dominate the prime movers since prehistory until the very end of the early modern era (1500–1800). But there was also an important difference because in some societies the first inanimate prime movers (sails, water wheels, and windmills) eventually evolved to claim significant shares of power used in transport and production of goods long before a new wave of mechanical prime movers deriving their power from the combustion of fossil fuels made its appearance during the 18th and 19th centuries.

Human muscles were the only prime movers during the millennia of hominin evolution (with our species, *Homo sapiens sapiens* emerging only about 190,000 years ago) as well as in preagricultural societies (in which all humans lived until roughly 10,000 years before present) that provided subsistence through foraging (gathering and hunting). Human exertions are limited by metabolic rates and by mechanical properties of human bodies, and before the domestication of draft animals the only way to substantially enlarge their overall scope was to rely on combined action of people pushing or pulling heavy loads, sometimes with ingenious assistance by levers, rolling logs, and sleds (Smil 2017). That is how Stonehenge, the great Egyptian pyramids, and the megalithic structure of Normandy, Andean highlands, or the Easter Island were built.

Simple handmade tools, ranging from wooden digging sticks to precisely finished stone arrowheads and bone needles, helped to enhance and focus the delivery of human power, and mechanical devices—mostly variations of the three simplest designs (levers, inclined planes, and pulleys)—expanded its scope, but their sizes and uses were ultimately dictated by human metabolism and body structure. Basal metabolic rate (BMR) of all large mammals is a nonlinear function of their body mass *M*: when expressed in watts it equals $3.4M^{0.75}$ (Smil 2008). This yields 70–90 W for most adult males and 55–75 W for females. Energy costs of physical exertion are expressed as multiples of the BMR: light work requires up to 2.5 BMR, moderate tasks up to 5 BMR, and heavy exertions need as much as 7 BMR or in excess of 300 W for women and 500 W for men.

Healthy adults can work at those rates for hours, and given the typical efficiency of converting the chemical energy into the mechanical energy of muscles (15%–20%), this implies at most between 60 W (for a 50-kg female) and about 100 W (for an 85-kg man) of useful work. Five to seven steadily working adults thus equal the draft power of an ox, and about six to eight men match the useful exertion of a good, well-harnessed horse. Of course, much higher rates (10^2 W) energized by anaerobic metabolism, can be sustained during brief spells. Humans were the most efficient prime movers when they walked inside large treadwheels where they deployed their largest back and leg muscles. These treadwheels were used to lift heavy loads in the antiquity (there is a fine bas-relief in the Roman tomb of Haterii from100 CE), the Middle Ages, and the early modern era (Pieter Bruegel the Elder's 1563 painting has a crane lifting a large stone to be added to his imaginary Tower of Babel). During the early 19th century a design accommodating up to 40 men side by side was used in English prisons as a form of punishment (Hippisley 1823).

Humans acquired more powerful prime movers with the domestication of draft animals. Working bovines, equids, and camelids were used for plowing, harrowing, pulling heavy cartloads or wagonloads, and pulling out stumps and lifting water from deep wells, but most of the labor in traditional societies still needed human exertion. Because draft animals have different weights (primary determinants of overall draft power), anatomies, metabolic efficiencies, and endurances, and because their potential power can be used to the best possible effect only with proper harnessing and well-designed tools, it is impossible to offer any simple conclusions regarding the substitution of human labor by animal work.

Working bovines included many cattle breeds and water buffaloes. Donkeys and ponies aside, working equines were more powerful. Some desert societies also used draft camels, elephants performed hard forest work in the tropics, and yaks, reindeer, and llamas were important pack animals in cold and high-altitude environments. Harnessed dogs and goats were also used for light loads. Comparison of plowing productivities conveys the relative power of animate prime movers. Even in light soil it would take about 100 hours of hoeing to prepare a hectare of land for planting. In contrast, a plowman guiding a medium-sized ox harnessed inefficiently by a simple wooden yoke and pulling a primitive wooden plow would do that work in less than 40 hours; a pair of good horses with collar harness and a steel plough would manage in just 3 hours (Smil 2017).

Cultivation relying solely on human labor was thus suited only for gardens or small fields, and only the use of draft animals made it possible to plant larger areas. Effective use of animals required adequate feeding and efficient harnessing, and their satisfactory combination became widespread only during the early modern era. The ability of bovines to survive on cellulosic feed (grasses or crop residues they can digest thanks to the microbial symbionts in their gut) made them the least demanding and the least expensive draft animals—but poor feeding, low body weight, limited endurance, slow pace of work, and ineffective harnessing restricted their draft power.

During the 19th century the European farmers could do 25%–30% more work in a day with a pair of horses than with a team of four oxen—and horses could work for up to 20 years, while oxen lasted normally for less than 10. But the most efficient use of horses was also more expensive: it required proper harnessing (horse collars fitted to animal's shoulders, originally a Chinese innovation that became the norm in Europe before 1200), but it was limited by relatively small sizes of medieval horses and by shortages of concentrate feed (mainly oats), and hence most of the heavy field and transport work continued to be done by oxen harnessed by neck or head yokes.

Performance of wheeled transport is heavily influenced by the quality of roads and the design of wheels and wagons: no draft animal could make good progress on soft, muddy, or sandy roads, even less so when pulling heavy carts with massive wooden wheels (initially full disk, spokes came around 2000 BCE in Egypt). When expressed in terms of daily mass-distance (t-km), a man pushing a wheelbarrow rated just around 0.5 t-km (less than 50-kg load transported 10–15 km), a pair of small oxen could reach 4–5 t-km (10 times the load at a similarly slow speed), and a pair of well-fed and well-harnessed 19th-century horses on a hard-top road could surpass 25 t-km (Smil 2017).

All animate prime movers have limited unit capacities, very high mass/power ratios, and specific feeding demands to support their best performance. Humans can sustain hours of useful work at 50–100 W, lighter and poorly harnessed draft animals can deliver 200–500 W, and even the most powerful horses can work steadily at no more than about 800–900 W. Higher output requires combining forces, a precept that all preindustrial cultures followed during the construction of their massive stone monuments. Domenico Fontana's erection of an Egyptian obelisk (originally brought to Rome during Caligula's reign) in St. Peter's Square in 1586, and Auguste de Montferrand's raising of Alexander's red granite column in the center of Saint Petersburg's Palace Square in 1832 are outstanding illustration of such tasks. In the first case 140 horses and 900 men were needed for the job (Fontana 1590), the second task required 1,700 soldiers and 75 officers (Luknatskii 1936). And before the introduction of internal combustion engines the world's first combines in California and Washington were pulled by more than 30 horses.

Mass/power ratio is a critical characteristic of prime movers because it allows for universal comparisons across the entire evolutionary span; obviously, the lower the ratio the more powerful the prime mover. Commonalities of mammalian metabolism make the mass/power ratio for humans and animals very similar, about 1,000 g/W. An 80-kg man (BMR of 90 W) engaged in moderately heavy work (up to 5 times BMR, or 450 W) with chemical-to-mechanical conversion efficiency of 20% will produce 90 W and require nearly 900 g/W; a large horse (750 kg) working exactly at the rate of one horsepower (745.7 W) will have mass/power ratio of just over 1,000 W/g.

The first commonly used inanimate prime movers were sails propelling river-borne vessels and coastal shipping, later deployed for voyages on the open ocean. Sails are simple fabric airfoils that convert wind's kinetic energy by generating lift (and drag) and, regardless of their specific design and efficiency, they can deliver optimal performance only when propelling ships whose drag is minimized by appropriate (stable and hydrodynamic) hull design and whose steering is optimized by a rudder (Block 2003; Marchaj 2000). All ancient vessels had square sails; triangular sails made their appearance only in the early medieval era. Medieval combination of larger and better adjustable square and triangular sails made it possible to sail closer to the wind, as close as 62° compared with the maximum of about 30° for the best Roman vessels (a gain of nearly 100°). Such ships, when equipped with magnetic compass, made the great journeys of European world discovery between the late 15th and the early 19th century.

The first stationary inanimate prime movers came into use long after the first use of sails—but we cannot conclusively date the origins of the first water-powered device, a simple horizontal water wheel rotating around a sturdy wooden vertical shaft and directly driving an attached millstone.

Lewis (1997) put its invention as early as the 3rd century BCE but its first surviving description comes from the 1st century BCE (Antipater of Thessalonica). By 27 BCE Vitruvius was describing more efficient vertical wheels (rotating around a horizontal shaft), turning the millstones by right-angle gears and powered by water impacting at their bottom (undershot wheels), just above their midline (breast wheels) or falling from above in the most efficient overshot wheels.

These wheels became relatively common in some parts of the Roman world already by the 2nd century CE (Wikander 1983); their numbers kept increasing during the subsequent centuries and the Domesday book (a remarkable inventory of England's economic capacities in 1086) listed about 6,500 of these machines (Holt 1988). While many parts of medieval Europe acquired an increasing number of watermills, capacities remained low: even during the early 18th century a typical mill would rate only a few kW. The most notable exception, an assembly of 14 massive (12-m diameter) wheels completed by 1685 at Marly, powered the pumps delivering the Seine water to Versaille fountains, but it never worked at its full capacity and it delivered just over 4 kW (Klemm 1964).

Small tidal mills were also built during the Middle Ages in England and in some regions along Europe's Atlantic coast, but the most powerful and durable tide-powered machines below the London Bridge pumped drinking water for the city since the 1580s until 1822 (Jenkins 1936). Three wheels powered 52 water pumps and lifted 600,000 L of water up to 36 m. Grain milling remained the principal use of water power, followed by cloth fulling (fluffing up and thickening of wool fabrics), with other uses ranging from operating blast furnace bellows to pulling wires, and in the early modern age also winding and water pumping in coal mines (Clavering 1995; Woodall 1982).

The origin of windmills is even more obscure than is the emergence of water wheels (Lewis 1993). What we know with certainty is that the first devices—crudely made, inefficient, with cloth sails mounted on vertical wooden axes turning millstones without any gearing—were used in Sistān (in today's eastern Iran) and that their subsequent westward diffusion, beginning during the 11th century, brought them to Byzantine lands and from there the Crusaders introduced them to the Atlantic Europe. During the Middle Ages countries bordering the Atlantic acquired the world's largest concentration of windmills and retained this primacy until the advent of 19th-century industrialization.

Post mills pivoted on a massive wooden central post that was kept perpendicular by sturdy diagonal quarterbars; their sails had to be turned into wind manually, which were rather unstable and inefficient, and their low height limited their power (which is proportional to the cube of wind speed). They were gradually replaced by tower (cap) mills: only their cap would be turned into the wind, at first manually from a gallery, since the mid-18th century automatically by using a fantail. The largest deployment of tower mills took place in the Netherlands for the drainage large polders and creation of new land for fields and settlements (Hill 1984; Husslage 1965). By the 19th century windmills were leading sources of mechanical power also in the southern part of England, in Picardy, Belgium, coastal Germany, Denmark, and southern Sweden.

Useful power of common medieval windmills was certainly lower than the power of typical contemporary water wheels, but the first reliable measurements of windmill performance were done only during the 1750s. At that time John Smeaton found a common Dutch mill (with 9-m sails) as powerful as 10 men or 2 horses, that is, conservatively converted, with capacity of about 1 kW (Smeaton 1796). Larger mills could have windshaft power well in excess of 10 kW, but large gearing losses (on the order of 50%–60%) reduced the useful power considerably. Typical useful power was 1–2 kW for small and 2–5 kW for large medieval European post mills, 4–8 kW for widely used early modern European tower mills, and 8–12 kW for the largest 19th-century devices in countries around the North Sea. By 1900 the total number of windmills in that region was in tens of thousands, and de Zeeuw (1978) estimated their aggregate power at no less than 100 MW.

Massive diffusion of American windmills came with the westward expansion of settlements and farms across the Great Plains where tower mills (with narrow blades or slats mounted on solid or sectional wheels and equipped with governors and rudders) became indispensable for pumping water for households, cattle, and steam locomotives (Wilson 1999; Fig. 2.10). Their useful power was less than 1 kW, and during the second half of the 19th century sales of these small windmills reached several million units and by 1900 their aggregate capacity was estimated at about 90 MW by the U.S. Bureau of the Census (1975)—but it was put at nearly 500 MW by Daugherty (1928).

In the first commercial steam engines, designed by Thomas Newcomen during the first decade of the 18th century, the piston was cooled with every stroke (condensation of steam took place on its underside), and they were so inefficient that they could operate profitably only in coal mines, mostly for pumping water from pits (Rolt 1963. James Watt's famous improvements, patented in 1769, included a separate steam condenser, an insulated steam jacket around the cylinder, and an air pump to maintain vacuum (Robinson and Musson 1969). Watt also designed a double-acting

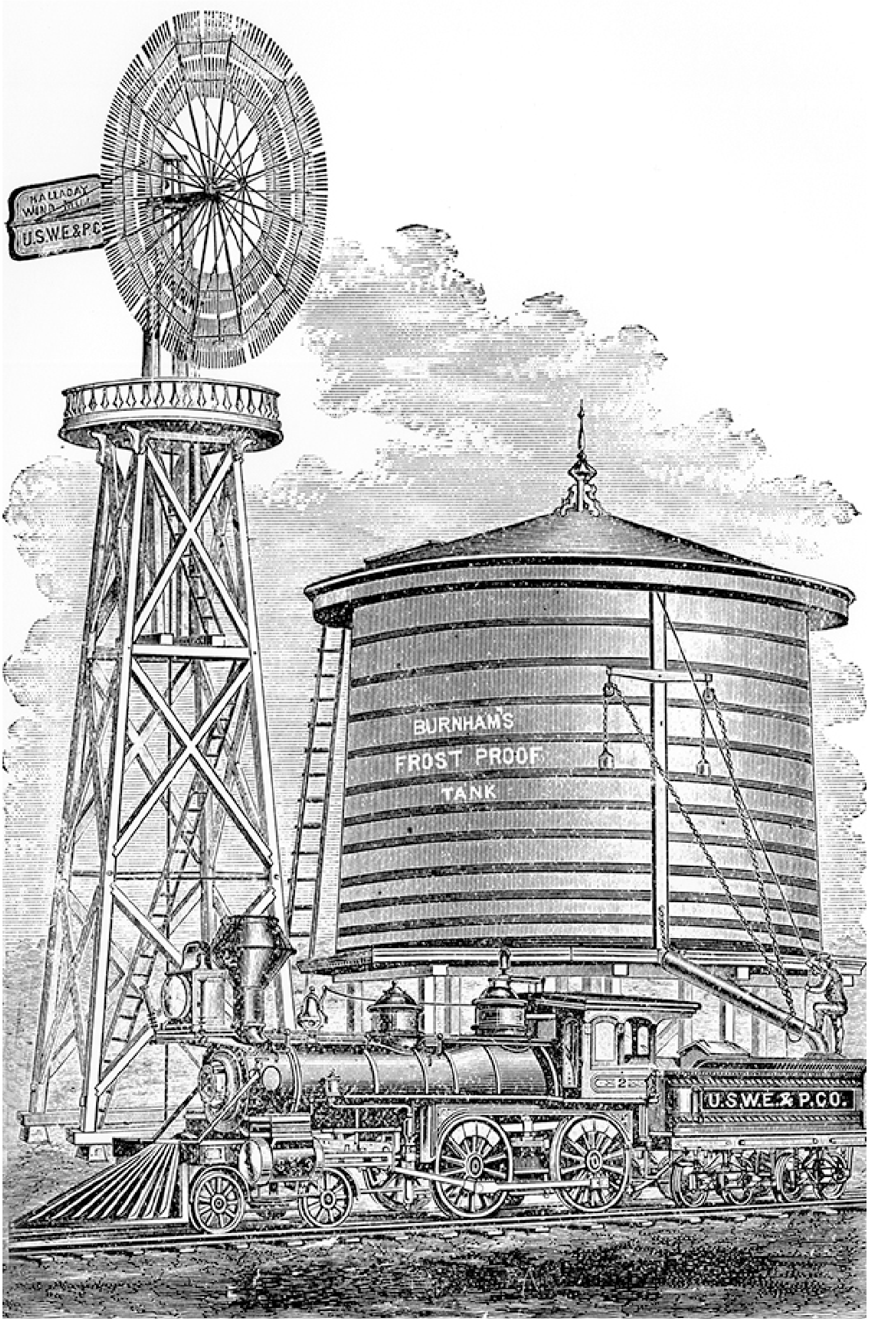

Figure 2.10 A late 19th-century American Halladay windmill. Reproduced from Wolff (1900).

engine (with piston driving also on the down stroke) and a centrifugal governor to maintain constant speed with varying loads.

As their efficiencies improved they began to be installed by a variety of industrial enterprises: nearly 500 of them were built by 1800. Because Watt refused to work with high pressures any developments of pressurized engines had to wait for the expiry of his patent. Once that took place (in 1800) the progress of mobile steam engines was fairly rapid. River steamboats began regular commercial service before 1810, the English Channel was first crossed in 1815, the 1830s saw the first trans-Atlantic voyages fully powered by steam, and the first scheduled railway service was offered by 1825 (Smil 2017). Steam engines remained the dominant mechanical prime mover during the entire 19th century, and by its end the largest units surpassed 1 MW (compared to 100 kW in 1800), worked under the pressure of 1.4 MPa (100-fold increase above the 1800 level), and achieved efficiency of about 20% (roughly a 10-fold rise compared to 1800).

But the machines had their inherent disadvantages, above all the enormous size and mass of high-capacity units due to high mass/power ratios and relatively poor conversion efficiency. The first drawback made them unsuitable for road transport and even more so in powered flight, and it also made it impractical to build larger units (in excess of 5 MW) required for thermal electricity generation. Even massive stationary triple- and quadruple-expansion engines had efficiencies of less than 20%, while smaller shipborne engines were about 10% and locomotive engines only 6%–8% efficient. Not surprisingly, once a better alternative became available steam engines retreated fairly rapidly: already by 1900 they were an inferior choice for thermal electricity generation, a few years later mass production of reliable gasoline engines ended a brief era of steam-powered automobiles, and before the beginning of World War I it was clear that it was only a matter of time before diesel engines would displace steam engines in shipping and on railroads.

Steam turbine had a particularly steep improvement curve (Parsons 1936). The first small prototype built by Charles Parsons in 1885 had power of only 7.5 Kw; the first 1-MW unit began to generate electricity at a German plant in 1899 (see Fig. 2.8), and the largest units installed before the beginning of World War I rated 20–25 MW and had efficiencies around 25% (Dalby 1920; Parsons 1911). Steam turbines thus moved from a prototype to a multi-MW commercial choice in less than two decades. As with so many other innovations, the rate of advances slowed down between the two world wars, but steep gains began again during the late 1940s and continued until the 1970s: since that time the performance gains have been only incremental, but the machines remain the world's most powerful continuously working prime movers.

Superiority of steam turbines is perhaps best illustrated by contrasting their current top ratings with those of the most advanced steam engines at the beginning of the 20th century (Smil 2006, 2017). Their rotation speeds are an order of magnitude higher (as much as 3,600 rpm compared to less than 100 rpm) as are their working pressures (as much as 34 MPa for supercritical generators vs. typically less than 2 MPa), their maximum capacities differ by two orders of magnitude (1.75 GW vs. less than 5 MW), and the largest steam turbines have mass/power ratios below 1 g/W, less than 1% those of the best steam engines (250 g/W). As a result, steam turbine-driven electricity generation needs only a fraction of materials to build the machines, and it avoids construction of enormous buildings that would be needed to house gargantuan steam engines.

This is a good place to note the benefits of electric motors whose rapid diffusion was made possible by solving the key challenges of large-scale electricity generation and transmission during the last two decades of the 19th century. Long before these converters revolutionized household work they brought an even more fundamental change to industrial production in general and to labor-intensive manufacturing in particular. The steam engine did not change the way mechanical energy was distributed in factories that used to rely on power produced by water wheels: ceilings in textile or machining plants remained full of long line shafts whose rotations were transmitted by belts to machines on the factory floor. This was expensive, awkward, dangerous, and inconvenient as accidental damage to any part of the system forced its complete closure while even a partial production capacity required the entire system to operate.

Electric motors eliminated the need for converting reciprocating power delivered by steam engines into rotary motion by using line shafts and long ceiling-to-floor belts. No less importantly, they allowed precise, on-demand, convenient power supply to individual machines on the factory floor while freeing the ceilings for allowing adequate natural or electric lighting (Schurr 1984). They also eliminated constant vibration produced by both steam and internal combustion engines. Electrification of industrial manufacturing was completed first in the United States (during the 1930s), then in Europe (by the 1950s), and many low-income countries went straight from using animate prime movers to relying on electric motors.

Electric motors have powered yet another important energy transition, from steam to electricity on railroads. In freight transport steam was displaced primarily by heavy diesel engines (this transition was complete in

North America and most of Europe by the late 1950s) but all of the world's fast trains are now powered by electricity (Clark 2011; Smil 2006). This trend began in 1964 with Japan's *Tōkaidō shinkansen,* and in 1981 France was the first European country to introduce comparably fast service with its TGV (*Train à Grande Vitesse*) whose variants now operate also across the Channel and in the UK (*Eurostar*), Belgium (*Thalys*), Italy (*Frecciarossa*), Spain (*AVE*), and Germany (*InterCity*). But the largest fast train network—16,000 km of dedicated track by the end of 2014 (Xinhua 2015)—has been built since 2006 in China.

That remarkable innovative decade of the1880s saw not only the introduction of the steam turbine, the world's most powerful continuously working prime mover, but also the first successes of the gasoline-fueled internal combustion engine: besides electric motors no mechanical prime mover has reached such aggregate production numbers. The steam engine is an external combustion machine, with water heated in a boiler and steam led into the piston chamber, while in internal combustion devices the working medium (hot gas) is produced by combustion of fuel inside the engine (intermittently in piston engines, continuously in gas turbines). Such devices had a conceptual history predating 1800 with many failed designs and prototypes introduced during the first half of the 19th century.

The decisive breakthrough came only in 1860 with a noncompressing (and hence low-efficiency) machine built by Jean Joseph Étienne Lenoir. Theoretical design of a four-stroke internal combustion engine was done first by Alphonse Eugène Beau (later known as Beau de Rochas) in 1862, but the first practical design of a four-stroke compression engine, by Nicolaus August Otto, followed only in 1876 (Payen 1993; Sittauer 1972). Otto's first engine, introduced in 1866, was a two-stroke noncompression engine fueled by coal gas; in 1874 its improved version was still very heavy (mass/power ratio of about 900 g/W) but more than twice as efficient (about 10%). The first four-stroke compression engine had efficiency of about 17%, and its mass/power ratio of 250 g/W was much lower than that of any similarly sized contemporary steam engine.

Otto's company eventually produced nearly 50,000 of these gas-fueled machines with the most common ratings between 5–10 kW. The next advance was to design a four-stroke compression engine running on gasoline, a fuel whose energy density is roughly 1,600 times that of the coal gas used in Otto engines and whose low flashpoint makes engines easy to start. Such a machine was first designed and built independently by three German engineers, by a duo of inventors in Stuttgart, and by an experienced mechanic in Mannheim (Walz and Niemann 1997). Gottlieb Daimler and Wilhelm Maybach had a prototype ready in 1883, the first motorcycle engine in 1885, and the first car engine (just 820 W) a year later. Karl Friedrich Benz completed his first two-stroke gasoline-fueled machine also in 1883 and used his first four-stroke 500-W machine to propel a three-wheeled carriage in 1885 (Fig. 2.11).

Rapid advances followed during the last 15 years of the 19th century. By 1895 Daimler and Maybach were selling a 4.5-kW engine with mass/power ratio of less than 30 g/W, and in 1900 came a 26-kW four-cylinder engine with mass/power ratio of less than 9 g/W that was used to power Mercedes 35, a high-performance vehicle that came to be seen as the first modern automobile. The Otto-cycle four-stroke gasoline fueled engine thus became a mature machine in just a single generation after its invention, and while the technical advances of the 20th century improved its performance (higher compression ratios made possible by the addition of anti-knocking compounds to gasoline) and increased its reliability (electronic controls of ignition) there were no fundamental changes of the basic design.

Today's automotive engines have power ranging from only about 50 kW for urban mini cars to more than 1 MW (more than 20 times higher) in the most powerful "sports" cars (Koenigsegg Regera at 1.316 MW, Lamborghini at 1.176 MW). Their compression ratios are typically between 9:1 to 12:1, and their mass/power ratios are mostly between 0.8 and 1.2 g/W. But even the most powerful gasoline-fueled engines are too small to propel massive ocean-going vessels or to be used by the largest road trucks and off-road vehicles or as electricity generators in emergencies or in isolated locations: those duties are filled by another internal combustion engine, one that initiates combustion through high compression and hence is inherently more efficient.

Rudolf Diesel laid the conceptual foundation of this engine during the early 1890s and then, with support and cooperation of Heinrich von Buz (general director of the *Maschinenfabrik Augsburg*), he developed the first practical engine by 1897. Its official testing showed power of 13.5 kW and a high mass/power ratio of 333 g/W—but its net efficiency was a bit above 26%, a performance superior to any contemporary converter of fuel to mechanical energy (Diesel 1913). The first marine diesels were installed in submarines already a decade before World War I, and by the beginning of World War II about a third of all ocean-going vessels were powered by diesels. Decades of vigorous post–World War II economic growth led to a steady expansion of intercontinental trade and construction of more powerful vessels: power of the largest two-stroke marine diesels was just over 10 MW by the late 1950s, and the largest marine diesel (Wärtsilä-Sulzer RTA 96C) now rates in excess of 85 MW, powerful enough to propel the

Figure 2.11 Cover illustration of the first (1888) catalogue by Benz & Cie. is a slightly modified version of the three-wheel vehicle that was patented and publicly driven for the first time in 1885. Photograph courtesy of DaimlerChrysler Classic Konzernarchiv, Stuttgart.

largest, and fastest (more than 45 km/h), container ships carrying more than 10,000 steel boxes (Smil 2010a).

The first automotive diesel engines came in 1924 for trucks, and in 1936 Mercedes-Benz 260D (a heavy, 33.5-kW four-cylinder six-seat saloon car) became the first diesel-powered passenger car. But the real transition to diesel vehicles got fully underway only after World War II. By the 1960s virtually all heavy trucking was converted to diesels, and they also propel all heavy agricultural machines and various off-road vehicles in construction and mining. Low-sulfur diesel fuel (<50 ppm S) and, most recently, of ultra-low sulfur diesel (<10 ppm S) has made diesel-powered passenger cars more acceptable: they are rare in North America, but in France two-thirds of cars are diesels, and in Germany close to 50% (Eurostat 2015a).

The gas turbine was the only new prime mover that was commercialized during the 20th century. Its concept goes back to the last decade of the 18th century, but its first successful prototypes were built during the late 1930s (Smil 2010a). World War II accelerated the development of jet engines, and the British industries tried to capitalize on Frank Whittle's (and Frank Halford's) pioneering designs by launching the first programs to produce jet-powered passenger planes. Geoffrey de Havilland began to develop Comet, the first commercial jetliner powered by de Havilland's Ghost turbojet, for the British Overseas Airways Corporation (BOAC) in 1946. The plane entered service in May 2, 1952, but the entire Comet fleet was grounded in 1954 after several fatal accidents caused by catastrophic decompression of the plane's fuselage.

As a result, Boeing's 707 (with four Pratt & Whitney's engines) became the most successful pioneering design in 1958, and the company strengthened its primacy with the introduction of the first wide-body plane, Boeing 747, in 1969. Eventually only two companies, America's Boeing and European Airbus, survived the competition to produce the world's large commercial jetliners, and all of their planes are powered by gas turbines made by one of the three remaining makers of jet engines, America's GE and Pratt & Whitney and British Rolls-Royce, or their consortia. Advances in the performance of jet engines are best illustrated by contrasting the performance of first commercial designs (turbojets) with the latest turbines (all turbofans).

Comet's de Havilland turbojet Ghost engine had a thrust of 22.25 kN, while today's most powerful turbofan, GE 90-115B, rates 512 kN (a 23-fold increase); the latest engines have thrust/weight ratio in excess of 6 compared to just 0.17 for the Ghost. And the first turbofans, introduced during the early 1960s, had a bypass ratio less than 2:1 (more than half of the air entering the engine was compressed by a frontal fan and then led around the engine's core), while the latest turbofan models have bypass ratios as high as 12:1 (only 8% of all air passes through the engine core where it oxidizes kerosene, and 92% of the thrust comes from the bypassing cool air). Specific fuel consumption of the latest turbofans is only about half that of the earliest commercial turbojets of the 1950s (Ballal and Zelina 2004).

Development of larger stationary gas turbines—used primarily to cover peak electricity demand and to power industrial compressors—has proceeded in parallel with the introduction of more powerful jet engines. The largest gas turbines do not work alone: their waste heat is used by attached steam turbines, and the resulting combined-cycle arrangements have net efficiencies as high as 60%. The largest machine in 2015 was GE's 9HA 02, capable of 510 MW in simple cycle and 755 MW gross in combined cycle (GE 2015). In addition to these large machines smaller aeroderivative turbines have become increasingly popular thanks to their flexibility and rapid installation.

Long-term comparisons of prime mover powers show large performance gains. Until about 10,000 years ago the peak performances were limited by the power of human muscles, affording short-term maxima of 100–200 W of useful work, and sustained exertion at 50–100 W. Domestication of draft animals increased sustained work rates to 300–500 W during the premodern era and to 400–800 W after 1800, when the brief exertions of heavy draft horses could deliver more than 2 kW/animal. Maximum sustained performance of the most powerful animate prime movers thus rose by an order of magnitude, from about 60–80 W for working adults to 600–800 W (average for well-fed 19th-century horses).

The power of water wheels rose slowly from small machines of the late antiquity capable of just 10^2 W to larger wheels with power of a few kW (10^3 W) after 1700 and to as much as a few hundred kW (10^5 W) by 1850. Windmills also had a slow capacity growth culminating in machines of no more than 10^4 W by 1900. Capacities of water wheels, the largest preindustrial inanimate prime movers, thus rose by three orders of magnitude in about two millennia. In contrast, capacities of steam engines grew exponentially: they surpassed those of the largest water wheels in less than half a century after their commercial introduction in the early 18th century, by 1850 the unit maxima were above 10^5 W, and by 1900 they exceeded 1 MW (10^6 W).

By that time the most powerful prime movers were water turbines whose capacity ascent began during the 1830s and whose brief primacy was ended by steam turbines introduced during the late 1880s. A century later steam turbines remained the world's most powerful continuously working prime movers (maxima up to 1.75 GW, commonly deployed sizes of 200–800 MW), but water turbines used in large hydro stations were not far behind. Capacities of the largest stationary fossil-fueled prime movers thus increased from 10^3 W (less than 3 kW for Newcomen's steam engines) to 10^9 W for the largest steam turbogenerators. That is a rise of six orders of magnitude (a million-fold jump) in 300 years—but 99.9% of that rise took place during the 20th century as the maximum rating of steam turbogenerators rose from 10^6 to 10^9 W (Fig. 2.12).

Finally, I must stress the endurance and continuity of dominant prime movers and the indispensable roles they have played in the development of their eventual substitutes and hence in their own demise. Animate energies continued to power coal mining during the entire 19th century, and in many countries they did so even until after World War II. These were the energetic foundations of modern civilization: men with picks, shovels, and (later) simple jackhammers cutting coal from underground seams,

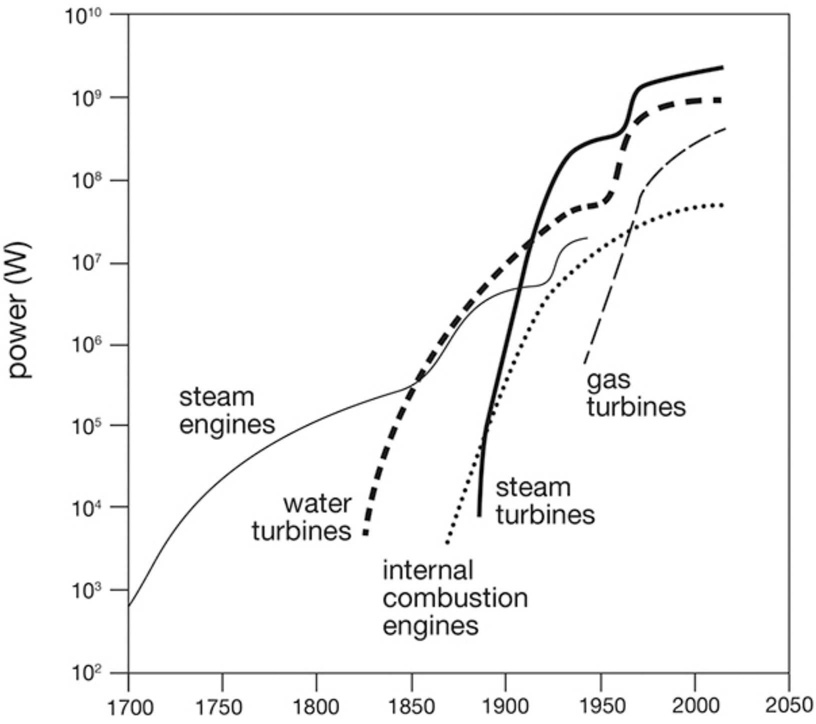

Figure 2.12 Maximum capacities of mechanical prime movers, 1700–2015. Based on Smil (2008) and Smil (2015c).

often working in incredibly confining conditions in narrow tunnels; women and children (and later also ponies harnessed to small wagons) moving the cut fuel to loading points; women (including teenage girls) ascending ladders with back loads of coal in baskets (Bald 1812); on the surface, horses (often with blinkers) walking in circle and turning the whims lifting coal (and miners) from deeper shafts.

The steam era was thus made possible only by muscular work whose exertions, brutality, and dangers are perhaps best conveyed by Robert Bold (1812) describing incredibly hard work of female coal carriers in early 19th-century Scotland ("beyond conception" as their daily exertions brought them close to the limit of human endurance), or by Emil Zola's (1885) shockingly faithful portrayal of brutal conditions in coal mines of northern France of the late 1860s. In turn, steam engines powered the mass-scale advances of the late 19th-century manufacturing that produced the devices and infrastructures of the modern electric industry. Steam locomotives (introduced in 1820s) remained essential in land transport of energy until the 1960s, and steam engine–powered tankers continued to transport crude oil until after World War II. Naturally, this continuity of energy sources and prime movers applies also to the now unfolding transition from fossil fuel to new renewable energies. I will present some examples of this continuing dependence on fossil fuels in Chapter 6.

Quantifying the Transitions: Uncertainties and Trends

Missing data, questionable accounts, and problems of using and comparing numbers of varying level of accuracy are to be expected when quantifying any long-term trends on the global scale. When accounting for the overall supply of primary energy, the most important uncertainty arises from the need to include traditional biofuels, and this is not true not only about estimating the more distant past but also about the recent rates of wood, charcoal, and crop residue consumption. Accounting for commercial production of fossil fuels and primary electricity is much easier as most countries have fairly reliable production statistics but non-negligible errors arise from converting the reported quantities into common energy denominators.

Four realities complicate the quantification of traditional phytomass fuels. First, in low-income countries—where wood, charcoal, and crop residues are either dominant, or very important, sources of household energy—most of the phytomass is harvested by the users (usually collected by women and children), and there are no systematic nationwide statistics of its use. Some European countries have fragmentary historical data that make it possible to reconstruct their wood combustion during the 19th century, but their accuracy is hard to assess. Similarly, some recent short-term local studies of rural and urban wood consumption offer useful guidance, but they are, obviously, poor substitutes for ongoing statistical surveys.

For most of the world we do not have either past or recent representative nationwide aggregates of biofuel consumption, and the best we can do is to offer some approximate averages. Second, in the West fuelwood is generally understood as tree stems cut up to size suitable for stoking stoves—but such a fuel is not burned by the majority of households in most low-income countries. Forest phytomass is a much better description because much (in some settings all) of what is burned does not come from felling and cutting up of mature trees but from opportunistic cutting and breaking off of small stems and branches and gathering of fallen twigs, and the phytomass does not come only from forests but also from commercial tree plantations (rubber, coconut), roadside plantings, tree groves, and backyard trees, and it also includes bark or roots (Smil 2013a).

Third, even if we had very accurate data about the annually consumed mass of woody matter their conversion to energy equivalents could be only approximate unless we would also know its specific composition. Softwoods (conifers) contain more resins whose higher energy content (up to 35 MJ/kg) raises their overall energy density to mostly between 19 and 21 MJ/kg compared to 17.5–20 MJ/kg for hardwoods (Smil 2013a). Consequently, if we were to use a generic mean of 19 MJ/kg, we could end up with errors on the order of ±10%. Fourth, that would be the case only when comparing absolutely dry wood, but very often the reported totals remain undefined, leaving us guessing if we are dealing with fresh, air-dry, or absolutely dry phytomass. The resulting differences are not trivial: freshly harvested wood has moisture content between 30% and 90% (it will not ignite when water content is above 67%); water content of air dry wood (cut into pieces and let dry protected from rain or snow) will be around 20%; and, obviously, absolutely dry wood (after desiccating at 105°C) will contain no water.

Collected wood will include some old dry litter-fall (branches and twigs) with very low moisture, and some fresh branches and slender young stems with high water content. We are left to use a generic mean (say 15 or 16 MJ/kg) and hence make possible errors on the order of ±10%. Similarly, crop residues harvest for fuel can have field moisture ranging from less than 20% (dry cereal straws) to more than 50% (plant stalks and leaves), and their energy content ranges commonly from 14 to 18 MJ/kg. Estimates of preindustrial consumption of biofuels can thus aim at just the correct order of the magnitude, and even the best appraisals for recent decades might have errors of 20%–35%. The best approach to estimate global supply of traditional biofuels is to establish reasonable annual per capita averages and multiply them by much better known population totals.

My reasoned estimate of typical Roman fuel needs (during the early imperial era) was at least 10 GJ/capita (Smil 2010b). Galloway, Keene, and Murphy (1996) found that in 1300 the average demand in London (including all household and manufactures) topped 1.5 t of air-dry wood per capita, or roughly 25 GJ. Kander, Malanima, and Warde (2013) collected many European figures for the 18th century, with annual per capita means around 1.5 t (25 GJ) in warmer climates (including France and Germany) to 2 t in Denmark (nearly 35 GJ) and up to 3.3 t (about 55 GJ) in northern Sweden, and such high wood consumption was also recorded in some forest-rich regions of Germany (Sieferle 2001).

As already noted, the U.S. average in 1850 was as much as 95 GJ/capita for all uses. Surveys of traditional rural energy use done in China of the late 1970s found that in a family of four to five people 12–15 GJ/capita were needed for cooking and water heating and that at least 3.3 MJ/m^2 were needed daily for minimum heating during four to five winter months in North China, an equivalent of 4–5 GJ/capita (Smil 1993). Consequently, minimum annual wood and crop residues used in Chinese villages added up to 16–20 GJ/capita. All of this evidence points to annual per capita supply of 20 GJ as a defensible average for the world's preindustrial population.

In order to improve my estimates for the 19th century I have used continental disaggregation for both the population totals and time-differentiated per capita consumption means ranging from the lows of 10 GJ in Africa for all periods to the high of 90 GJ in North America in 1850 and 30 GJ/capita in 1900. These calculations result in about 20 EJ of biomass energy in 1800 (equivalent of 1.3 Gt of air-dry wood for all domestic and productive uses), about 25 EJ in 1850 and 22 EJ in 1900, and their conservative error range would be ±15%. For comparison, Fernandes et al. (2007) put the global biofuel use at 1 Gt in 1850 and at about 1.2 Gt in 1900, respectively about 17 and 20 EJ/year.

As already noted, integration of my estimates shows that the world's 19th-century energy supply was dominated by solid biofuels (total of about 2.4 ZJ), while fossils fuels (until the early 1860s essentially only coal, afterward also small but rising amounts of hydrocarbons) delivered no more than about 0.5 ZJ. Wood-dominated phytomass thus supplied at least 85% of the 19th century's thermal energy, making it the last century of the millennia-long wooden era. During the 20th century the relative importance of biofuels kept on declining while their aggregate global output kept on increasing, reflecting the needs of rapidly growing rural populations in low-income countries of Asia, Africa, and Latin America.

Accuracy of the recent biofuel consumption estimates has not improved that much in comparison with older assessments. Fernandes et al. (2007) estimate the uncertainty range of their global biofuel total for the year 2000 (2.457 Gt) at ±55%, the same as in 1950 (and they put it at ±85% in 1850). My best calculations have the global rate rising from 22 EJ (1.45 Gt) in 1900 to 27 EJ (1.8 Gt) in 1950 and 35 EJ (2.3 Gt) in 1975. For the century's end FAO estimated 1.825 Gm^3 of "wood fuel," 75 Mm^3 of "wood residues," and 49.2 Mt of "wood charcoal" (FAO 2016). Charcoal production (using FAO's standard conversion factor of 6.0) consumed 295 Mm^3 wood, making a grand total of 2.195 Gm^3. With average density of 0.65 t/m^3 and 15 GJ/t of air-dry wood this equals just 21.5 EJ or 1.43 Gt. But most of the woody phytomass does not originate in forests and FAO total excludes crop residues.

My best estimate of wood consumption (including wood for charcoal) for the year 2000 is about 2.5 Gt of air-dry matter (2 Gt of absolutely dry matter, or 35 EJ), and crop residues (about 20% of their total mass) added about 10 EJ for the grand total of 45 EJ or an equivalent of 3 Gt of air-dry wood. For comparison, Yevich and Logan (2003) estimated that 2.06 Gt (about 31 EJ) of traditional biofuels were consumed in 1985 in low-income countries; Turkenburg et al. (2000) put the end-of-the-century total at 45 ±10 EJ; and Fernandes et al. (2007) estimated 2.457 Gt of solid biofuels (roughly 37 EJ) in the year 2000, with wood contributing 75% and crop residues 20%, and with households burning 80% of the total and productive activities the rest. Despite major uncertainties all of these numbers cluster around 40 EJ (35–45 EJ, 2.3–3.0 Gt of all solid biofuels) and imply the doubling of wood and crop residue harvests for fuel during the 20th century accompanied by a steady decline of average per capita consumption rates everywhere except in some parts of the sub-Saharan Africa.

In contrast to scarce information regarding the use of traditional biofuels, we have numerous figures for the British coal extraction going back to the late 16th century as well as data for other early European coal producers and American statistics going back to the beginning of the 19th century. Given the relatively recent beginnings of oil and gas production (during the 1860s), we have even better information regarding the cumulative output of hydrocarbons. We also have reliable national totals for primary electricity generation: between 1882 and 1956 it was (except for negligible contribution by a few geothermal plants) only hydroelectricity, afterwards came increasing and then stagnating additions of nuclear generation, and since the 1980s we have seen rising contributions by photovoltaic conversions and wind turbines.

While modern production figures for fossil fuels and primary electricity are generally reliable, their conversion to a common energy denominator introduces some uncertainties. Energy densities (all rates are given as lower heating values) of hydrocarbon fuels span only narrow ranges: 41–43 MJ/kg for crude oils and 35–40 MJ/m^3 for natural gases. We have detailed information on the quality of virtually all crude oils and natural gases entering the global market, and hence the conversions to energy can be done very accurately, but even when using generic global means (42 GJ/t for oils and 37 MJ/m^3 for natural gases) the cumulative global error is most likely less than 5%.

Much greater uncertainty arises with coal conversions: for bituminous coals the difference between the best and the poorest varieties is at least 8 MJ/kg (20–28 MJ/kg); the best lignites contain as much as 18 MJ/kg, and the poorest ones have less than 10 MJ/kg. Moreover, all of these rates change in time as coal extraction proceeds to tap seams of lower quality. That is why both the International Energy Agency and the United Nations statistics use country-specific values (for example, Chinese bituminous coal at just 20.75 GJ/t, Russian bituminous coal at 25 GJ/t but lignite at only 7.86 GJ/t), but even those may not catch the quality changes over time. These differences are a major source of conversion errors. For example, using 28 GJ/t for bituminous coal (as BP does) may bring a global error in excess of 10%.

An insurmountable problem comes when converting primary electricity to a common energy equivalent. The two basic choices are using electricity's thermal equivalent (1 Wh = 3,600 J, 1 kWh = 3.6 MJ) or converting with the average prevailing rate of thermal generation (depending on its efficiency that could be now mostly between 10 and 10.5 MJ/kWh for the conversion rates of 36%–34%). The choice matters: a country with a high share of hydroelectric or nuclear generation will end up with a relatively small primary energy equivalent when adopting the first option, and an inflated equivalent when using the second choice.

Energy statistics published by the International Energy Agency (IEA 2015a, 2015b) and also those released annually by the United Nations Statistics Division (UN 2015) use a hybrid solution: thermal equivalent for hydroelectricity (and now also for solar and wind), but for nuclear electricity they assume 33% efficiency (1 kWh = 10.9 MJ; ideally, this rate should be adjusted every year). In this book I follow the same hybrid solution except that I assume higher average efficiency (about 38%) when converting recent nuclear electricity generation. The U.S. Energy Information

Administration uses an annually adjusted thermal conversion factor for nuclear electricity net generation (11 MJ/kWh in 2015), and it applies the average fossil-fuels heat rate to convert electricity generated by all renewable conversions (average of 10 MJ/kWh in 2015) in order to approximate the amount of fossil fuels that have been replaced by these nonfossil sources (USEIA 2015b). Finally, British Petroleum's annual *Statistical Review of World Energy* converts all electricity by equaling 1 kWh to 9.5 MJ, that is, by assuming conversion efficiency of 38% for thermal generation (BP 2016).

Comparison of global totals for the year 2010 (all converted to EJ) indicates the cumulative effect of these uncertainties: the world's primary energy consumption was put at 536.07 EJ by the USEIA, at 534.12 EJ by the IEA, at 511.26 EJ by the UN, and at 508.65 EJ by BP, a difference of only about 5% between the two extreme values. But this gross energy supply is not consumed, it must be adjusted for preconsumption losses and nonenergy uses. Coal's losses during sorting, cleaning, transportation, and storage are considerably smaller than the errors in China's official statistics as well as less than the inherent uncertainty of converting bituminous coal and lignite extraction to energy equivalents; nonfuel uses of coal (mainly as a feedstock for chemical syntheses) are only about 1% of the global supply, and hence I have reduced extraction totals by that amount.

Transportation losses of crude oil and natural gas are similarly low, but crude oil refining yields many products that are used as feedstocks, lubricants, and paving materials: recent global mean of oil's nonenergy uses is about 14% according to the IEA; the U.S. share is roughly 12%. Natural gas is the principal feedstock for the production of ammonia, methanol, and ethylene. In order to account for the losses and nonenergy uses of hydrocarbons I have subtracted 15% from the recent supply of crude oil and 6% from the recent extraction of natural gas. The resulting global series is presented in Appendix A both in terms of absolute global aggregates (in EJ) and in shares of overall consumption, and I will use it for tracing the grand global energy transition from traditional biofuels to fossil fuels.

Comparing the spans of specific energy transitions cannot be done without defining their onsets and progressive milestones. Given the antiquity of coal's small-scale localized extraction, it is particularly necessary to impose a meaningful threshold to begin that particular count. Choosing 5% of the total global fuel supply as the beginning of a transition period would mean that the global transition from biofuels to coal reached that marker by about 1840 (although by that time the shift was restricted to less than a dozen countries). The first conclusion of this global quantification is that the relative importance of biofuels had not changed dramatically during the first half of the 19th century, but it began its accelerated decline after 1850: by 1860 the share of biomass fuels fell below 85%, by 1880 it was just above 70%, and by 1890 it was less than two-thirds (keeping in mind that all of these milestones are just the best estimates).

Although we will never be able to pinpoint the year it is most likely that sometime during the latter half of the1890s fossil fuels (that is, overwhelmingly coal) began to supply more than half of the world's energy derived from the combustion of all fuels. Once more I stress the fact that, contrary to a commonly held impression that the 19th century was the era of coal, on the global scale and in its entirety, that century still belonged very much to the wooden era. Coal was the only fossil fuel replacing biofuels during the century's first six decades, and even by 1900 coal accounted for about 95% of all fossil energies.

Bituminous coals and lignites reached the highest share of the global fuel consumption, about 55% of the total, during the century's second decade. Even though coal's importance declined to less than half of all fuel energies by the late 1940s, the fuel remained the world's most important source of fossil energy until 1964 when its contribution was surpassed by crude oil. By 1970 coal and crude oil supplied, respectively, about 30% and 40% of all fuel energy, by 1980 the relative gap had widened marginally to roughly 29% and 41%, and by the century's end the two fossil fuels provided, respectively, about 25% and 37% of all fuel energies (Fig. 2.13). Because all of these comparisons exclude the nonenergy products the oil shares presented here are lower than those commonly calculated by using gross energy content of all produced crude oil.

Because coal's declining relative importance was accompanied by a steady increase in its absolute production—from about 700 Mt of bituminous coals (including a small share of anthracite) and 70 Mt of lignites in 1900 to more than 3.6 Gt of bituminous coals and nearly 900 Mt of lignites in the year 2000 (nearly six-fold increase in mass terms and a more than a fourfold multiple in energy terms)—coal ended up as the century's most important fuel. Biofuels still supplied about 20% of the world's fuel energy consumed during the 20th century, coal accounted for about 37%, oil for 27%, and natural gas for about 15%. Looking just at the shares of the three fossil fuels, coal supplied about 43%, crude oil 34%, and natural gas 20%. This conclusion runs, once again, against a commonly held but mistaken belief that the 20th century was the oil era that followed the coal era of the 19th century.

Coal was in a big lead during the first half of the 20th century (its energy content accounted for half of all fuels and 80% of all fossil fuels), crude oil in its second half (35% of all fuels, more than 40% of fossil fuels)—but by the year 2000 coal ended up significantly (about 15%) ahead of crude oil, roughly 5.2 ZJ vs. 4.4 ZJ. This means that even when using the total energy

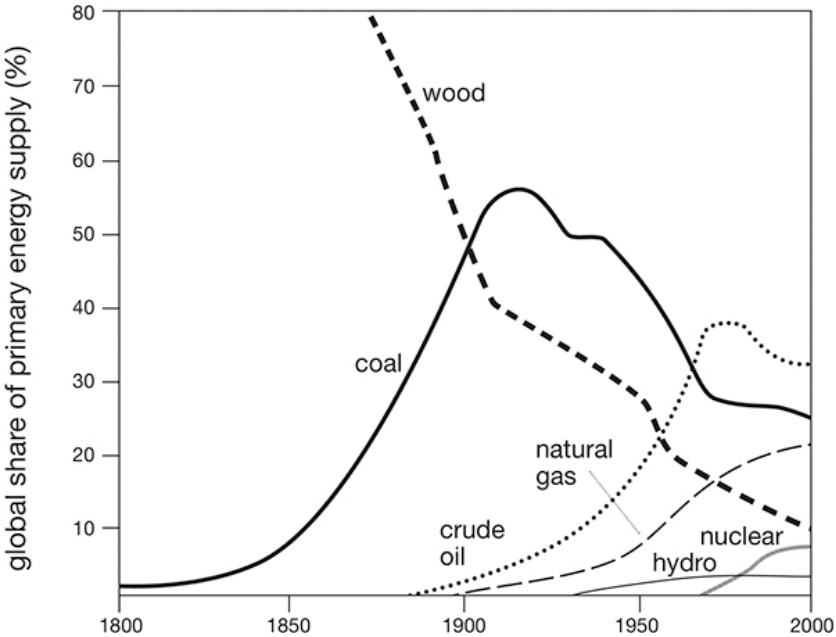

Figure 2.13 Shares of global primary energy consumption, 1800–2015. For data see Appendix A.

content of globally produced crude oil (including all nonenergy applications) coal would either just edge out liquid hydrocarbons or, allowing for the inherent uncertainties in converting coal to common energy equivalents, the 20th century's cumulative extraction of the two fuels was basically equal.

As already explained, when comparing the progress of individual energy transitions, I begin the count once a fuel or a prime mover had risen to claim at least 5% of an overall market (total production or capacity), and I then trace approximate time spans needed to reach the major milestones of 10%, 15%, 20%, 25%, 33%, and 40% of the overall supply. Comparing the time spans for the three successive fuel transitions reveals some remarkable similarities. Coal replacing biofuels reached the 5% mark around 1840, it captured 10% of the global market by 1855, 15% by 1865, 20% by 1870, 25% by 1875, 33% by 1885, 40% by 1895, and 50% by 1900. The sequence of years for these milestones was thus 15–25-30–35-45–55-60 (Fig. 2.14).

The milestones for the liquid fuels displacing coal and biofuels (crude oil reached 5% mark around 1915, and it will never capture 50% of the total fuelmarket) were spaced at virtually identical intervals as differences of about five years are not significant given the inherent uncertainties in

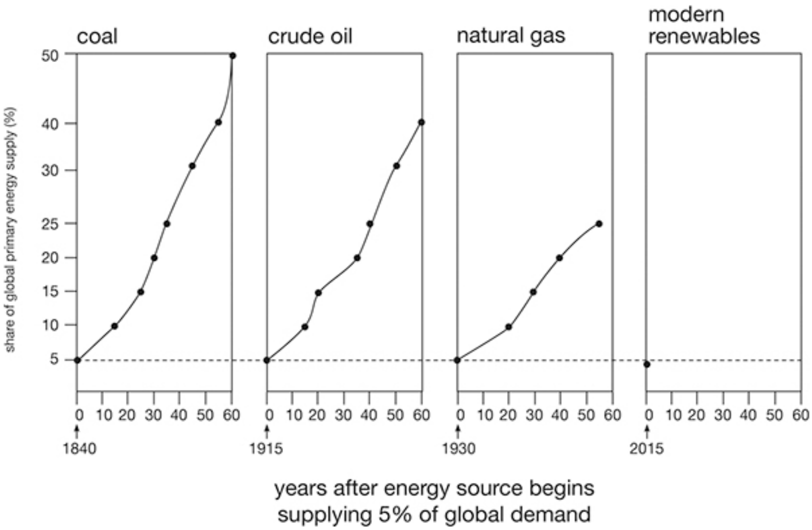

Figure 2.14 Time needed by fossil fuels to reach global consumption milestones. Plotted from data in Appendix A. Modern renewables are still below 5%.

aggregate accounting: 15–20-35–40-50–60 years. Finally, the substitution of liquid and solid fuels by natural gas (with methane reaching 5% of the global fuel market by about 1930) has the shortest sequence, either 20–30-40–55 years (because natural gas has yet to reach 33% of the global primary energy supply) or even just 20–30-40 years because in 2015 natural gas was very close, but still not at 25% after its nonfuel uses are subtracted.

There is, once again, a notable similarity to coal and oil sequences, but natural gas has taken significantly longer to reach 25% of the overall market, roughly 55 years compared to 35 years for coal and 40 years for oil. And the intervals for oil and natural gas transitions change little if they are counted only as the share of the fossil fuel substitutions (leaving the biofuels out): they become, respectively, 10–20-30–35-50–55 and 20–30-40–45. From a purely statistical point of view a set of mere three sequences does not provide any foundation for conclusive generalizations about the tempo of global fuel transitions.

At the same time, similarity of the three outcomes is not entirely coincidental particularly given the fact that the substitutions have involved three very different kinds of fuels that serve identical, or similar, final consumption niches but whose extraction, distribution, and conversion require very different techniques and infrastructures. And no less significant is a clear absence of any indication suggesting an accelerating progress of later transitions: if anything, natural gas has had a more difficult time of reaching the milestones previously claimed by both solid and liquid fossil fuels. At the same time, it is also necessary to take into account the absolute quantities involved: as the global fuel production increases it is more challenging to replicate the same relative rise in absolute energy terms.

As coal extraction rose from 5% to 25% of all fuels (between 1840 and the late 1870s), that increase required adding on the order of 250 Mt of coal or less than 7 EJ of energy; the same increase of the total fuel market share for crude oil (between 1910 and 1945) called for adding extraction of some 300 Mt of oil or about 11 EJ of energy, while the ascent of natural gas from 5% to 25% of global fuel production took place mostly during the rapid post–World War II expansion of global energy demand (between 1940 and 1990), and it entailed adding more than 70 EJ of energy, an order of magnitude more than during coal's rise a century earlier. **Vastly increased absolute size of today's energy demand means that—even with considerably greater technical and organizational means at our disposal and even in the cases where resource availability is not a constraint—it is much more challenging to develop a new source of primary energy supply to the point where it can start making a real difference (10%–15% of the total market) and then to elevate it to a truly major global role.**

An obvious question to ask is: "Would a clever statistical analysis reveal some definite, generally applicable, rules or patterns governing the transition process?" During the late 1970s, while working at IIASA, Cesare Marchetti asked this very question and found his answer by applying the Fisher-Pry model to the market shares of successively introduced fuels or primary forms of electricity. The model was originally developed to study the market penetration of new techniques, and it assumes that technical advances are essentially competitive substitutions, that once they capture at least a few percent of their respective markets they will proceed to completion and that the rate of fractional substitution is proportional to the remainder that is yet to be substituted (Fisher and Pry 1971).

Because the adoption (market penetration) of technical advances tends to follow a sigmoid curve, all that is needed is to calculate the market fraction (f) of a new technique and then express it as f/1-f—and when that function is plotted on a semilogarithmic graph it will appear as a straight line, making it possible to make apparently highly reliable medium- to long-range forecasts of technical advances. This method was developed to deal with simple two-variable substitutions, and the original paper includes such examples as synthetic vs. natural fibers, plastics vs. leather, open hearth furnaces vs. Bessemer converters, electric arc furnaces vs. open hearth steelmaking, and water-based vs. oil-based paints (Fisher and Pry 1971).

Marchetti was impressed by "the extraordinary precision" with which the fuel data could be fitted into straight lines. In the earliest stage of the substitution process there were just two competitors (coal vs. biofuels), but in later stages there were as many as six on the global level (biofuels, coal, oil, natural gas, hydroelectricity, nuclear electricity). In his first paper he presented what became an often-reprinted historical evolution of primary energy sources for the world beginning in 1850 and boldly extended to 2100 (Fig. 2.15). Marchetti (1977, 348) chose to interpret his plots in the most enthusiastic fashion, claiming that

> the whole destiny of an energy source seems to be completely predetermined in the first childhood . . . these trends . . . go unscathed through wars, wild oscillations in energy prices and depression. Final total availability of the primary reserves also seems to have no effect on the rate of substitution.

Two years later, in a longer report, he marveled how the penetration rates remained constant during the first three-quarters of the 20th century despite such major perturbations as wars and periods of both economic stagnation and rapid growth. This led him to conclude that "it is as though *the system had a schedule, a will, and a clock*" and that it is capable to reabsorb all perturbations "elastically without influencing the trend" (Marchetti and Nakićenović 1979, 15). To say, as Marchetti did, that it is the system

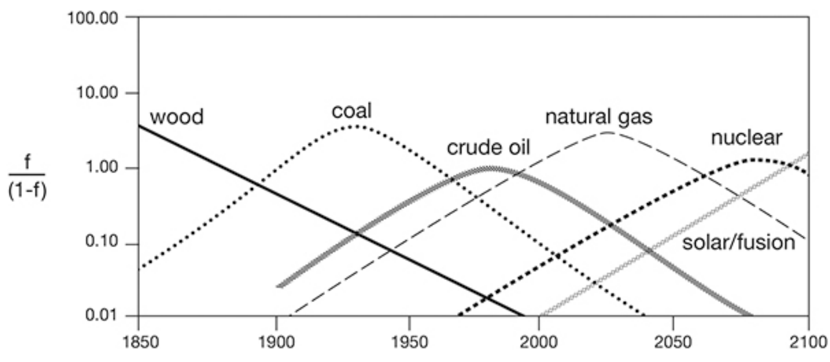

Figure 2.15 Marchetti's clock-like model of global primary energy substitutions, 1900–2100. Based on Marchetti (1977). The category *solar/fusion* refers to the combination of solar energy conversions and nuclear fusion: Marchetti had to posit its steady post-2000 ascent in order to make up for the anticipated continuing declines in coal and oil extraction. In reality, solar contributions remain negligible, and there is no nuclear fusion (and virtually no prospect for its significant pre-2050 commercial diffusion).

which is making the decisions is, of course, an obvious case of extreme techno-determinism: any attempts to change the course of energy transitions would be futile because humans are not decision makers; they are, at best, only optimizers.

These conclusions appeared to be well supported by the semilogarithmic f/(1-f) plots of global primary energy substitutions, and the approach seemed to provide an uncommonly reliable long-range forecasting tool. But even at that time a closer look revealed that unruly realities do not quite fit such smooth deterministic patterns, and a few years before Marchetti published his findings several powerful forces began to affect the global energy system in unprecedented ways. Four decades after Marchetti's original publications it is obvious that his model had several weaknesses, that his conclusions were excessively, and indefensibly, deterministic, and that the system's dynamics can be, and has been, greatly influenced by human decisions and actions.

Actual trajectories do not show the predicted orderly declines and rises, and differences between the model and reality have become particularly pronounced after 1980 (Fig. 2.16). Marchetti's application of the substitution model to energy transitions replicates reasonably well only two major

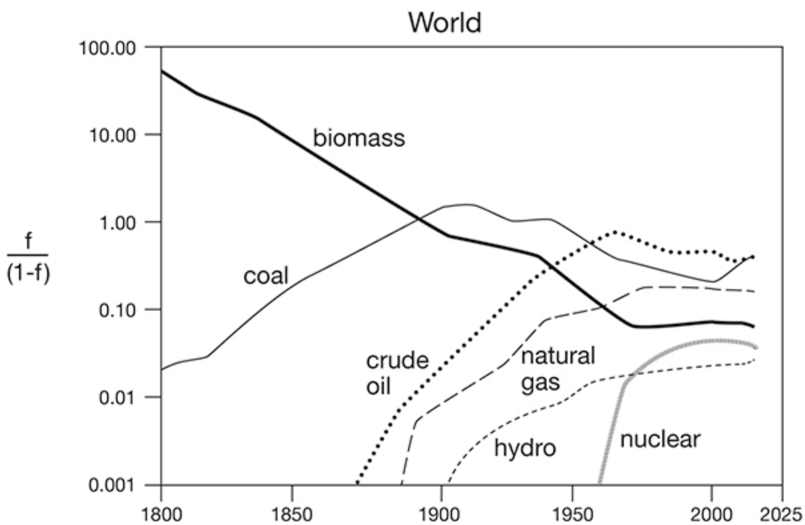

Figure 2.16 Fisher-Pry plot of the global primary energy transition from biomass fuels to coals, hydrocarbons, and primary electricity, 1800–2015. Data points calculated from statistics in UNO (1956, 1976) and BP (2016). The most remarkable phenomenon is the post-1970 stasis of all fossil fuel shares. Calculated from data in Appendix A.

realities: coal's ascent, the fuel's relative peak and pre-1980 decline; and crude oil's pre-1970 rise to become the most important fossil fuel. Everything else has turned out differently. Most notably, that overly mechanistic/deterministic application was quite incapable of capturing the post-1970 departures from the expected immutable tracks: the global trend for coal and oil was mostly sideways rather than down, while natural gas continued to gain its market share at a considerably slower pace than expected, and although nuclear electricity came close to the anticipated share that share was calculated by Marchetti by inexplicably omitting hydro generation, and it was arrived at by an entirely unforeseen route.

The two rounds of OPEC's large price rises (1973–1974 and 1979–1980) triggered these shifts, but other factors contributed as the newly set trends persevered during the periods of both very high and very low oil prices. The two price rises, coming after generations of very cheap oil, slowed down the growth of global energy demand and stopped the growth of oil production for 15 years (1979–1994). But once the global oil consumption reached its relative peak (at about 46% in 1979) its subsequent decline was much slower than the retreat that was to be expected if it were a mirror image of its pre-1979 ascent. At the same time, the post-1975 natural gas extraction had also slowed down while coal production continued to grow more vigorously than expected. As a result, by the late 1980s, just a decade after Marchetti began to promote his deterministic model, his predictions of oil and coal shares in global energy consumption were significantly below the actual levels.

By the century's end this disparity had only increased, and it widened even more during the first 15 years of the 21st century. Oil's slower decline is not surprising given the domination of transportation market by liquid fuels and the rapid rise of automobile ownership in China and India. Coal's increased market share has been due above all to the fact that China and India have been rapidly expanding their coal extraction and that the United States (and other affluent countries) have continued to rely on coal for large shares of their electricity generation. As a result, by 2015 crude oil supplied about 30% of the world's primary commercial energy needs, 20% above Marchetti's prediction of 25%. Coal's 2015 share was about 29%, close to oil's share and very far above the meager 5% mark expected by Marchetti's clock. And natural gas delivered about 24% of the world's primary energy in 2015, far below Marchetti's expected 60% (Figure 2.15).

Lower-than-expected growth of per capita energy needs in Europe and North America (and no growth in some countries), continued efficiency gains and the need for costly infrastructural development for LNG imports (see Chapter 1) explain the slower ascent of natural gas. Only the nuclear electricity generation now claims (when converted by using the prevailing conversion efficiency of fossil-fueled electricity generation) the share expected from the substitution model—but the route to this point was quite unlike Marchetti's prediction. During the 1970s and the early 1980s nuclear contributions rose much faster than anticipated. Subsequently, the U.S. plant orders ceased, European programs were abandoned or slowed down, and only Japan, China, and India continued to build nuclear reactors; nuclear share first reached a plateau and since the year 2000, after surpassing 6% of the world's primary energy supply, it has declined to less than 5% of the total by 2015.

Marchetti's (1977) clockwork transition had the traditional biofuels—wood, charcoal, crop residues, and dried animal dung—disappearing from the global primary energy supply before the year 2000. In reality, given the fact that more than 2.5 billion people rely on them for cooking and heating, their annual consumption has been recently nearly twice as large as in 1900! In relative terms, their importance has been declining, from nearly 50% in 1900 to about 11% in the year 2000 and roughly 8% in 2015. For comparison, the UN put their 2012 share at 9% of the global primary energy supply (UN 2015). **But even at 8% in 2015 they would have supplied more primary energy than either hydro or nuclear electricity and more than four times as much as all new renewables including wind, solar, and modern biofuels.** But I hasten to add that in terms of useful energy their shares have been much smaller because the efficiency of their combustion in small simple household stoves and open fires is greatly inferior to the performance on modern high-efficiency stoves, boilers, and engines.

Moreover, as already noted, Marchetti's original analysis did not include hydroelectricity: that was inexcusable because after more than 130 years of development it remains the world's most important source of renewably generated electricity, and, so far, its annual output was surpassed by nuclear fission for only two years (2001 and 2002). By 2010 hydro generation was 28% ahead of the nuclear fission, and by 2015 the gap had grown to 55% (although nuclear electricity converted at 9.5 MJ/kWh is ahead in terms of primary energy). Finally, there are no signs of a smooth ascent of the "solar/fusion" category Marchetti posited for the 21st century. In 2015 there was no fusion-generated electricity, and no prospect of it for decades to come.

The world's most important fusion research effort, multinational collaboration to build ITER (International Thermonuclear Experimental Reactor) facility in Cadarache in southern France, was to be finished by 2019, but it is much behind schedule and actual experiments are not expected before 2025, and even that date could slip (Clery and Cho 2016; ITER

Project 2015). And while photovoltaic electricity generation has been advancing rapidly (globally from just 1 TWh in the year 2000 to about 250 TWh 15 years later), its overall contribution to primary energy supply has remained quite marginal: even when converted to primary energy at 9.5 MJ/kWh it accounted for no more than about 0.5% of the world's primary energy supply in 2015.

This evidence makes only one possible conclusion regarding any orderly progress of energy transitions: the internal clock that was to keep primary energy sources on schedule as they enter and exit the global fuel and electricity supply has failed. By the year 2000 every one of the five trends charted by Marchetti departed significantly from the expected course, and the disparities rose further by 2015. Since 1970 the system has not behaved in a predetermined manner beyond anybody's control but has responded to an unprecedented concatenation of economic, technical, and social realities that have, once again, invalidated the merit of simplistic deterministic models.

The only part of Marchetti's analysis that remains correct is the general conclusion regarding the slow pace of the substitutions, but the actual time span he assigned to the process is questionable. Marchetti assumed that about 100 years needed to go from 1% to 50% of the market, a span that he called time constant of the system. But the only resource that has traversed that entire span in 100 years was coal: it reached 1% of the global primary energy supply just before the end of the 18th century, and it surpassed 50% a century later. As explained, crude oil's share has never reached 50%, and it has been receding from its brief sojourn above 40%. By 2015, more than 100 years after it surpassed 1% of global energy supply, natural gas still has not reached 25%. And after two decades of rapid advances neither wind- nor solar-generated electricity have reached 1% of global primary energy consumption.

Based on Marchetti's evidence the 100-year span required to gain 50% of global supply appears to be a singularity restricted to coal displacing traditional biofuels. Given the recent shares of major sources in the global primary energy supply it appears not just unlikely but virtually impossible that one of them—be it crude oil or natural gas, an entire class of new biofuels (fast-growing plantation wood, ethanol, and biodiesel), or any type of primary electricity (hydro, nuclear, solar, wind, geothermal)—will be able to provide half of the world's energy needs within the next 50 years. Natural gas would be the most likely source to rise to 33% as it displaces coal and some liquid hydrocarbons, but even the fastest conceivable development of wind and solar electricity could not vault them, individually, over the 25% share by 2050.

Prime mover transitions are much harder to quantify than the sequential waves of new primary energies, the simplest reason being relatively abundant and fairly accurate fuel production and electricity generation statistics. In contrast, only few countries have detailed historical information regarding their labor forces, capacities of agricultural machinery, or aggregate power of electric motors deployed in industries, households, and transportation. Transition from animate labor to water wheels, windmills, and steam engines presents a particularly great challenge as we have to resort to concatenated assumptions when calculating aggregates of human and animal labor. Available estimates of global population totals differ by nearly 40% for the year 1800, and the disparity is still almost 15% for 1900 (USCB 2015). Child labor was common in all preindustrial societies as well as during the early periods of industrialization, and this reality affects the estimates of economically active population—but we have no actual data on worldwide labor participation by children.

Long labor days were common in all traditional agricultures during planting, transplanting, and harvesting, but relatively long periods of low activity followed during post-harvest season: this reality complicates the estimates of typical labor burden. And while long labor days (10, even 12 hours) prevailed in many early industrial enterprises it would have been impossible to maintain high levels of exertion throughout. Inevitably, all of this requires highly approximate assumptions regarding total labor force, its typical deployment, and average power of useful labor (dependent not only on gender and age but also on nutrition and overall health). And the task is not easier when quantifying animal traction. Historical estimates of working animals outside of a few Western nations are just best guesses, and draft power also depends on the animal's sex, age, health, experience, endurance, harness, soil, and terrain. Steady pulls equal about 15% of body mass for equines and 10% for other draft species at speeds ranging typically just around 0.7 m/s for oxen and about 1 m/s for horses.

These rates produce, as already noted, 300–500 W for smaller and 500–800 W for larger animals. The need for multiple assumptions results in totals that are correct only in terms of their orders of magnitude. I have calculated that during the late Roman Empire—assuming labor of some 25 million adults (at 60 W for 300 8-hour days) and 6 million animals (at just 300 W/head for 200 8-hour days)—animate labor added up to 30 PJ a year (Smil 2010b). In contrast, maximum conceivable power of water wheels (assuming about 25,000 mills, high average power of 1.5 kW per machines, and a high load factor of 50%) would be about 300 TJ. Even very liberal assumptions indicate that water power in the late Roman Empire supplied no more than 1% of all useful energy provided by animate exertion.

Setting sails aside (their overall energy contribution is hard to quantify at any time and on any scale), common inanimate prime movers (water wheels and wind mills) remained marginal sources of power as recently as the early part of the 19th century. My approximate calculations indicate that by 1850 draft animals supplied roughly half of all the world's useful kinetic energy, that human labor provided as much as 40%, and inanimate prime movers delivered between 10% and 15% of the total. That changed rapidly during the century's second half due to the widespread adoption of steam engines; water turbines were the second most important class of inanimate prime movers, and the aggregate power of internal combustion engines and electric motors remained limited until after World War I.

In 1900 inanimate prime movers contributed 45%–50% of all kinetic energy, animal labor—about 410 million cattle, 100 million horses, and 40 million water buffaloes (PBL 2010)—provided about a third, and human labor (population of 1.65 billion) no more than a fifth of the total. By 1950 human labor, although in absolute terms more important than ever (with population at 2.5 billion), was a marginal contributor (maximum of about 5%), animal work (with 770 million cattle, 80 million water buffaloes, and 70 million horses) was down to about 10% of the total, and inanimate prime movers (dominated by internal combustion engines in road vehicles, with steam and water turbines in distant second place) contributed at least 85%, and very likely 90%, of all useful work.

This indicates a fairly orderly transition on the global scale, with inanimate prime movers increasing their share of useful work by nearly 10% a decade between 1850 and 1950. After they reached 10% share in 1850, it took them 30 years to go to 25%, then about 20 years to provide half of the total, 30 years to get to 75%, and some 20 years to supply 90% of all useful work. If these estimates are used in a standard binary Fisher-Pry substitution model (inanimate prime movers displacing animate power), there is an excellent fit for nearly 150 years beginning in 1850: only the most recent reality departs (although not dramatically) from the model's expectations as animate labor still provided at least 4%–6% of all useful energy in 2000 rather than a maximum of 2% indicated by the f/(1–f) trend.

In the absence of even approximate information regarding the total capacities of water wheels and windmills in 18th-century Europe, Americas, and Asia, as well as the total capacities and load factors of early 19th-century steam engines working on those continents, it is impossible to pinpoint the time when the work of steam engines surpassed the useful work of the two long-established inanimate prime movers: the most likely decade was the 1830s. Steam engines were the world's sole fuel-converting commercially deployed inanimate prime mover for 150 years, between

1710s and 1860s (when Nicolaus Otto began selling his stationary horizontal engines), and they remained the world's leading mechanical prime mover for nearly a century. By 1930 they still powered nearly all trains and more than 80% of all ships, and supplied most power in industrial enterprises. And although steam engines were deployed in some fieldwork (heavy plowing in the United States), agricultural transition from animate to inanimate prime movers took off only after 1900.

Even in the richest countries the transition from draft animals to internal combustion engines (either tractors with a variety of field implements or self-propelled machines, mainly various harvesters and combines, as well as trucks used to deliver farm supplies and transport harvested crops, milk, and animals) took more than half a century when measured by the numbers of remaining working horses, but it took place much faster when looking at the aggregate power of the two kinds of prime movers. The first gasoline-powered tractors were built around 1890—John Charter in Sterling, Iowa, in 1889 and John Froehlich, also in Iowa, in 1892 (Williams 1982)—but by 1910 there were still only some 1,000 machines in the United States.

America's aggregate tractor power had surpassed the combined power of horses and mules during the early 1920s and reached 90% of the total by 1950 (USBC 1975). Consequently, the time elapsed from the commercial takeoff to gaining 50% of all deployable power was only about a dozen years, but the time span from introducing the first tractor to reducing the main competition to a marginal share was more than 60 years. In Europe the mechanized fieldwork became common only after World War II, and hence the spans from introduction of tractors to their near complete dominance were one or two decades longer. In most parts of Asia this transition is still underway, and in some countries of the sub-Saharan Africa it has not even started.

Perhaps nothing illustrates better the gradual process of agricultural mechanization than the fact that in the year 2000 low-income countries, with some 80% of the world's population, had fewer than 30% of the world's 27 million tractors (compared to nearly 20% in the United States alone) and, given much larger capacities of American machines (the largest ones now rate nearly 450 kW), an even lower share of total tractor power. In the year 2000 the global mean was 196 machines per 100 km^2 of arable land, with EU at more than 900, the United States at nearly 260, China at 82, and Nigeria at less than 10 tractors (World Bank 2015). My approximate calculations show that in 1950 the useful work done by draft animals and by tractors were roughly equal, and that in the year 2000 field and transport service provided by some 500 million animals still supplied perhaps as much as 20% of all mechanical energy in farming (excluding human labor). But a transition within this transition, from gasoline-powered to diesel-powered tractors, was fairly rapid: diesel tractors were introduced in the early 1930s and by the 1960s all more powerful machines were diesel-powered.

There is no simple way to quantify the transition to mobile (automotive and truck) internal combustion engines because these vehicles displaced a variety of transportation modes and specialized conveyances, some powered by human and animal muscles (litters and wheelbarrows, horse-drawn carts, wagons and omnibuses, towed canal barges), others by wind (sail ships) and steam (steam ships and trains). Moreover, car ownership did not necessarily eliminate all of the previous uses: in many countries (most notably in Japan and in many EU nations) high levels of car ownership coexist with a widespread use of public transport, and in some cities cycling remains popular. Perhaps the best way to address this transition in urban settings is to point out the years when animate power was reduced to a marginal role.

The late 18th- and early 19th-century Western cities were full of horse-drawn vehicles including wagons, carts, carriages, cabs, barouches, buggies, coaches, and diligences. Horse-drawn omnibuses and streetcars were added during the late 1820s and early 1830s (New York omnibuses in 1827, London streetcars in 1831). By the mid-19th century horse-drawn streetcars became the leading means of urban public transport in all large cities, and although they began to disappear during the 1880s with the introduction of electric traction, some cities kept them on some routes into the 20th century: New York until 1917, Pittsburgh until 1923, and Mexico City until 1932 (Roess and Sansone 2013). Tipping points between aggregate urban horse power and power installed in electric motors for public transportation in major Western cities was reached mostly between 1895 and 1910.

We can time quite accurately three important shifts away from steam engines: to steam turbines in thermal electricity generation, to diesel engines in shipping, and also to diesel engines on railroads. The first transition was a rapid one because steam turbines displaced steam engines in new power plants in just a dozen years after their introduction. The first small steam turbogenerators were ordered in 1888, the last major American coal-fired station with steam engines (16 massive Westinghouse-Corliss machines) was New York Edison's East River in 1902, and the last British installation of that kind was London's County Council Tramway power station in Greenwich completed in 1905 (Dickinson 1939). Power plant market was thus completely claimed by steam turbines in just 14–17 years after their commercial introduction.

Conquest of marine shipping by diesels can also be dated quite precisely, starting with *Selandia*—the first large (for its time, 6,800 dwt) commercial ocean-going vessel with diesel engine launched by Burmeister & Wain in Copenhagen in November 1911—and ending with *Liberty* ships, the dominant cargo carriers (10,856 dwt) during World War II (Smil 2010a). During the early 1940s diesels or steam turbines would have been the best choice for the wartime cargo fleet, but the urgent need was met most rapidly by powering them with obsolete but much-tested and cheaper vertical triple-expansion compound oil-fired steam engines whose production ended in 1945 (Elphick 2001). Many steam engines continued to work well into the 1950s, but by that time all new large ships were diesel-powered. This means that large marine diesels needed about 40 years to move from pioneering designs to a near-complete dominance of that transport niche.

Prime mover transition on railroads was not that straightforward: diesel locomotives began to be introduced in both Western Europe and the United States during the late 1920s. In the United States they captured half of the market by 1952 and accounted for 90% of all locomotives by 1957; a Fisher-Pry plot shows slightly bent lines because of a relatively slower substitution progress during the war and a very rapid rate of change after 1950 (Sharif and Kabir 1976). Steam locomotives were almost completely gone from the U.S. railroads by 1960 and in Western Europe about a decade later, but in China and India many of them served into the 1990s. Some countries (Japan, France, Germany, Russia) electrified most of their traction and hence both their fast passenger trains and heavy freight trains rely on electric motors, but where the transition on railroads was solely, or largely, from steam to diesel engines, its duration was 35–45 years from the first models to near-complete dominance.

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CHAPTER THREE

National Transitions: Commonalities and Particularities

All complex social and economic phenomena are marked by national peculiarities, but simple binary approaches are often surprisingly powerful tools for bundling such differences into larger categories. There is no need to succumb to any simplistic environmental determinism in order to realize that the fortunes of modern societies have been shaped to a large degree by the fundamental differences between the tropical environments (their climates, soils, and vegetation) and their temperate counterparts (Sachs 2001). Similarly, a simple division between the rich nations (other labels, including affluent, high-income, modern, or even postmodern might be better, but I prefer not to use the term *developed*) and the poor countries (low-income, modernizing, industrializing; again, I prefer not to use the term *developing*) captures a great deal of fundamental differences in terms of achievements ranging from per capita income to infant mortality and from access to education to political freedoms (UNDP 2015).

But such convenient divisions also hide a great deal of intragroup variability: the true tropics (year-round humid and rainy) differ greatly from seasonally dry tropical regions, and, as comparisons of the UNDP's Human Development Index (HDI) illustrate so well, economic accomplishments commonly measured in terms of GDP per capita are not reliable indicators of actual quality of life. Just a single notable example illustrates this reality: South Korea's HDI of 0.898 (world's number 17) ranks far ahead of Saudi Arabia's (0.837, number 39), although Saudi per capita GDP is nearly 60% higher than the Korean mean (UNDP 2015). Analogically, national patterns of energy transitions show significant variations among countries whose economic achievements are very similar, as well as similarities among some countries at different stages of economic development.

There have been two basic patterns of economic progress that broadly correspond to two principal paths of grand energy transitions and to two prevailing modes of typical affluence. The first one can be simply labeled as early innovators whose eventual attainment of high average per capita energy use created the first affluent societies. This (relatively homogeneous) group encompasses leading economies of Western Europe and the United States and Canada, but it, too, contains some notable outliers. In England and Wales the grand energy transition from biofuels to fossil fuels began already during the 16th century and was nearly complete by the end of the 18th century—while other early European innovators had accomplished most of this process only during the 19th century. In contrast, differences in reliance on the two principal preindustrial inanimate prime movers were much less consequential because in aggregate even relatively common use of water wheels (in France and Germany) or windmills (in Holland and England) was greatly surpassed by the total contributed by animate labor.

The much larger group of late innovators (late followers) includes all countries whose high (or at least very substantial) dependence on nonfossil energies lasted until the second half of the 20th century and where the rates of fuel and prime mover substitution (and the consequent lifting of average quality of life above the subsistence level) have proceeded at generally much faster rates than in the first group as the process of energy transition from biofuels to fossil fuels was compressed into just two generations. Again, this group has its outstanding performers (South Korea, post-Mao China), relative laggards (India, Indonesia), and worrisome cases (Pakistan, Bangladesh). In between are the countries that began to modernize during the 19th century but had attained higher standard of living only after World War II: Japan and Russia are the most notable examples in this category that might be labeled early followers.

I will trace energy transitions in eight countries, starting with the UK and France, the two great European powers. Britain was the first society to accomplish the epochal energy transition from biomass fuels to coal; more recently it had pioneered commercial generation of nuclear electricity, and during the last three decades of the 20th century the North Sea discoveries also made it a vigorous developer of offshore hydrocarbons. France's transition from wood to coal got fully underway only during the early 19th century, the republic's reliance on coal persisted until after World War II, but then its bold development of nuclear energy (in response to the first round of OPEC's oil price increase) set it apart from all other affluent nations.

In order to encompass a wide range of European experiences I also take a closer look at the Netherlands and Sweden, the two nations whose energy transitions could not have been more different. Netherlands had a precociously "modern" economy energized by a remarkable 17th-century energy transition, and it was able (after first reverting to a more common energy transition pattern) to chart once again a special course thanks to the discovery of one of the world's largest natural gas fields. During the 19th century Sweden continued to enjoy advantages of abundant wood supply, and even though it is still more dependent on phytomass than any other European nation except Latvia and Finland, it was also an early adopter of nuclear fission.

No survey of national energy transitions can leave out the two leading producers, the United States and Russia. The United States—until 2009 the world's largest producer and consumer of energy (it was surpassed in both categories by China)—deserves especially close attention. Before World War I resource-rich Russia was on a trajectory of promising economic development, including its pioneering contributions to oil industry. But the 1917 revolution followed by prolonged civil war, establishment of the USSR (in 1921), more than two decades of brutal Stalinist rule (1929–1953), enormous damage done by World War II (1941–1945), and economic mismanagement of the post-Stalin era (1953–1991) left the new Russia (USSR was dissolved in December 1991) as a peculiar amalgam of strengths and weaknesses. Finally, the two Asian energy superpowers, Japan and China, differ greatly in most of the key economic aspects as well as in terms of natural endowment—but they share a common trait of compressing the modernization process into remarkably short periods.

A curious reader might ask why not to include other major, or notable, energy users in this survey. Above all, why not Germany, the EU's largest economy and a great pioneer of technical advances in general and of energy innovations in particular? This exclusion is largely due to statistical complications caused by Germany's unstable history. There was no united Germany during the earliest stages of grand energy transition, and the country had different borders (and hence incomparable populations and different economic outputs) at the time of its establishment in 1871 (after the defeat of France and annexation of Alsace-Lorraine), in 1918 (after its defeat in World War I), in 1939 (after its annexation of Austria, Bohemia, Moravia, and a large part of Poland), in 1945 (after its defeat in World War

II deprived it of all territories east of the Oder), between 1945 and 1990 when it was divided into two countries (official foundation of West and East German states took place in 1949), and after October 1990 (when the two states were reunited).

Ensuring long-term comparability of German data is thus a tiresome exercise, but fortunately there is no need for any painstaking reconstruction if all that is needed is to grasp the country's long-term energy transition in relative terms because in all of the affected territories the shift was overwhelmingly just a straightforward displacement of traditional phytomass by coal, accomplished before 1900, and then continuing high dependence on coal with only a minor addition of imported crude oil. World War II led to the rise of large-scale industries designed to overcome the limited supply of crude oil by producing coal-based substitutes for liquid fuels.

Such surrogates were not needed after World War II when the damaged economies of both German states based their reconstruction first on coal and later on rising imports of oil and natural gas. At the time of reunification in 1990 the Western energy supply was much more diversified than the Eastern, still heavily coal-based economy. In the year 2000 united Germany embarked on a deliberately engineered, and relatively ambitious, transition from fossil fuels to renewables, and this *Energiewende* will get a great deal of attention in Chapters 4 and 5.

And why not India, the world's second most populous nation (and soon to be the number one) and now also the world's third largest (in terms of purchasing power parity) economy? That exclusion is explained by the stage of India's recent economic development. While India's population will soon surpass China's total and its economy (in terms of purchasing power parity) is now the world's third largest, the country remains poor, and it is a relatively low consumer of energy even when compared to China: India's per capita GDP is only about 40%, its consumption of crude oil and natural gas only about 35%, and its primary energy use just 25% of the respective Chinese rates. Moreover, large parts of countryside still depend heavily on biomass fuels (including dried dung), and more than 300 million Indians still have no access to electricity. Simply put, India's energy transition is still in its early phases, and it does not offer any unprecedented lessons.

Germany and India aside, the examined country set includes all of the world's largest as well as most innovative economies of the past two centuries. Britain was the largest Western economy until it was surpassed by the United States in the early 1870s: Maddison put the British GDP at less than 2% above the U.S. total for 1870 (Maddison Project 2015). When expressed in purchasing parity values, the U.S. GDP was surpassed by

China in 2014, although in nominal and in per capita terms it remains far ahead. In 2015 Japan was the world's fourth largest economy (behind India and ahead of Germany), while Russia, France, and the UK claimed, respectively, the sixth, ninth, and tenth place. In 2015 the combined population of the examined nations was about 30% of the world total, but their aggregate economic product was equal (in purchasing power parity terms) to 47% of the global output, and their energy consumption added up to 53% of the world's primary energy supply.

Tracing these eight energy transitions makes it clear that national peculiarities matter. British experience was not only a pioneering one but also quite unique, as has been the recent French energy policy. The United States rose to affluence along a trajectory that differed greatly from the European quest for high-energy societies. China's belated quest for modernity has been energized by a highly idiosyncratic energy transition. Japan has the distinction of being the only one of the world's five largest economies to be almost entirely dependent on energy imports. Russia, on the other hand, has a surfeit of every kind of energy, but its enormous export capacity has not made it either very rich or very stable. In the closing section of this chapter I will survey some long-term trends and search for some wider generalizations and larger patterns.

Finally, the unfolding shift away from fossil fuels will be of an unprecedented magnitude, and hence the experiences of the six large economies are much more relevant than the performances of small (be it in territorial or population sense) nations, and particularly those countries that are fortuitously endowed with abundant resources (be it Norway, Kuwait, or Brunei). In such economies energy transitions can happen very rapidly, and their experiences have little relevance for nations with large populations, large territories, and the requisite needs to develop extensive infrastructures (be it the United States, Russia, or China).

United Kingdom and France: Great European Powers

Studies of the UK's historical trends have been helped by the availability of unusually long statistical records as well as by the country's stable territorial extent following the Acts of Union approved by the English and Scottish Parliaments in 1707. In contrast, France had undergone several territorial changes (in 1815, 1860, the loss of Alsace-Lorraine in 1871 and its recovery in 1918, and the short-lived World War II changes between 1940 and 1944). Pre–World War I energy transition in all major European economic powers was overwhelmingly just a shift from the reliance on traditional phytomass to a near-total dependence on coal—but on the continent the process began to unfold more than 200 years after its English beginnings.

Why an offshore-island country became the world's first society to undergo the process of industrialization energized primarily by coal remains a fascinating, and contentious, topic for historical analysis. This section follows the process of this primordial transition from wood and charcoal to coal and its consequences as Britain lived on an extended coal plateau for a never-to-be-surpassed period of nearly three centuries, and then it notes those post–World War II developments that have profoundly changed the country's energetic basis (and hence its very economic foundations) and ended all underground coal mining in 2015.

United Kingdom

Tracing the earliest history of Britain's energy transition from wood to coal is a task that has been made relatively easy thanks to several revealing inquiries into this subject, including Nef (1932), Flinn (1984), Mitchell (1984), and Fouquet (2008). English coal—known and used sporadically since the Roman times—became an increasingly important fuel during the first half of the 16th century when its falling prices made it a popular choice among poorer households. But even the late Elizabethan nobility still disdained the use of coal with its sulfurous smoke, and the regal example was needed to overcome that resistance as Elizabeth's successor (James I, crowned in 1603) began to use coal in his London palace (Brimblecombe 1987).

Nor was coal enthusiastically adopted by industries. As its price declined, coal began to be used first in manufactures that required relatively low heat supply (smithing, brewing, dying, and production of salt, lime, and soap). After 1610 glassmakers began to switch to coal thanks to the introduction of reverberating (heat-reflecting) furnaces that produced sufficiently high temperature. Because of gradually rising demand nearly all of the coalfields that later made the country the world's largest fuel producer (in the Northeast, Yorkshire, Midlands, Wales, Scotland) were opened for commercial exploitation before 1640, and fairly reliable data show annual extraction (no more than 25,000 t by 1600) surpassing 2 Mt by 1650 and reaching 3 Mt by 1700.

Quantitative reconstructions of this earliest energy transition can be only approximate. Warde (2007) concluded that the choice of a precise date for the tipping point between the two kinds of fuel is arbitrary: his compilations show that coal surpassed biomass as the source of heat most likely around 1620, perhaps a bit earlier. By the middle of the 17th century the

British coal supplied two-thirds of all thermal energy, by 1700 about 75%, by 1800 about 90%, and by 1850 its share was in excess of 98%. This supremacy lasted for another 100 years: by 1950 coal's share was still 91%, and by 1960 it declined to 77%, the rate it had reached already during the first decade of the 18th century. This means that coal dominated the country's thermal energy use (supplying more than 75% and as much as 99% of the total) for about 250 years, a period of dependence unmatched by any other nation (Fig. 3.1).

Final coal uses had seen many shifts during this long period: first came the coal combustion as a direct source of heat for households and manufactures; steam engines created a new market for coal as a source of mechanical energy for stationary industrial applications. Adoption of metallurgical coke introduced another powerful positive feedback. I have already described how the new fuel, introduced in 1709, finally began its ascent during the 1760s; by 1780 coke price was down by two-thirds compared to 1740, and coal use for coking rose from less than 3,000 t in

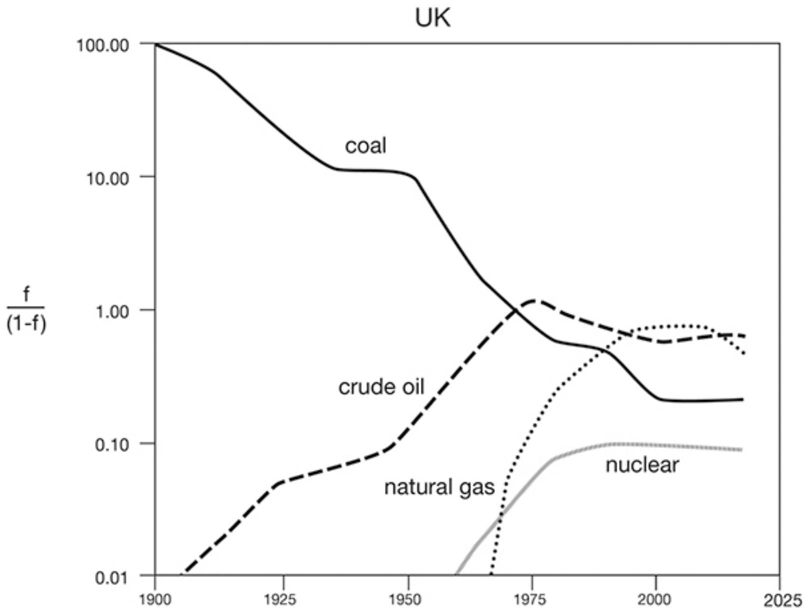

Figure 3.1 Fisher-Pry plot of the primary energy transition in the UK, 1900–2015. Data points calculated from statistics in UNO (1956, 1976), Hicks and Allen (1999), and BP (2016). By 1900 there was virtually no wood use; hydroelectricity has been always a marginal source, and its shares are not shown. Recent hydrocarbon shares have leveled off, nuclear electricity began an early retreat, and underground coal mining ended in 2015.

1750, and 170,000 t by 1800 (Harris 1988). The next important new market for British coal was the production of town (coal) gas for illumination. But during the first half of the 19th century coal demand got its largest boost from the emergence of mobile steam engines used extensively after 1830 on railroads and in ship propulsion.

This transportation revolution led to steady increases of demand for iron for railways, and hence for more coal to produce coke for blast furnaces. After the introduction of Henry Bessemer's converter (patented in 1856, widely adopted only after additional process improvements made it possible to use high-phosphorus ores) it became possible to produce, for the first time ever, inexpensive steel (Smil 2016a). A smaller new market emerged for nonenergy uses of coal (specifically coal tar) as a feedstock for syntheses of organic chemicals, but by far the most important (and enduring) new use of coal that arose during the last two decades of the 19th century was electricity generation.

British coal production peaked in 1913 when 1.1 million miners in 3,024 deep mines extracted 292 Mt of coal (DECC 2015). The output was reduced less by World War I than by two general strikes in 1921 and 1926, but the interwar peak of 280 Mt in 1923 was close to the record. In 1947, at the time of its nationalization (creation of the National Coal Board), annual extraction was still 200 Mt (190 Mt from deep mines), and its postwar double peak, in 1952 and 1958, was 228 Mt. Rising oil and gas consumption (first from imports, starting in the 1970s from the North Sea) reduced it to 130 Mt (122 Mt from deep mines) by 1980, and the coal miners' strike of 1984 marked the beginning of its end (DECC 2015).

During the strike year the output from deep mines fell to only 35 Mt, between 1986 and 1988 it rose once again just above 100 Mt, but the subsequent decline was not arrested by the industry's reprivatization in 1994. By the century's end British coal extraction was only 31 Mt (17 Mt from deep mines) and employed just 11,00 workers, and by 2010 deep mines produced just 7 Mt while surface mines shipped 11 Mt and coal imports rose to 27 Mt. And, as already noted, British deep coal mining ended in December 2015. Social dislocations of this shift have been considerable (Hicks and Allen 1999). At the time of nationalization in 1947 the coal industry's labor force totaled 707,000, by 1990 that total fell to just 10,000, and by 2014 only 4,000 people worked in all British mines.

But because the country's electricity generation remained highly dependent on coal, and because Britain's remaining blast furnaces still need metallurgical coke, the shortfall in domestic production has to be filled by increasing coal imports: in 2001 they surpassed domestic output, and in 2013 they were nearly 50 Mt, coming mostly from Russia, China, and the

United States. As a result, "bringing coals to Newcastle" has changed from a proverbial description of a superfluous activity, if not an outright folly, to a quotidian commercial reality. And Newcastle is not just a stand-in for the UK: coal imports come to both the west and east coast of England, and one of the eastern receiving ports is Redcar, about 50 km southeast of Newcastle (SSI 2015).

Decline of the British coal mining was accelerated by the discoveries of the North Sea hydrocarbons (first natural gas in the West Sole field in 1965, then crude oil in the giant Forbes field in 1970) and by a temporary conversion of Britain into one of the world's leading producers of oil and one of the largest users of natural gas (Hall and Atkinson 2016). British geologists were among the pioneers of the global search for oil, and British engineers developed some of the world's earliest oilfields, particularly in Burma (Burmah Oil Company was set up in 1886) and in Persia. In 1908 William Knox D'Arcy drilled the first Middle Eastern oilfield at Masjid-e-Soleiman, and the Anglo-Persian Oil Company, the precursor of British Petroleum, was set up a year later (Ferrier 1982). The country was thus an early, and relatively substantial, importer of crude oil and, as already noted, Britain also pioneered LNG imports.

Natural gas consumption began to make a real difference only with the development of the North Sea fields: in absolute terms it increased nearly ninefold between 1970 and 2000 (from about 11 Gm^3 to nearly 97 Gm^3), in relative terms from less than 5% to 39% (Fig. 3.1). By 1980 the UK was the world's 7th largest producer of natural gas; it kept that rank for more than a decade, and when its output peaked (137.4 Mt in 1999) it rose to the fourth place with 4.4% of the global output. But a decade later the UK's gas was in 13th place (and just 1.6% of the global total), and the latest projections are for continuing production decline.

British crude oil production rose from just 200,000 t in 1970 to the peak of about 137.4 Mt by 1999 (placing 8th worldwide that year, ahead of Iraq and Canada and just behind Norway), and it enabled the country to satisfy not only its own demand but to become a temporary exporter. By 2006 the declining production (76.6 Mt) slid about 7% below the total consumption (82.3 Mt), and by 2014 the country produced an equivalent of less than 60% of its oil needs. In relative terms crude oil consumption surpassed 10% of all British primary energy only in 1952, but then it rose rapidly to 50% by 1973, declined afterwards to about 35% by 2000, and was still at 37% by 2015 (Fig. 3.1).

Britain's short streams offer a limited opportunity for the development of large water projects, and the contribution of hydroelectricity to the overall primary energy never rose above 1% (less than 0.1% by 1950, 0.7% in

2015). But the country had a pioneering nuclear program with the first station, Calder Hall, commissioned in 1956 (Williams 1980). Nuclear electricity's eventual peak contribution (in 2000) was close to 9% of all primary energy. Subsequent closure of old stations with Magnox reactors (Bradwell in 2002, Calder Hall in 2003, Chapelcross in 2004, Dungeness A and Sizewell A in 2006, Oldbury in 2012, and Wylfa in 2015) reduced its share to less than 8% by 2015.

Realities of British primary energy supply at the beginning of the 20th century had thus hardly any resemblance to those inexorably scheduled penetrations that Marchetti and Nakićenović (1979) envisioned just 20 years earlier: in the year 2000 coal was at about 16% rather than at 3%, oil was at 35% rather than at a mere 1%, and natural gas was at 39% rather than at around 80%; only nuclear electricity was close to the forecast share of 10%. And the only notable change by 2015 was an increase of renewable electricity generation, primarily due to both onshore and offshore wind, to more than 7% of the total primary energy supply: coal remained at 16%, oil was slightly up at 37%, and natural gas was down to 32%.

France

With a much larger territory than Britain, and with most of its *départements* having extensive and fairly productive forests, France was able to rely on wood and charcoal as the principal sources of heat for generations after phytomass became a marginal source of energy in the British Isles. The best indication—based on the most comprehensive set of historical data of energy production, trade, and use (Barjot 1991)—is that during the early Napoleonic times more than 90% of France's primary energy came from wood, that that share declined to about 75% by 1850, and that it slipped below 50% before 1875 (or perhaps during the late 1860s). By 1880 coal provided about 55% of all primary energy, and it then dominated France's primary energy supply until the late 1950s when it yielded to imported crude oil whose share rose to as much as 68% by 1973 (Fig. 3.2).

But unlike in the UK, where wood was entirely displaced by cheap coal, wood has never disappeared from the French energy balance: its share declined from nearly a third in 1900 to less than a quarter by 1920 and to less than 10% by the early 1960s, and since the 1970s it has remained at 4%–5%, with the highest consumption in Franche-Comté, Auvergne, and Bourgogne (ADEME 2013). French coal production reached 1 Mt/year by

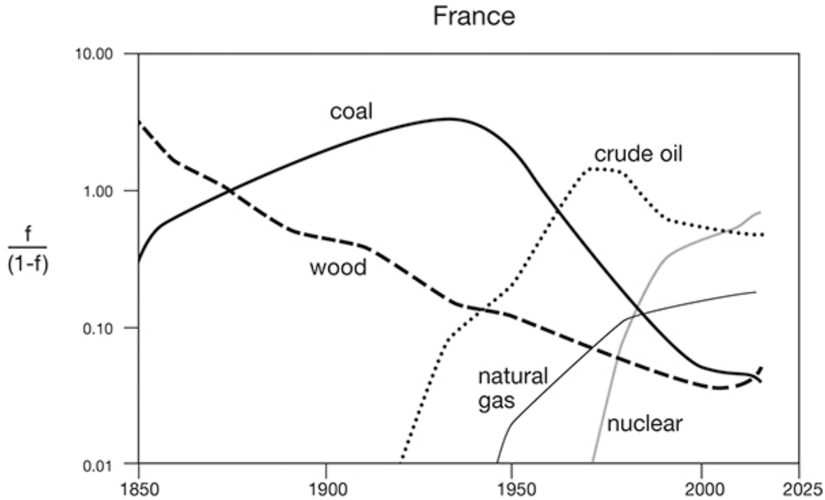

Figure 3.2 Fisher-Pry plot of the primary energy transition in France, 1850–2015. Data points calculated from statistics in Barjot (1991), UNO (1976), and BP (2016). Wood share has been declining for more than 150 years, coal's importance peaked before World War II, and determined promotion of nuclear generation has made it the single most important source of the country's primary energy, a globally unique achievement.

1820 and 4.4 Mt by 1850; then it took off, surpassing 20 Mt by 1882, and its pre–World War I peak was 41 Mt, compared to 190 Mt in Germany and 202 Mt in the UK. Not surprisingly, even during its most productive decades (1930–1970), it had to be supplemented by imports from the UK and Germany. Bituminous coal came from three main regions: Bassin du Nord et du Pas-de-Calais (maximum output of 29 Mt in 1959, extraction ended in 1990), Bassin de Lorraine (maximum of 15.6 Mt in 1964), and collieries of Centre and Midi with maximum output of 15.1 Mt in 1958 (de Ladoucette 2004).

Coal's relative contribution to France's energy balance peaked during the 1920s and 1930s, and after World War II it retreated quite rapidly, first due to imports of oil, rising strongly since the mid-1950s, and then due to expanding nuclear generation (after 1980). Coal supplied just 5% of the primary energy by the year 2000, the output has been below 1 Mt since 2004, and *Charbonnages de France*, a state enterprise formed in 1946 after the nationalization of private coal companies, was disbanded in 2008. Much like the older British coal industry, French coal mining, immortalized by Zola's *Germinal*, now belongs to the continent's industrial history.

France, alone among the world's major economies, followed a bold and effective course in order to reduce its high dependence on imported oil: in March 1974 the government initiated the first large-scale (16-unit) program designed to make the nuclear generation the dominant mode of the country's electricity production (Larroque 1997–1999; Reuss 2007; WNA 2015b). French nuclear development began during the late 1950s with three gas-cooled reactors, but in 1969 the French military mastered the uranium enrichment (a key necessity for de Gaulle's independent nuclear *force de frappe* initiated in 1958), and the subsequent enlargement was based on standardized sizes of America's Westinghouse pressurized water reactors (PWR) that use enriched fuel.

Only two sizes of these reactors, produced by Framatome (established in 1958), have been used, the most common a 900-MW unit (34 reactors) and a larger 1.3-GW unit (20 reactors). The third size, rated at 1.45 GW (only four units in operation), was made by Areva, the world's largest nuclear company that was set up in 2001 by merging Framatome with Cogema. The company had later encountered serious operational and financial setbacks, and in June 2015 the French government handed over its reactor business to EDF, the state electricity corporation, leaving it with fuel production, enrichment, and disposal (Bezat 2015).

While the U.S. nuclear program was beset by innumerable delays and cost overruns, the French program, based on standardized reactors, proceeded almost faultlessly, with the generation rising from just 14 TWh in 1973 to 415 TWh in the year 2000 and 437 TWh in 2015. By 2015 France had 58 operational reactors (one under construction and 12 in permanent shutdown) that have been strategically distributed around the country: Massif Central and Midi-Pyrénées are the only regions without them. Their total capacity was 63.13 GW, but because they constitute such a large part of the total installed power (77% in 2015, planned to be reduced to 50% by 2025) they cannot be used (as is the norm elsewhere) only for the base load generation and must be operated in the much more challenging load-following mode (WNA 2015b).

As a result, their average lifetime capability factor has been lower (about 78%) than in neighboring Switzerland (nearly 88%) or in South Korea (87%). Even so, French reactors now generate more than 400 TWh a year, or 75%–77% (depending on the contribution by hydro stations) of all electricity, a share not matched (not even approached) by any other major economy: in 2014 only two other countries, Hungary and Slovakia, had shares in excess 50%, and the only other important EU economy with the nuclear share of electricity generation above 40% was (just, at 41.5%) Sweden (IAEA 2015). Nuclear electricity's share of the French primary energy supply rose from 0.2% in 1965 to more than 7% by 1985 and to nearly 33% by 1990, and it has been above 35% since 1993.

This impressive gain has been a major factor in reducing the absolute level of French oil imports: by 1993 they were nearly 30% below their peak 1973 level, and in 2014, despite the intervening economic growth, they were 40% lower than in 1973. As in the British case, the expectations of future shares based on apparently fixed rates of market penetration proved to be far off. Marchetti and Nakićenović (1979) foresaw the French primary energy shares in the year 2000 at just 1% for coal, less than 10% each for oil and gas, and more than 80% for nuclear electricity—while the real shares were, respectively, about 5%, 37%, 14%, and 37%, and only small shifts took place by 2015, with coal at 4%, oil at 32%, natural gas at 15%, and nuclear generation at 41% (Fig. 3.2).

Netherlands and Sweden: Very Different Experiences

European countries combine a range of environments, resource endowments, and historical experiences with abundant quantitative information that makes it possible to reconstruct their long-term energy trajectories, while modern statistical sources allow for detailed post–World War II appraisals. Netherlands and Sweden differ greatly in most respects, most obviously as far as the prevailing ecosystems are concerned: one of the world's most intensively cultivated man-made agroecosystems vs. extensive boreal forest growing on rugged, recently glaciated, land. But these two relatively small economies have been among the leaders in technical development and innovation.

Netherlands

The Dutch case is so noteworthy because the country had experienced a highly idiosyncratic path to a high-energy society on two widely separate occasions. Holland, the country's key province, had undergone a very early, and a very atypical, energy transition during the 17th century, and I had already noted the exceptional post-1960 Dutch energy transition from coal to natural gas: here I will take a closer look at both of these transformations. The Dutch Republic (founded in 1581) was one of the great pioneers of adopting fossil fuels and inanimate sources of energy, and it had done so in two rather uncommon ways, by large-scale production of peat and by an extraordinarily high reliance on wind power.

Exploitation of these resources resulted in a relatively high per capita use of inanimate energies, enabled a high degree of urbanization (already more than 60% of people were city dwellers during the 17th century), powered the industrial development of the Dutch Golden Age, and provided the best explanation how a population of just 1.5 million people could "manage to play leading parts on almost every scene of human activities" (de Zeeuw 1978, 3) and enjoy by 1650 average annual energy consumption that was higher than India's average in the year 2000. Peat, the youngest fossil fuel, was the principal source of household and industrial heat (brewing, baking, brickmaking), and, fortuitously, every one of Holland's major cities had nearby resources that could easily be extracted and inexpensively transported. Peat's annual consumption during the 17th century averaged about 1.6 Mt (equivalent of about 25 PJ or nearly 800 MW), but coal and firewood were also imported, and Holland's windy climate and flat landscape provided excellent conditions for harnessing wind by sails and mills.

Assumptions and simplifications are needed to estimate the aggregate output of these two prime movers, and hence de Zeeuw's calculations (1978) must be seen only as revealing approximations. Some 3,000 windmills (with average power of 2.5 kW) generated less than 200 TJ (about 6 MW), and sailing ships contributed annually another 150 TJ (nearly 5 MW) of power. These are relatively small aggregates (each less than 1% of the peat's energy content), but they resulted in large savings of human and animal labor and reduced the amount of land needed for the animal feeding: replacing the windmills would have required at least 300,000 workers or some 50,000 horses, and feeding those animals would have claimed a sixth of the country's total area in addition to the existing crop fields. After the best peat deposits were depleted and shipping became more expensive due to extensive silting of shallow waterways and harbors, Holland ceased to be an exception, and its energy use began to resemble that of the neighboring countries.

Although coal was mined on a small scale in the southeastern part of Limburg province since the 16th century, most of the coal consumed during the 17th and 18th centuries was imported from Britain, Liège, and later also from Germany (van der Woude 2003). During the 17th century the imports were about 65,000 t/year, rising to more than 200,000 during the 18th century (Unger 1984). Imports of wood were not large (it would have been too expensive as household fuel) but were critical for such urban enterprises as bakeries and potteries in Amsterdam and Delft. According to van Zanden (1997) peat extraction still accounted for as much as 65% of all primary energy during the first decade of the 19th century, by 1840 coal's share reached 40% of all energy, and by 1860 it was 58%, but Unger (1984) concluded that coal and peat each supplied 50% by 1800.

As van der Woude (2003) made clear, despite a relatively large amount of available data on shipping, prices, and taxes, it is impossible to make any reliable reconstruction of pre-1850 energy consumption breakdown, but that did not prevent Gales et al. (2007) from recreating that breakdown on an annual basis starting in 1800 when they put the share of primary supply at roughly 35% for animate energies, 25% for peat, 20% for wind, and 10% each for firewood and coal. Leaving aside estimates for animate energies and wind (both entailing enormous uncertainties: see this book's second chapter), this implies a peat:coal:wood ratio of roughly 56:22:22.

Domestic coal became a notable contributor to the Dutch energy balance relatively late: large-scale commercial exploitation of Limburg coal began during the 1870s, and in 1902 a new state company (*Staatsmijnen*) was added to the basin's private collieries (IsGeschiedenis 2013). In 1910 coal provided 90% of all primary energy, peat just 5%, and crude oil imported from Sumatra (at that time part of the Dutch East Indies) about 3%. With the exception of World War II years the output of four state and eight private mines remained between 12–14 Mt/year between 1925 and 1967 (de Jong 2004). Domestic coal production reached the peak of about 14 Mt in 1937, it fell to less than 6 Mt by end of World War II, and then climbed back above 12 Mt during the 1950s when the competition from imported oil was making the future of South Limburg mines precarious, and after 1958 outright unprofitable.

The enormous Groningen gas field (extending over about 900 km^2) was discovered near Slochteren on July 22, 1959, and gas deliveries began in December 1963. The magnitude of this discovery—initially appraised at 60 Gm^3 but eventually raised to 2.8 Tm^3 or nearly 50 times the original estimate (Correljé and Odell 2001)—placed the field among the rarest of all hydrocarbon resource categories, that of supergiant natural gas fields (with reserves of at least 850 Gm^3). Groningen gas had truly revolutionized the country's energy balance because virtually all industries and households, as well as the expanding greenhouse cultivations of vegetables and flowers (van der Velden and Smit 2014), were converted to its consumption. And, as an additional benefit, part of CO_2 emissions from natural gas burned to heat greenhouses is used to boost the CO_2 content of their atmosphere to about 1,000 ppm (2.5 times the ambient concentration) in order to improve plant growth and greenhouse productivity (NGMA 2014).

Even after converting the Dutch economy to natural gas there has been still plenty left for exports, and the earnings from gas sales—recently on the order of $10 billion a year—made it much easier to end the Dutch coal mining. In December 1965 the Dutch government decided to phase out all of the coal mining in the Limburg province within 10 years; by the time the last two operating Limburg mines, the Oranje Nassau I and the Laura Julia, shut down in December 1974 Dutch mines extracted about 570 Mt of coal (de Jong 2004). These closures removed the economic basis for more than 200,000 people in one of the most densely populated regions of the country and did away with some 45,000 mining and 30,000 related jobs.

Largely successful countermeasures included subsidies for new industries and relocation of some government offices from the capital, and the *Staatsmijnen* (DSM after 1967) was given a major stake (40% share) in the Groningen's development and transformed itself into a producer of a variety of industrial and consumer goods (DSM 2015). Groningen gas production rose rapidly to more than 80 Gm^3 by the mid-1970s, and as a result the Dutch transition from solid to gaseous fuels was faster than in any other European country (Roels 2001). In 1950 coal supplied 83% of the country's primary energy and oil a bit less than 17%. By 1959, at the time of Groningen's discovery, Rotterdam became Europe's leading oil port and refinery center for the Middle Eastern oil, but the Dutch primary energy supply was still led by coal with about 55% of the total; crude oil delivered 43% and natural gas less than 2% of the total (UNO 1976).

Afterward the country not only converted rapidly to the new fossil fuel (Fig. 3.3)—a shift that was further aided by the belief that the gas should be produced and sold as fast as possible before the nuclear energy will soon become dominant—but it also began its large-scale exports to its neighbors. Dutch natural gas exports more than tripled between 1970 and 1973 to 33 Gm^3, reached 40 Gm^3 by 1980, and leveled off afterwards. In the year 2000 they were 24 Gm^3, a decade later nearly 33 Gm^3, and in 2015 they reached 40.6 Gm^3, all delivered by pipelines to Germany (importing 40% of all sales), Italy, UK, Belgium, and France (BP 2016).

Natural gas reached 1% of the country's primary energy supply in 1958; prior to the Groningen discovery this was methane recovered from coal mines. In 1965, when the decision was made to close down all of the country's coal mines, natural gas supplied 5% of the country's primary energy, by 1971 it rose to 30%, and by 1975, with almost 46%, it was only a couple of percent behind the imported crude oil. During the same time, coal's share fell from 26% to 2.5% (the small remainder being mainly coking coal for smelting iron). After its brief peak output of the mid-1970s Groningen extraction was deliberately restricted in order to extend the field's lifetime;

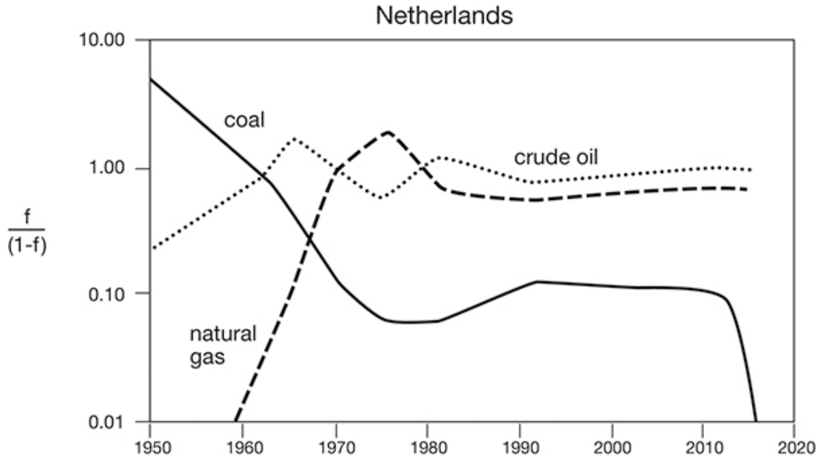

Figure 3.3 Fisher-Pry plot of the fossil fuel transition in the Netherlands, 1950–2015. Biomass and hydroelectricity make negligible contributions, and nuclear fission supplies less than 5% of all electricity. Data points calculated from statistics in UNO (1976) and BP (2016). Post-1975 stagnation of fossil fuel shares is obvious.

by 1990 more than half of Dutch gas supply came from smaller onshore and offshore fields, and Groningen's output fell to less than 30 Gm^3 by the year 2000 (Roels 2001).

By 2010 the production was back to 50 Gm^3, but that rise was short-lived and the field's future looks even less promising, not because of any unforeseen declines in its reserves but because of its declining ability to be the largest and most competitive source of seasonal flexibility in North West Europe (Norlen and Sutorius 2015). In order to limit the risk of local building-damaging earthquakes induced by gas recovery the Dutch government reduced Groningen's output to 16.5 Gm^3 during the first half of 2015, and in December 2015 a court-mandated order lowered the total for 2016 to 27 Gm^3. That will ensure the security of supply, but a nearly 50% cut compared to 2014 output largely eliminates the field's long-standing ability to act as a swing supplier of EU gas. Swing capacities from the British and Danish sources have also become virtually exhausted, Troll field remains the only option for Norway, higher LNG imports are possible but remain expensive, and hence it is most likely that Russian supply will increasingly fill Northwestern Europe's seasonal gas needs.

But the restrictions will prolong the Groningen's life: managed output would have always prevented the field's phaseout to be as steep as was its ramp-up, with the output peaking in 1976, during the 12th year of production, at nearly 90 Gm^3. Groningen's rapid development and the closure of all coal mines meant that after reaching 5% of the Dutch primary energy supply it took natural gas only a year to go to 10%, three years to reach 25%, and six years to 50%. In contrast, it took U.S. natural gas 20 years to go from 5% to 10% and 50 years to go from 5% to 25%, while the analogical Soviet spans were, respectively, just 8 years and 10 years. Until 2012 the outlook was another decade of extraction stabilized at about 47 Gm^3 and followed by a gradual decline to less than 10 Gm^3 by 2035 (OG 2012), but with the remaining reserves 650 Gm^3 as of January 1, 2015, there could be two more decades of production at about 25 Gm^3 followed by a gradual phaseout.

In any case, in the absence of rising imports the share of domestically produced gas in the nation's primary energy supply would keep decreasing: it has already declined from 40% in 2000 to 36% in 2014, and only extraordinary efforts aimed at raising the share of domestically produced renewables would prevent rising dependence on imports: Dutch net energy imports rose from 27% in 1990 to 40% by 2014 (IEA 2015b). In 2009 the official Dutch goal was to produce 20% of all primary energy used heat and electricity generation from renewable sources by the year 2020, and achievement that would have required annual output of about 670 PJ, with phytomass energies and wind each supplying about 40% of that total (ETB 2009). But five years after setting that goal renewable energies contributed just 3.3% of the country's primary energy supply (BP 2016).

Sweden

With small domestic resources of coal and with no hydrocarbons, Sweden energized its early modernization overwhelmingly with wood and, to a much lesser extent, with water power (Magnusson 2000). At the beginning of the 19th century imported coal accounted for a just a fraction of 1 percent of the total primary energy supply, but abundant wood supply put the average per capita energy use at the same high level as in England (Kander and Stern 2014). Afterward, the British supply rose rapidly, but the Swedish consumption had actually dipped a bit and it began to rise only after 1880. Wood was still nearly 90% of the total by 1870, and only during the first decade of the 20th century did wood's nationwide share fall below 50% (Energy History 2015).

But not in the countryside. Lindmark and Andersson (2010) showed that while the urban firewood consumption had leveled off after 1860 and then fluctuated around 1.5 m^3/capita a year (in 1920 it was 1.6 m^3), rural consumption rose after 1870 and then stayed at about 2.5 m^3 (in

1920 it was 2.6 m^3). With an average of four people in rural families that would amount to annual household consumption of about 10 m^3 or at least 90 GJ. But because the average household size decreased by a third during the 19th century (at its beginning it was six people), the per capita growth of firewood consumption was much higher than the gain in average household consumption.

Abundant wood supply converted to charcoal could also support a large-scale iron production based on excellent domestic ores and oriented toward exports. The world's oldest documented blast furnace began to operate during in the second half of the 12th century in Lapphyttan in the mining region of Norberg (Rydén and Ågren 1993). Swedish iron exports went initially through Danzig, after 1620 mostly through Dutch ports, and by the 1650s England became the leading buyer (Evans, Jackson, and Rydén 2002). Swedish iron exports averaged about 40,000 t/year during the 1740s, and they dominated the British imports until the 1760s (King 2005).

With British coke-based smelting ascendant, those exports ceased during the 19th century, but Swedish iron producers did not switch to coke. Arpi (1953) estimated that by 1850 a quarter of the country's wood harvest was converted to charcoal; half a century later the fuel remained dominant but its use became much more efficient. In the early 1800s it was not uncommon to consume 8 kg of charcoal for every kg of iron, but a century later the best Swedish furnaces required less than 0.8 kg of charcoal per kg of hot metal (Greenwood 1907). By 1930 wood's share was down to about 36%, but it rose once again during World War II when the limited domestic coal mining rose temporarily above 0.5 Mt/year.

Wood consumption fell rapidly right after the war, and coal followed after 1950 as oil imports soared: in 1970 nearly 75% of all primary energy came from oil, less than 10% from wood. OPEC's first round of oil price increases led to the reversal of newly acquired oil dependence. Although the Swedish program was not as transformative as the French expansion, the country built six reactors during the 1970s and another six during the early 1980s (WNA 2015c). But after the Three Mile Island accident in the United States in 1979 a national referendum in 1980 stopped any further nuclear expansion, and Riksdag set 2010 as the year of eliminating all nuclear power. By 1990 nuclear electricity supplied 30% of the country's primary energy, but during the 1994 election campaign the Social Democrats promised to phase out one nuclear reactor while in office. Barsebäck 1 (boiling water reactor) was shut down in 1999, followed by Barsebäck 2 (another BWR, which had a grade 2 incident on IAEA's seven-point International Nuclear Events Scale in July 1992) in 2005.

At that time Norway was trying to promote large-scale exports of natural gas as an obvious substitute for reduced nuclear generation (Löfstedt1997). That did not happen: by 2015 natural gas was just 1.5% of the Swedish primary energy supply. Instead, 1.2 GW of capacity lost by the closure of Barsebäck reactors was more than replaced with additions of 1.050 GW to the remaining reactors by 2008 and with another 569 MW commissioned by 2014. The remaining 10 reactors had also improved their capacity factors (Forsmark to more than 90%, national mean to 78%), and nuclear electricity generation rose from 54 TWh in the year 2000 to 55.6 TWh in 2010 and 62.2 TWh in 2014 (Svensk Energi 2015). Oskarshamn 2 was the third reactor to be closed (in 2015), and the intended decommissioning of the remaining units is between 2017 and 2045 (WNA 2015c). But the intended 2010 nuclear phaseout has not been the only great miscalculation along Sweden's energy transition trajectory.

Since the 1970s successive Swedish governments have been outlining bold plans for the transformation of the country's energy supply, and the country's scientists and engineers have been publishing even bolder scenarios for future energy transitions. The first such plan was to make Sweden a leader in the commercialization of a fast breeder reactor—until the reality intervened and the pursuit was ended in the mid-1970s (Fjaestad 2015). In 1978 Johansson and Steen (1978) identified a transitional path that was to energize Sweden solely by domestic and renewable sources by the year 2015 when half of the country's primary supply was to come from energy plantations covering 6%–7% of the nation's territory. Even more audaciously, Swedish wetlands were to be turned into an important source of pelleted reed phytomass (Björk and Granéli 1978). In the new "solar Sweden of 2015" energy inputs were to be only electricity, methanol, wood, and heated water (Lönnroth, Johanssonan, and Steen 1980).

In reality, there was no change in the share of energy supplied by wood during the 1980s, but during the 1990s willows became the species chosen for new mass tree plantations. *Salix viminalis* was to be harvested for the first time 4–6 years after planting and afterward every 3–4 years for at least another 20 years (Helby, Rosenqvist, and Roos 2006). Wood combustion was to be used for district heating and in combined heat and power electricity generation plants. New tree farms received subsidies of 10,000 SEK/ha at planting, and in 1998 the Swedish Environmental Protection Agency expected more than 100,000 ha to be in production by 2005 and the total of nearly 400,000 ha by the year 2020. But after reaching about 14,000 ha by 1996, willow plantations stopped expanding and, not surprisingly, there has been no mass production of pelletized reed phytomass either.

The next big promise came in February 2006: the minister for sustainable development Mona Sahlin announced that Sweden aims to become the world's first oil-free country by 2020, and to do so without any nuclear generation (COI 2006). She justified the goal by referring to the tripling of oil prices between 1996 and 2006: "A Sweden free of fossil fuels would give us enormous advantages, not least by reducing the impact from fluctuations in oil prices." Critics have conceded that the goal might be possible for heating but not for industrial and transportation uses, and the intervening plans make it clear that the chance of having no nuclear generation by 2020 is nil.

In fact, in June 2016 Sweden abolished the nuclear capacity tax that will make large investments, needed to extend the lifetime of nuclear reactors, possible, and upgraded reactors (with independent core cooling) at Forsmark and Ringhals stations should be able to operate until the mid-2040s (WNN 2016). And while Sweden's oil consumption declined by about 18% between 2005 and 2015, it still accounted for 27% of all primary supply and nuclear generation supplied 24%: to be free of oil and without any nuclear generation the country would have thus to convert about half of its primary energy supply to renewable energies in just six years, obviously an impossible goal.

United States and Russia: Energy Superpowers

They were the two leading ideological opponents during most the 20th century, but the two countries share not only rich resource patrimonies but also some important historical traits, none more nation-forming than the expansion into "empty" territories, eastward into Siberia and Central Asia for Russia, westward of the Mississippi and the Rockies for the young United States. In energy terms, both countries have a rich history of pioneering technical achievements, including the launching of modern oil industries, state-sponsored construction of giant hydroelectric dams, and economic development based on excessive use of abundant domestic resources. The last trait is readily seen by their relatively high rates of per capita energy use and high energy intensity of their economies.

But differences are profound, arising, above all, from deep history of Russian autocracy and U.S. democracy, from the seven decades of Communist rule in Russia and from different orientation of economies (America's consumer society vs. decades of Stalinist militarized economy). Moreover, the modern development of Russia and the United States started at very different levels. The prerevolutionary Russia was far behind the United States in terms of energy consumption, the country's tipping point from wood to fossil fuels and primary electricity came only during the Soviet era (about half a century after coal surpassed wood in the United States), and the overall Soviet per capita energy consumption, and even more so the discretionary energy use by households, have never approached U.S. levels.

United States

America's historical statistics offer a comprehensive basis for following the changing composition of primary energy supply but also the shares of mechanical energy supplied by various prime movers. Data for the American transition analyses are taken mainly from the *Historical Statistics of the United States, Colonial Times to 1970* (USBC 1975) and Schurr and Netschert (1960), and secondarily from Daugherty (1928) and Milici (2003) and from many series maintained on-line by the U.S. Energy Information Administration. The United States is also one of a few countries where we can rather accurately follow the prime mover transitions in agriculture, while other data make it possible to trace the replacement of open-hearth steelmaking by electric arc furnaces and the displacement of steam engines by diesel locomotives on the country's railways (Sharif and Kabir 1976). Studies of long-term U.S. energy transitions include Daugherty (1928); Schurr and Netschert (1960); Hunter (1979); Perelman, Giebelhaus, and Yokell (1981); Hunter and Bryant (1991); Ayres, Ayres, and Warr (2003); and O'Connor and Cleveland (2014).

America's transition from wood to coal was delayed due to the country's extensive forests and low population density. America's commercial coal mining began in 1758 with a small shipment of Virginia coal to Manhattan, and Pennsylvania (with bituminous coal and anthracite) and Ohio, the other two states with extraction going back to the 18th century, were soon joined by Illinois and Indiana. Production estimates begin in 1800 when the three states in the Appalachia mined about 100,000 t of coal (Eavenson 1942). Coal extraction supplied 5% of the total primary energy output by 1843, and the subsequent rise of coal was rapid, reaching 10% of all fuel energy supply just eight years after it passed the 5% mark, 20% share in two decades, in 1863.

For some parts of the country with the oldest European settlements this transition was an environmental salvation. On March 6, 1855, Henry David Thoreau (1817–1862) noted in his diary that "our woods are now so reduced that the chopping this winter has been a cutting to the quick. At least we walkers feel it as such. There is hardly a wood-lot of any consequence left but the chopper's axe has been heard in it this season" (Thoreau 1906, 231).

In 1700 Massachusetts's forest cover was about 85%, but by 1870 the combined demand for fuelwood, construction, and ship timber reduced it to only about 30% (Foster and Aber 2004). Coal reached a third of the total primary energy supply just before 1875 and half of the total in just over four decades after it passed the 5% mark. In 1884 coal contained more energy than wood, and by 1900 the U.S. coal industry produced two-thirds of all fuel energy.

America's commercial crude oil extraction began on a very small scale—15 barrels (about 2 t) a day from a single well—in 1859 at Oil Creek near Titusville, PA (Owen 1975). Then it grew very rapidly, from less than 300 t in 1859 to about 70,000 t a year later, to nearly 300,000 t in 1861, to more than 700,000 t in 1870, 3.6 Mt in 1880, and close to 9 Mt in 1900. By that time Pennsylvania's production—mainly from the country's first giant oilfields in Bradford (discovered 1875) and Allegany (since 1879)—was supplemented by extraction from California's Brea-Olinda (since 1884) and McKittrick (since 1887) and Corsicana field (drilled in 1894) in Texas. Oil supplied only 0.6% of all energy derived from fossil fuels in 1860, its share rose to 1% in 1870 and 4.4% by 1880, and by 1900, as natural gas began to make its first inroads, it fell to about 3.1%.

But because wood was the country's leading fuel until the early 1880s (and it still provided just over 20% of the total by 1900), oil's contribution to the total primary energy supply remained marginal, rising from a mere 0.1% in 1860 to 0.3% in 1870, 1.9% in 1880, and 2.4% in 1900. American oil production intensified right at the beginning of the 20th century as new giant oilfields (California's Kern River, discovered in 1899, and Midway-Sunset in Texas, with its famous Spindletop gusher, drilled in 1901) began their production (Linsley, Rienstra, and Stiles 2002). Discovery of the state's biggest field, the East Texas in 1930 (followed by the West Texas in 1936) led to supply glut and the enforcement of production quota by the Railroad Commission of Texas whose monopoly lasted until 1971 (RCT 2015).

In 1900 the United States had only seven giant oilfields; by 1925 there were 75, by 1950, 220. Consequently, there were no resource limits on extraction, and it rose rapidly, driven by the demands of mass car ownership, expansion of shipping, use of oil for industrial and domestic heating and for electricity generation required by the wartime effort. World War II was the first major conflict in which the U.S. forces were energized primarily by refined oil products. In relative terms oil supplied 7.1% of America's fossil fuels (and 6.1% of all primary energy) in 1910, the two shares rose to 12.5% and 11.2% by 1920 and to 20.6% and 18.5% by 1925. Crude oil began to supply more than a quarter of America's primary energy by 1933 and more than a third by 1948.

After World War II the pace of new major oil discoveries slowed down dramatically, with Alaska's North Slope being the only giant find of the 1960s. The U.S. oil extraction peaked in 1970 with about 535 Mt and afterward, although it remained the world's third largest, the country became increasingly dependent on imports. But the downslope of the extraction curve did not mirror its ascent: Hubbert's (1956) often-cited production curve anticipated annual production of 1.2 billion barrels in 2000, but the actual rate was 2.8 billion barrels, nearly 2.5 times higher, and the output in 2008 was almost 70% above the rate forecast for that year. And because the declining domestic production was promptly supplemented by increasing crude oil (and refined products) imports, there was at first no, and later only a slight, decline in terms of the relative contribution of liquid fuels to America's primary energy supply: the share was about 43.5% in 1970, 43.6% a decade later, and in 2008 it was still 38.5%.

By 2008, when the output was only as high as it was in 1947, a new extraction technique began to make a difference only a few years after the beginning of its routine commercial use in Texas (PWC 2013). This technique combined two established processes—horizontal drilling and hydraulic fracturing—to extract oil from abundant deposits of oil-bearing shales. First, the output decline that began in 1971 was reversed, and production rose by nearly 7% in 2009; economic downturn nearly stopped its rise in 2010 (just 2.2% up) but the next four years saw annual increase of, respectively, 3%, 15%, 15%, and nearly 17%. In 2015 U.S. crude oil output was 567 Mt, about 5% ahead of Russia's production and virtually identical to the Saudi extraction (BP 2016). Hubbert's curve for U.S. oil became bimodal with a new peak close to the 1970 record. This led not only to substantially declining imports but, in December 2015, to the lifting of the 40-year-old ban on crude oil exports (Harder and Cook 2015), and it also kept the overall U.S. oil supply at a high level, providing about 36% of all primary energy in 2015.

Extraction of natural gas could not begin on a larger scale without long-distance pipelines, but once the fuel's share reached 5% of all primary energy (in 1924) it expanded nearly as fast as the oil production: just 11 years later it was at 10%, after 27 years at 20%, and in 1957 natural gas surpassed 25% of the country's primary energy production. Consumption trend was very similar, and it kept rising until 1972 when it peaked at about 32.5%—but, as with crude oil, this was not followed by any precipitous retreat. The fuel's share declined to just below 23% by 1990, and then it settled on only a slightly fluctuating plateau before horizontal drilling and hydraulic fracturing began to make the difference three years before it started the crude oil turnaround.

In 2005 U.S. natural gas production was 17% below its peak in 1973, only as high as it was in 1968; in 2006 it made a slight, 2.5%, gain, but then it kept on rising, unaffected by the 2008–2010 recession, to reach a new record in 2011 and a new high in the next four years. In 2014 natural gas extraction was 42% above the 1973 peak, and 2015 set another record, about 5% above the 2014 total. Again, a new production technique invalidated another supposedly unerring Hubbert's curve, and commenced another wave whose rise decisively surpassed the previous crest. As a result, natural gas supplied 29% of the country's primary energy in 2015, a higher share than in 1975.

Fisher-Pry plots of America's primary energy consumption show a steady post-1850 ascent of coal and corresponding decline of wood use and the peak coal share (at nearly 77% in 1910) followed for the next 50 years by a decline that was almost a perfect mirror of the late-19th-century ascent. By 1960 coal's share was down to less than 22%, but then its retreat slowed down and after reaching a low of just over 16% in 1976, it began to recover and by the century's end it stood at nearly 23%. But as shale gas began to provide less expensive, and considerably cleaner, fuel, coal use in electricity generation began to decline, and this retreat was the main reason why the fuel's share of primary energy supply fell to 21% in 2010 and to 15.5% in 2015, and why in the first quarter of 2016 U.S. coal extraction declined to its lowest level since 1981.

But despite all of these changes, and also because wood consumption has remained fairly steady after 1960, we have a remarkable phenomenon of established sources of America's primary energy not deviating too far from their specific consumption shares for more than 50 years: coal was 22% in 1960 and almost 16% in 2015, oil's shares were at 36% and 35%, natural gas supplied 27% and 29%, and hydro energy contributed 4% and 3% (Fig. 3.4). Importance of these new plateaux is highlighted by comparing the current shares with those that would have followed if the fuels continued on their pre-1970 trajectory: by 2010 coal would have been down to only about 3% of the total primary energy supply, oil would have supplied no more than about 20%, while natural gas would have claimed about 75% of the market, all very different from actual outcomes.

Nor has the nuclear electricity generation conformed to the clocklike substitution model (Cantelon, Hewlett, and Williams 1991; CSIS 2013; Smil 2003). Fission was seen as the sector's ultimate savior since 1954 when Lewis L. Strauss, at that time the Chairman of the U.S. Atomic Energy Commission, told the National Association of Science Writers in New York that nuclear electricity will be "too cheap to meter" (Strauss 1954). But the industry had slow beginnings during the 1960s, based on deploying a

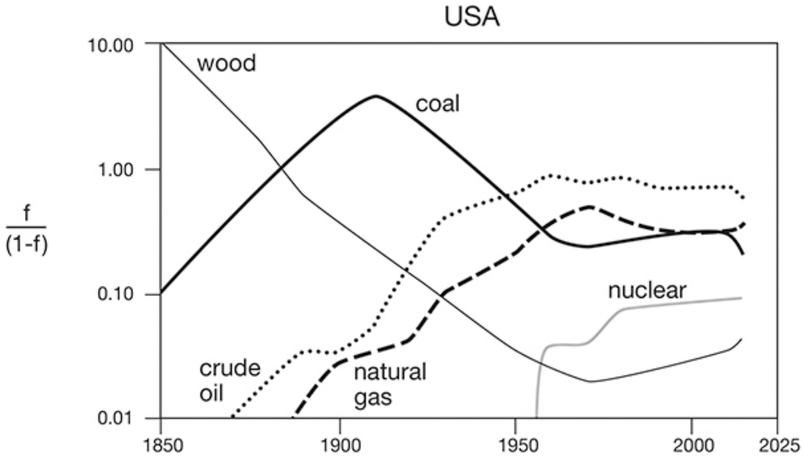

Figure 3.4 Fisher-Pry plot of the primary energy transition in the United States, 1850–2015. Data points calculated from statistics in Schurr and Netschert (1960) and USEIA (2016). Shares of all fuels have seen some ups and downs but had changed little since 1960.

modified version of the submarine reactor, far from the best possible design to maximize the economy and safety of plant operation.

Major construction delays during the 1970s and the end of all new nuclear power plants orders in 1978 preceded the Three Mile Island accident that did not result in any release of radioactivity into the atmosphere but that had dented the confidence in the industry's long-term safety and strengthened the argument against further development of nuclear generation. But the accident was not the key turning point. Nuclear retreat had, above all, reflected a profound change in the electricity market, from decades of annual 7% growth (doubling every 10 years) to growth rates on the order of 1%–2%, including some years of no growth.

In 1974 General Electric, the country's largest supplier and innovator in the electricity sector, envisaged that not only all U.S. generation would be nuclear by the year 2000 but that about 90% of it would be supplied by fast breeder reactors. But the last U.S. experimental breeder reactor was shut down in 1982, long before reaching any commercial capability (Cochran et al. 2010). Construction improvements during the 1980s made it possible to complete most of the stations ordered before 1979 by 1990 (but the last reactor at Watts Bar station of the Tennessee Valley Authority, begun in 1973, was connected to the grid only in 1996); none of those much-expected second or third generation of improved, inherently safe reactors made its appearance. Any subsequent generation gains came from improved performance of aging reactors as the share of nuclear electricity rose to 4% by 1980 and 8% by 2000 and since that time has remained close to that level.

American statistics also allow us to trace the transitions in the final uses of fossil fuels (Schurr and Netschert 1960; USBC 1975; many USEIA databases). In 1900 75% of all coal was burned to produce heat for industries, institutions, and households, about 20% were used to power mobile steam engines, and less than 1% went to generate electricity. In 2000 nearly 90% of all coal was consumed in electricity generation and less than 10% to produce heat; by 2014 power plants consumed 96% of all shipped coal, but, as gas-fueled generation rose, the share of electricity generated by coal declined to less than 40% (38.6%) compared to 45% in 2010 and 56% in 2000 (USEIA 2015a).

Refined oil products have seen a similar decline in uses for heat, and their rising prices have made them too valuable to be used in large-scale electricity generation: their contribution peaked in 1978 when they generated nearly 17% of U.S. electricity, and then it fell to less than 3% in 2000, and less than 1% by 2015. High energy density of refined fuels made them the leading energizers of transportation: in 1900 that sector claimed less than 10% of their total supply, by 2000 it was about two-thirds, and in 2015 it was above 70%. Only the final uses of natural gas have not undergone any major transformation, with heat production claiming more than 90% in 1900 and about 80% a century later. Thereafter a shift away from coal led to the rise of natural gas used for electricity generation: 35% of all gas went to power plants in 2015 (USEIA 2015e).

American statistics also offer a unique opportunity for a fairly reliable quantification of the shifting shares of prime movers. Starting in 1849–1850 they provide the total power of draft animals and of all inanimate prime movers disaggregated as automotive engines, electricity-generating equipment, machines in factories, mines, and on farms, engines on railroads, ships, and aircraft as well as sailing vessels and windmills (Daugherty 1928 USBC 1975). The two data series are in a reasonably close agreement as far as the total power of working animals is concerned. Daugherty (1928) puts it at about 5.8 GW in 1849 and 16.8 GW in 1899, the U.S. Bureau of the Census (1975) at 4.4 GW in 1850 and at about 14 GW in 1900, differences of, respectively, about 30% and 20%; I will use the more conservative series.

In 1850 draft animals accounted for about 70% of the country's total prime mover capacity; their share fell below 50% during the early 1870s as the steam engines (mostly on railroads but also in factories and on ships) became the dominant prime mover. By 1900 the aggregate power of draft animals fell to just below 30% of the total, and after 1910 its decline accelerated as internal combustion engines had the highest aggregate capacity of inanimate power, followed by steam turbines in electricity-generating plants. Aggregate power of draft animals claimed just 1% of the total by 1930 and less than 0.2% by 1950 (Fig. 3.5). As for the total power of all prime movers (excluding human labor), it rose from about 6.3 GW in 1850 to nearly 48 GW in 1900, 355 GW in 1950, 26 TW in 1990, 38 TW in 2000, and 65 TW in 2010.

Automotive engines have accounted for more than 90% of these totals since 1940, after rising from just 0.15% of the total in 1900 (when steam engines and draft animals were dominant) to 50% by 1917 and to 85% by 1930. Most of the 2.5-fold aggregate power increase between 1990 and 2010 is explained by the rising vehicle power of cars in general and SUVs in particular. In 2014 SUVs surpassed four-door sedans as the best-selling vehicles and claimed nearly 37% of all sales (WSJ 2015). As a result, average power of light-duty vehicles rose by about 90% in those two decades, compared to just 30% increase in total road vehicle registrations.

I have used the best available U.S. statistics to calculate a more relevant indicator of the prime mover transition, namely the shares of actually performed useful work, and I include human labor in this account. These calculations yield different shares than do the capacity numbers because

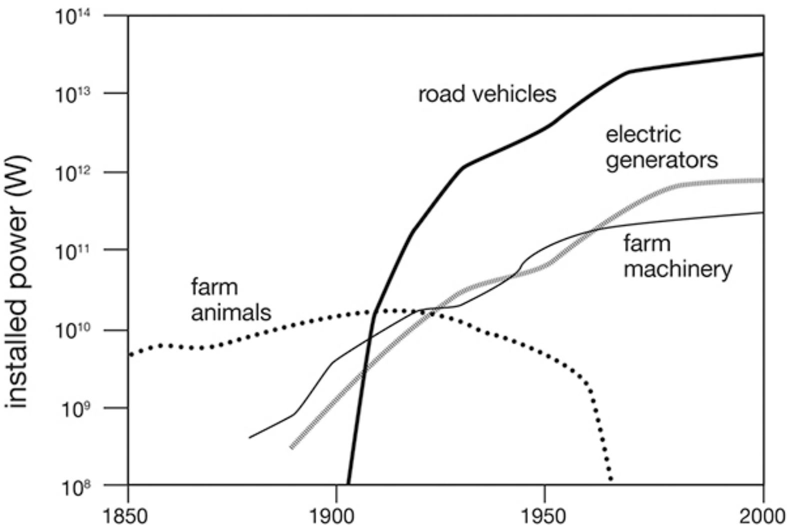

Figure 3.5 Capacity of animate and inanimate prime movers in the United States, 1850–2000. Plotted from data in USBC (1975) and USEIA (2016). Dominance of automotive engines is due to their very large numbers, now in excess of 250 million.

the typical annual load factors of prime movers range from as little as 200 hours for car engines and about 1,000 (800–1,200) hours for draft animals to more than 6,000 hours for large steam turbogenerators. My estimates indicate that in 1850 nearly half of America's useful power was provided by animals, roughly a sixth by people, and just over a third by inanimate prime movers, mostly by steam engines complemented by water wheels, water turbines, and windmills.

By 1900 human contribution declined to only 5%, animal work (despite a large increase in the total number of working horses and mules) fell below 20%, and steam engines and water turbines provided at least 75% of all useful power. By 1930 animate exertion supplied only some 3% of all useful power, and internal combustion engines delivered more than a third of all useful inanimate power. By 1950 people and working animals contributed no more than 1% of all useful work, and mass car ownership translated into more useful energy delivered by automotive internal combustion engines than by all other, mobile and stationary, prime movers.

But the situation was different on the country's farms. Total number of horses and mules on America's farms rose from about 5 million in 1850 to about 20 million by 1900, and it peaked in 1918 at 26.72 million, but by 1940 there were still more than 13 million of draft animals (USBC 1975). As a result, the combined power of inanimate prime movers in agriculture surpassed the power of draft animals only at the beginning of the 1920s; by 1930 machine power was about 60% of the total, a decade later 80%, by 1950 it reached 90%, and by 1960 there were still more than three million horses on U.S. farms, but their aggregate power was only about 1% of the total. The transition from animate to inanimate prime movers was accomplished—its Fisher-Pry plot shows the expected fairly straight lines—and the USDA stopped counting the draft animals.

The last important case of American energy transitions I will consider is that of nonfossil sources of electricity generation. As already explained, thermal and hydro generation began simultaneously in 1882, and by 1890 water power produced about 25% of the total output of approximately 1 GWh; 60 years later the total rose to nearly 400 GWh, and water power (whose share rose to as much as 35% during the first two decades of the 20th century) remained as important as in 1890 with 26% of the total. Its relative decline began only during the 1950s, thanks to a rapid expansion of fossil-fueled generation, a process that continued during the 1960s (by 1970 coal-fired generation was 4.5 times the 1950 level, and the multiples for oil- and natural gas-fired generation were, respectively, about 5.5 and 8.3) when two new sources of electricity production—nuclear fission and geothermal steam—began to make small inroads.

Geothermal generation remained quite marginal (its share has never surpassed 0.5% of the total), but nuclear power, after passing the 1% mark in the first quarter of 1970, ended the decade with a nearly 11% share. Completion of many nuclear plants and better performance of established reactors pushed the share steadily upwards during the 1980s and the early 1990s, and it touched the 20% mark in 1995 before stabilizing at just below that level. As a result, by the year 2000 fossil-fueled generation—largely coal-fired (73%), with natural gas at 22%, and liquid fuels at just 5%—was relatively more important (with about 72.5% of the total) than it was in 1900 when its share was about 65%.

While nuclear generation became a major component of the country's electricity supply, the most remarkable fact concerning the U.S. electricity system during the 20th century was a highly conservative nature of its development: fossil fuel–based and hydro generation accounted for 100% in 1900 and for about 80% by 2000. This inertia is even more remarkable given the fact that those two modes of electricity generation had expanded about 650 times during the 20th century, from less than 5 GWh to nearly 3 TWh. But the shift is now underway: by 2015 fossil fuels and hydro supplied about 73% of U.S. electricity (almost 10% less than in 2000) as new renewables (wind and solar) produced nearly 7% of the total (USEIA 2015a).

Russia

Tracing Russia's energy transition is much more challenging than dealing with America's energy trajectory. The two principal reasons are inferior statistics (both in terms of availability and quality) and territorial changes. Czarist Russia kept basic accounts, but its statistical sources were generally less abundant, and their continuous series began later than in Western Europe or in the United States, while the Soviet data were known for their limited availability and questionable quality. In the USSR many basic figures were categorized as state secrets during the Stalinist era, and many more were released as propaganda tools, not as reflections of reality. Fortunately, basic output data for fuels and electricity are much less in doubt than, for example, the levels of GDP, and there is no shortage of rich technical information for the post-1960 years.

History of the Russian Empire (pre-1917), of the USSR (beginning in 1917 with the Bolshevik takeover, in 1921 with the formal constitution of the Soviet Union), and the new Russian Federation (following the dissolution of the USSR in December 1991) presents numerous challenges of adjusting statistics due to changing territorial extent and population counts. But these changes did not have a major effect on tracing the country's grand transition from wood to fossil fuels because in most of the territories under its control they had taken place relatively late: wood dominated until the end of the 19th century, and its share fell to less than half of all primary energy only after World War I during the time of the Soviet power (1917–1991), the era for which fairly reliable fuel and annual electricity statistics were available from the USSR's Central Statistical Office (*Tsentral'noie statisticheskoie upravlenie SSSR*).

Despite some early exploitation of coal, peat, and oil, the Russian Empire was an epitome of wooden society. Local, small-scale coal mining was done in several regions of European Russia during the 18th century, by 1801 at least 25 sites were exploited, and Siberia's major coalfield (centered on Kuznetsk) was discovered in 1826 (Ministerstvo Energetiki 2016). Oil deposits in the Caspian Sea (Baku) and north of the Caucasus (Maikop) were the sites of some of the world's first drilling and refining efforts (starting, respectively, in 1848 and 1854 and hence predating the U.S. activities; see Fig. 2.4). But aggregate extraction of fossil fuels during the first half of the 19th century remained limited, and it amounted to a tiny fraction of U.S. output.

In 1850, when the United States mined more than 7.5 Mt of coal, Russia produced only about 56,000 t, roughly a 500-fold difference in per capita terms. And in 1913 the U.S. per capita output of fossil fuels was 20 times the Russian extraction of coal and crude oil. During that last peaceful year before the upheavals of World War I Russia produced nearly 30 Mt of coal, 10 Mt of oil, and less than 2 Mt of peat, an equivalent of about 1.3 EJ of primary energy (or 8.2 GJ/capita) compared to U.S. extraction of fossil fuels that added up to 17.6 EJ or 181 GJ/capita. Russia thus remained a wood-based economy for much longer than the major Western European economic powers.

Much like contemporary Sweden, northern and central European Russia and Siberia were virtually 100% wooden societies until the 1850s, while villagers in the southern, steppe zones, of Ukraine and the southern Volga basin also burned a great deal of cereal straw. Data assembled by Kafengauz (1994) show that during the late 1870s 71% of the country's industrial boilers were fueled by wood and that wider industrial adoption of coal and oil came only during the 1880s when the completion of railway lines from the Donetsk coal basin and rapid increases of Caspian oil extraction made the fuels more readily available. That was the time of rapid economic expansion (industrial growth as much as 8%/year between 1888 and 1900), with coal output quintupling and oil production rising nearly 20-fold during the century's last two decades (Kafengauz 1994).

But insufficient information prevented Kafengauz (1994) from reconstructing total fuelwood consumption during the closing decades of the 19th century, and his published totals refer only to wood used by railways and industries. Those totals amounted to 4.97 Mt of coal equivalent in 1887, 6.68 Mt in the year 1900, and 9.7 Mt in 1913 or, respectively, to about 144, 194, and 281 PJ of wood energy, and they would have supplied about 56%, 30%, and 20% of the country's total primary energy during those three years. That this represented only a fraction of the country's total wood use is readily apparent when comparing the average per capita consumption with fairly reliable U.S. figures that include all fuelwood.

Russian consumption of 194 PJ of fuelwood in 1900 prorates (with 118 million people) to just 1.6 GJ/capita (or only about 100 kg), while at that time the much more advanced and considerably more industrialized U.S. economy averaged about 28 GJ of wood per capita, nearly an 18-fold difference. No inhabitants of typical village or small-town houses could survive the Russian winter by burning less than 2 GJ of wood a year per capita. Even a small house in the northern part of European Russia or in Siberia required at least 100 GJ/year: recall that in 1850 U.S. households averaged no less than 100 GJ/year, and Swedish data (for a milder climate) show average rural per capita consumption of 2.5 m^3 (solid) during the closing decades of the 19th century (Lindmark and Andersson 2010), or at least 20 GJ/capita.

Given the absence of any published data or estimates, I have done an approximate reconstruction of Russia's total fuelwood use, and my best estimate is that in 1900 (with at least 25 GJ/capita for 100 million people) wood still provided no less than 75%–80% of Russia's primary energy, and that the aggregate consumption of fossil fuels and primary electricity surpassed that of fuelwood only during the early 1930s (compared to the U.S. tipping point half a century earlier in 1884/1885). Stalinist industrialization of the 1930s (between 1928 and 1938 coal output rose by about 360% and oil extraction was up by 260%) had finally reduced wood to no more than a third of all primary energy, and its share fell below 10% during the 1950s when the USSR began its rise to become the world's leading energy producer and exporter.

Russia's oil production surpassed coal extraction already by 1890 and in 1899, with just over 9 Mt/year, the country became briefly the world's largest producer of crude oil, but most of it was exported by foreign investors who dominated its extraction (Samedov 1988). Because of these relatively large exports domestic consumption remained low: in 1900 it was only about 10% higher in energy terms than the total coal combustion. Baku production began to decline after 1900, and by 1913 it was two-thirds of its 1901 peak and Russia's coal consumption was more than twice as large as its oil use. By 1950 this difference was roughly 4.5-fold, and coal remained the largest contributor to the Soviet primary energy supply until

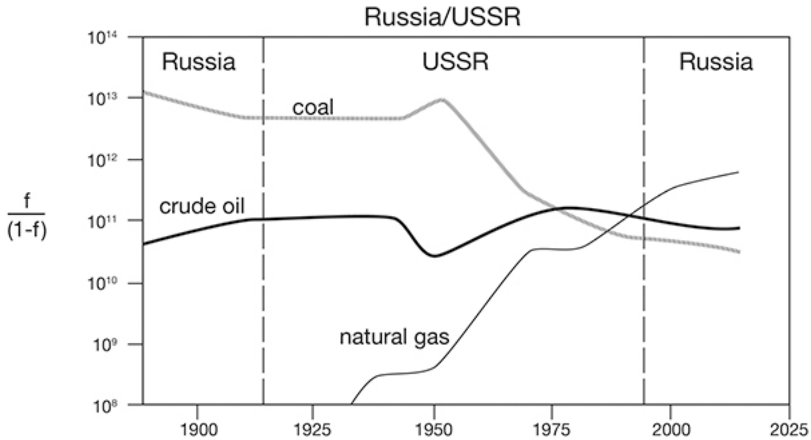

Figure 3.6 Fisher-Pry plot of the primary energy transition in the Russian Empire, the USSR, and the Russian Federation, 1900–2015. Data points calculated from statistics in TsSU (1977) and BP (2016). Wood was the largest source of primary energy until the late 1920s, but as there are no reliable statistics of its use, and as hydro and nuclear generation supply each only about 5% of the total, the plot shows only fossil fuels.

1974 (or nearly three decades longer than in the United States) when it was finally surpassed by crude oil (Fig. 3.6).

By the time of the USSR's dissolution in 1991 coal contributed just over 20% of the Soviet energy use. The post-Communist era has been marked first by repeated strikes, chaotic coal industry privatization, and closures of old inefficient mines, and then by frequent changes of ownership and mergers within an unstable industry. This combination of events has had a largely negative impact on the level of Russian coal production (Ignatov & Company Group 2009). While the country's coal reserves (particularly in Siberia's Kansk-Achinsk basin) remain enormous, coal's share in primary energy supply has been declining since 1991, and by 2015 it accounted for less than 15% of the total (Fig. 3.6).

Coincidentally, 1974, the year when oil use surpassed coal consumption, was also the year when the Soviet crude oil extraction surpassed the U.S. total and the USSR became the world's largest oil producer, the position it occupied until 1991. This distinction was achieved thanks to two successive spatial transitions experienced by the Soviet oil industry. Baku produced 75% of Russia's oil in 1913, and still nearly 72% of all Soviet oil in 1940, but by 1960 its share was down to about 12%. The "second Baku"—the Volga-Urals region where oil production began in 1929, the first giant oilfield (Tuymazy) was discovered in 1937 and the second one (Romashkino) in 1948—became dominant during the 1950s, and it produced 70% of the Soviet oil by 1960.

The second shift began with the discoveries of supergiant fields in Western Siberia, an oil-bearing province twice the size of Alaska. The first indication of that basin's hydrocarbon riches came with an accidental gas and water gusher right at the outset of drilling R-1 Beryozovo well in September 1953 (Karpov 2008). Principal discoveries came only during the early 1960s with the discoveries of supergiant Samotlor and Ust'-Balyk in 1961 and Mamontovo in 1965 (Li 2011). These fields were rapidly developed and connected by long-distance pipelines to the European USSR and to Central and Western Europe, and their output still dominates the Russian extraction.

As a result, the Soviet oil production nearly quadrupled during the 1950s, and then it more than doubled (growing roughly 2.4 times) during the 1960s so that even with rising exports oil's share of domestic primary energy consumption rose from 16% in 1950 to 26% in 1960 and 34% in 1970. Oil's contribution peaked between 1974 and 1983 when it reached a brief plateau of between 35%–37%, and natural gas became the country's leading primary fuel in 1984 (Fig. 3.6). Discoveries of the world's largest gas fields in Western Siberia—Urengoy in 1966, Yamburg and Yubileinoye in 1969—made the USSR, and then Russia, the world's largest repository of gaseous fuels: in 2015 Russia's gas reserves accounted for about 17% of the world total, a higher relative share than the Saudi share of global oil reserves. Their rapid development more than quadrupled the Soviet gas output during the 1960, more than doubled it during the 1970s, and nearly doubled it during the 1980s (CIA 1978; Kortunov 1967; Ministerstvo Energetiki 2016; Smith and Thomas 1982).

USSR became the world's largest natural gas producer by surpassing the United States in 1983, and for the rest of its existence it also remained by far the world's largest gas exporter as most of the European countries had gradually become dependent on pipeline deliveries from Western Siberia. Even with these large export commitments the USSR was able to boost its share of gas consumption from just below 10% of the total in 1960 to just over 20% a decade later and then to 32% in 1980 and 41% in 1990—and the fuel became even more prominent in post-1991 Russia where its share rose to nearly 55% by 2015 (Fig. 3.6).

History of the USSR was shaped by grandiose electrification plans. Lenin's famous dictum that Communism equals the Soviet power plus electricity was put into practice by the establishment of State Commission for

Electrification of Russia (GOELRO) and its plans for expansion of both thermal hydrogenating capacities (Nesteruk 1963). Projects completed during the pre–World War II years also exacted a high price in terms of human suffering and death (many were built with the forced labor from GULag). Even more grandiose plans followed after World War II but, fortunately, only some of them were realized: perhaps the greatest unrealized project was, thankfully, the Stalinist diversion of great Siberian rivers to the arid core of Soviet Central Asia.

Soviet achievements have been particularly notable in developing the country's hydro generation potential. With 852 TWh considered economically feasible, it had the second highest capacity (far behind China and ahead of Brazil) in the world (Nesteruk 1963; WEC 2016). Pre–World War II hydro capacities rose from just 16 MW in 1913 to nearly 1.6 GW by 1940, and the postwar growth brought them to about 15 GW by 1960, 52 GW by 1980, and 85 GW by 1990. The Volga-Kama dam cascade harnessed 11.5 GW and the Angara-Yenisei dam cascade—including Bratsk (4.6 GW, completed in 1967) and Krasnoyarsk (6 GW, operating since 1964) and Sayano-Shushensk (6.4 GW since 1978)—totals 22 GW (RusHydro 2016). The USSR also had the world's highest dam, 300-m Nurek on the Vakhsh River in Tajikistan with 3-GW capacity.

But given the country's large fossil fuels consumption even such a vigorous development of hydroelectricity has not made an exceptional difference: water power's share rose from just 0.5% of all primary energy in 1950 to 3.8% by 1970, and then it remained at that plateau until 1991. Soviet electricity generation remained dominated by large central stations with turbogenerators of up to 800 and 1,200 MW, the largest station with capacities in excess of 2 GW, and with high-voltage transmission lines throughout European Russia from the White Sea to the Black Sea and extending from western Ukraine to central Siberia, spanning five time zones.

And despite some early bold plans for its development, the USSR's nuclear electricity generation, made infamous by the catastrophic accident of Chornobyl reactor in the Ukraine in 1985 (Bariakhtar 1995; IAEA 2006; WHO 1991), never became as important as the hydroelectric generation. A small 5-MW experimental Obninsk reactor was the world's first nuclear installation to produce electricity in 1954, but the first Soviet commercial plant began operating only in 1963, seven years after the British Calder Hall. By the year 1990 14 plants located mostly in Russia and Ukraine supplied 3.4% of the Soviet primary energy. In post-Communist Russia the nuclear share has been somewhat higher, but at about 6% in both 2010 and 2015 it was still less than hydroelectricity's contribution (WNA 2015d).

But Ukraine now has (after Chornobyl's closure) 15 working reactors, and it derives about 45% of its electricity (and 20% of all primary energy) from fission.

History of the Soviet energy consumption is one of impressive absolute gains as total domestic energy supply increased from 1.1 EJ in 1913 to 59 EJ in 1990 (a nearly 54-fold expansion) and as annual per capita use had tripled from about 70 to more than 210 GJ. But the country's energy transition has been very idiosyncratic, with its long dominance by coal, decades of relatively high share claimed by oil, and the post-1970 shift toward natural gas. Setting fuelwood aside, coal was about 63% of the Soviet consumption in 1930 and 61% in 1960, crude oil was 35% in 1930 and 30% in 1960, and natural gas rose from just 8% in 1960 to 39% by 1990. Post-1990 Russia has been more dependent on natural gas (and hence it generates less carbon per unit of its overall fossil fuel consumption) than any other large economy: in the year 2000 52% of its modern primary energy came from natural gas, and the shares were 55% in 2010 and nearly 53% in 2015. For comparison, in 2015 the natural gas shares were 20% in the United States, 21% in Germany, and less than 6% in China.

Exports of Russian natural gas rose to nearly 210 Gm^3 by 2015, and almost160 Gm^3 went to the countries outside of the former USSR, with Germany and Italy being the largest EU buyers (Gazprom 2016). Gazprom now supplies about 40% of the EU's total gas consumption, extending the reach of the Russian influence all across the continent leading to arguments about the risks of this dependency and about the ways to reduce its extent (Dickel et al. 2014). For Russia there is the well-known downside of excessive dependence on exports of hydrocarbons, with nearly 70% of the country's foreign earnings coming from their sales. And this abundance of the cleanest of all fossil fuels has slowed down Russia's adoption of new renewables: by 2015 the country had only minuscule capacities for solar and wind generation.

Japan and China: Asia's Leaders

The two countries that share so much (from ancient beliefs and sign script, *kanji* being the most extensive part of Japan's triply-complex writing system) have also differed in so many ways. These differences became particularly consequential during the late 19th century when they searched for their own paths to modernity. Japan, after its forced opening to the West in 1853, embraced—selectively but enthusiastically—many Western ways, while China's reformers could not set that weakened and seemingly spent empire on a new course (Esherick and Wei 2013). The culmination of this divergence came in 1895 when new Japan won its first military victory by defeating much larger but weaker China (Jansen 2000).

During the first half of the 20th century both countries had lost in both economic and human terms, China due to long civil war (following the Qing dynasty demise in 1911) and the Japanese aggression, Japan due to its delusionary quest for Asian supremacy that ended in total defeat in 1945. Then the paths diverged again, as Japan embarked on what was, up to that time, the fastest economic modernization while China had to endure three decades of misery under the Maoist rule. In 1980, four years after Mao died, Deng Xiaoping began to steer China along an accelerating modernization path that had (when measured in purchasing parity terms) increased the country's GDP 60 times between 1980 and 2015 and made China the world's second largest economy. Meanwhile Japan, after reaching the apogee of its economic power in 1989, slipped into decades-long pattern of stagnation and under-performance, a shift that may be replicated in China. Obviously, energy use reflected all of these ups and downs.

Japan

The Japanese case is noteworthy not only because of the country's unique history (nearly 250 years of pre-1853 isolation), rapid rate of its modernization, and the size of its economy, but also because of it extraordinarily high dependence on imports. South Korea (with the world's 13th largest GDP in 2015) aside, no other major economy has so few domestic resources. Japan's energy transition followed the Western pattern—but it did so at a distinctly accelerated rate. This compression was initially the function of Japan's delayed modernization: when Commodore's Perry naval ships landed in Japan in 1853 the isolated country ruled by the xenophobic Tokugawa shōgunate was a traditional society powered by human labor, by combustion of wood cut in mountainous regions and converted to charcoal, and by burning of rice straw and other crop residues in intensively cultivated lowlands.

After Meiji restoration (resumption of imperial power and the transfer of the capital from Kyōto to Tōkyō in 1867) the country pursued a broad-based program of modernization, and energy transition had to be one of its critical components. Progress of Japan's industrialization and militarization was so rapid that 10 years after it defeated China Japan was once again victorious in 1905 after a longer conflict with imperial Russia (Jansen 2000). Japan's historical statistics contain a complete energy balance series starting in 1880—when wood and charcoal supplied 85% of all primary energy, coal 14%, and oil just over 1%—and hence they allow us to quantify the country's grand energy transition from its early stages (Bank of Japan 1999; IEE 2015; JSA 1987–1988).

Coal consumption surpassed biomass energy in 1901 (when it claimed 57% of the total vs. about 39% for wood and charcoal), and rapid pre–World War II industrialization increased the aggregate energy use about 2.6-fold between 1920 and 1940, with the biomass share falling to only about 10%, coal (after peaking at about 77% in 1917) to about 66%, and hydroelectricity rising to 16% of the total. Defeat in World War II cost the country dearly: in 1946 energy use was 55% below the 1940 peak, and the prewar level was not surpassed until 1955. By that time Japan's swiftly rising oil imports were shifting the country's primary energy use toward hydrocarbons: oil use surpassed coal energy in 1961 (with nearly 41% vs. about 39%; it was also the year when the domestic coal production peaked at about 55 Mt), by 1970 it reached almost 72%, and three years later it topped 77% of the total energy supply, a relative peak that was virtually identical to that reached by coal in 1917.

In 1974 (following the OPEC's first period of rapid oil price rise) oil imports declined for the first time since 1946, and deeper reductions followed after 1977: in 1982 Japan imported 25% less oil than in 1973. After a short period of stagnation import growth resumed in 1987, a new record was set in 1997, but by the century's end the oil import was only 15% above the 1980 level, by 2010 it was below it, and by 2015 Japanese oil imports were (despite the intervening loss of nuclear electricity generation) 24% lower than the record rate. Oil's falling share of primary energy consumption has been accompanied by steadily rising shares of imported LNG, from 6% in 1980 to 14% in 2000 and nearly 23% in 2015.

And much like France and Sweden, Japan chose to rely on nuclear generation in order to reduce its high dependence on imported energy. The first commercial reactor at Tōkai was the British gas-cooled design; all other installations have been BWRs and PWRs, including Kashiwazaki-Kariwa, the world's largest nuclear power plant built between 1985 and 1997 on the coast of the Sea of Japan (installed capacity of 7.965 GW in seven reactors). In 2010 Japanese reactors produced nearly 30% of the country's electricity (and 13% of its primary energy), but all of them were shut down in the aftermath of the March 2011 Fukushima Dai-ichi accident (level 7, the highest, on the INES scale) that followed the Tōhoku earthquake and tsunami (IAEA 2015).

Once again, Fisher-Pry plots of Japan's post–World War II energy transition do not indicate any inevitable, preordained trends (Fig. 3.7). Even during the pre-1973 period when inexpensive crude oil exports were surging, coal's share was not correspondingly plummeting (the fuel was

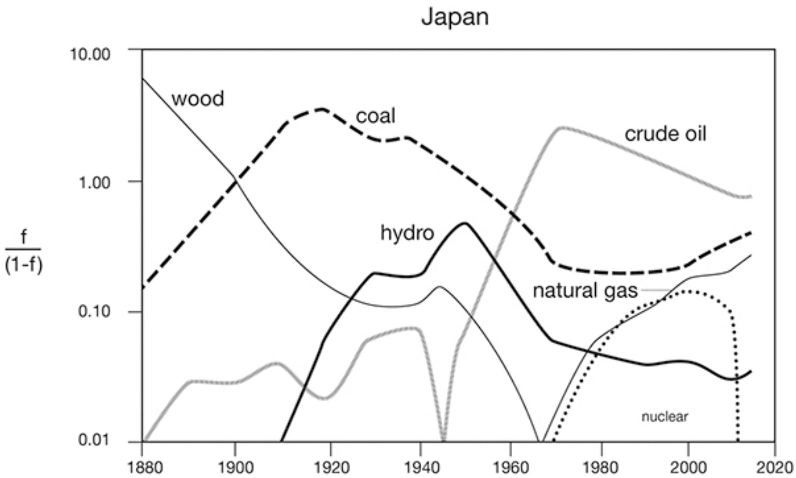

Figure 3.7 Fisher-Pry plot of the primary energy transition in Japan, 1880–2010. Data points calculated from statistics in JSA (1987–1988) and IEE (2015). A highly idiosyncratic transition pattern, with only natural gas and coal recently ascendant.

needed for electricity generation and to produce coke for the country's large iron industry), and it had actually increased between 1980 and 2010 (by about 40%, from 17% to 24%) and afterward it rose even further (to nearly 27% in 2015) due to the need to make up the lost nuclear generation. In contrast, until 2010 oil share has been retreating steadily after reaching its peak in 1973, but in Fukushima's aftermath it rose again nearly 10% to 42% in 2014. Growth rate of LNG imports was almost matching the rise in oil imports during the 1970s; it slowed down considerably during the 1980s, and after growing steadily it doubled between 1995 and 2015, reaching about 23% of primary energy.

And there is nothing on the immediate energy horizon to displace these three fossil fuels. Japan's short streams offer no untapped possibilities for major hydro projects, and water power's share has been declining steadily since the end of World War II, from nearly 40% in 1946 (an anomalously high share due to the wartime destruction of other components of Japan's energy supply) to about 15% by 1960 and to less than 4% since the year 2000. Bold plans for further nuclear expansion (generating 40% of all electricity by 2017, 50% by 2030) were shelved after Fukushima: the best that can be now hoped for is a gradual restart of most of the 43 operable reactors shut down in 2011 (five were restarted by August 2016).

A notable characteristic of Japan's energy transition has been the country's rising dependence on imported fuels. At the beginning of the 20th century Japan's energy imports were less than 4% of the total supply; by 1940 crude oil and refined products still accounted for no more than 7% of the total. After the immediate postwar low of just over 2% the 1940 share was reached again by 1950, by 1960 imports surpassed 50%, and since 1970 they have been above 99% of the total supply, and their composition and magnitude have changed substantially. In 1970 Japan imported about 26% of its natural gas, 57% of its coal, and 100% of its oil consumption: by 2010 all of these shares were virtually 100%, and total imports rose by more than 70% from about 10 EJ in 1970 to more than 17.3 EJ by 2010 and nearly 18 EJ in 2015. This near total dependence on imports creates a particularly daunting challenge of replacing foreign fossil fuels by domestically harnessed renewable energies.

China

China has the earliest documented use of coal (in iron smelting) going back to the end of the Han dynasty. Coal was packed around tube-like crucibles filled with iron ore, and the liquid iron was cast into interchangeable molds to produce plowshares, thin-walled cooking pots, and pans (Needham 1964). Although locally important, coal was not widely used, and even after modern coal production began during the 1880s its growth was slow and for decades it remained dwarfed by biomass energies. Given China's large rural population this demand was always large in absolute terms, but per capita energy consumption of fuelwood and straw was always only a fraction of European rates because many regions have been deforested for centuries, and because recurrent droughts and poor harvests limited the supply of crop residues.

Ensuing rural energy shortages were widespread even at the beginning of China's current modernization drive. The first series of rural energy surveys done across China in 1979 set the average daily requirements at just 3.25–3.75 MJ of useful energy per day per capita (Smil 1988). Given the average combustion efficiency of about 10% this implies annual per capita combustion of less than 13 GJ of biomass fuels, equivalent to only about 800 kg of woody biomass or nearly 900 kg of crop residues. In contrast, preindustrial fuelwood use in the forest-rich United States averaged annually about 90 GJ/capita. But the 1979 surveys showed that even the minimum energy needs were not often met, with the average supply shortfall amounting to just over 20%.

In 1980 it was estimated that 500 million peasants (63% of the total) suffered from serious fuel shortages for at least 3–5 months of the year, and by 1982 the nationwide share was still nearly 50%, with the highest rates, in excess of 60%, in the worst affected provinces of Xinjiang, Hebei, Hunan, and Sichuan and in the most densely inhabited parts of Tibet. By the late 1980s rural energy shortages were much reduced thanks to the rising output of coal from small local mines, return of privately owned wood groves, and improved stove designs that raised typical efficiencies from just 10%–15% to 25%–35% (Smil 1988).

My approximate reconstruction of China's primary energy use shows the share of biomass energies fairly constant during the first half of the 20th century, falling only marginally from more than 99% in 1900 to nearly 98% by 1949. Rising coal output lowered it to about 60% by 1957 and to 50% by the mid-1960s. But in the countryside crop residues and woody phytomass still supplied about 90% of all household energy use during the early 1970s, and this share fell to below 70% by 1980, below 50% by 1988, and to 33% by 1998 (Fridley et al. 2008; Zheng 1998). In terms of the total primary energy supply, biomass provided about 40% in 1970 and no less than 28% in 1979. By 2000 this share was more than halved to 13% and by 2015 it fell below 5%.

China's tumultuous modern history—collapse of the last imperial dynasty, subsequent loss of central government control, war with Japan (1933–1945), and the protracted civil war between the Nationalists and the Communists (1927–1936, 1945–1950)—prolonged the country's transition from biomass to fossil fuels and hydroelectricity: it took about 65 years for these modern energies to progress from 1% to 50% of the total primary energy supply (1900–1965). Only then the pace of substitution speeded up as the biomass energy share was reduced to 25% in less than 20 years (1965–1983), but the reduction from 25% to 10% took more than two decades (1983–2006). In absolute terms this means that in 2006 China's biomass energy was 25% above the 1980 level and the highest ever in China's long history, amounting to nearly 200 Mt of oil equivalent. The post-2006 surge in fossil fuel consumption reduced the share of traditional biofuels to less than 5% of the total by 2015, that is, to a level comparable to the U.S. share.

China's post-1949 transition from biomass to fossil fuels was dominated by coal (China Energy Group 2014; NBS 2015). China's case is an excellent illustration of slow pace of energy transitions as well as of the imperatives of scale: the country's demand for energy has been so large and its huge coal resources could be tapped so readily that it has proved very difficult to displace the fuel that is not only inconvenient to handle but whose combustion causes severe air pollution and whose extraction (particularly in small rural mines) has been uncommonly deadly. During the early years of the 21st century accidental deaths in China's coal mines were about

37 times the U.S. mean (Wang et al. 2011). In 2014 the official claim was less than 1,000 fatalities, but that still was (per t of extracted coal) nearly 15 times the U.S. rate (USDL 2015).

Total coal output in mines opened with foreign investment surpassed 1 Mt by 1903, in 1911 it was just over 5 Mt, during the early 1930s (before Japan's invasion of Manchuria in 1933) it was approaching 30 Mt, and in 1940 it reached about 46 Mt. In 1949, when the Communist Party took control, coal output was only about 32 Mt (Thomson 2003). China's first Stalinist five-year plan boosted the extraction to 130 Mt by 1957, and a key goal of Mao's infamous Great Leap Forward was to produce more coal and steel than the UK. Grossly exaggerated official claims had the coal extraction reaching nearly 400 Mt by 1960. Whatever the real total, most of this fuel was of inferior quality, and it was largely wasted in the Maoist campaign of iron smelting in primitive "backyard" furnaces whose diversion of labor from farming was a principal reason for the world's largest man-made famine (Smil 1999).

After the Leap's collapse coal production returned to more orderly ways, with output rising to about 350 Mt by 1970 and surpassing 600 Mt by 1978 when Deng Xiaoping set China on the road toward post-Maoist modernization. During that year the country also resumed its regular statistical reporting, and all post-1978 outputs and shares reflect these official figures (NBS 2015). China's post-1980 record of economic growth would have been impossible without abandoning the key Maoist precepts—and without continuous dependence on coal. So much has changed in China since 1980, but high reliance on coal has remained a fundamental constant, and so has the questionable quality of China's national statistics.

In the early 1950s China derived more than 95% of its primary commercial energy (leaving biomass contributions aside) from coal, and the share was still over 90% by the end of the first five-year plan in 1957. After the supergiant Daqing oilfield went into production, coal's share decreased to about 86% in 1965 and to 72% by 1975. During the first years of China's post-1980 modernization coal's share actually rose to about 76% by 1985, declined to 69% by the year 2000, and a decade later, as China's coal extraction had more than doubled in 10 years, it was at 68%. New coal output records were set between 2011 and 2013, but the production fell by nearly 2.5% in 2014 and, again, by more than 3% in 2015. But in September 2015 the National Bureau of Statistics revised, without any explanation, its previous data on energy content of produced coal (up to 14% higher than originally reported) and on annual extraction between 2000 and 2013, with new totals up to 7% higher (USEIA 2015f). Obviously, these revisions affect the totals of primary energy supply, and they also slightly elevate coal's shares in it.

In 1980, at the beginning of economic modernization, China's coal share was at nearly 72%, and by 2010 it was still at 69%. China's extraordinary dependence on coal means that the country now accounts for more than 40% of global extraction, and that the mass it produces annually is larger than the aggregate output of the United States, India, Australia, Russia, Indonesia, and Germany, the world's second to seventh largest coal producers. No other country is as coal-dependent as China: the fuel has recently accounted for 95% of all fossil fuels used to produce electricity, and with thermal generation supplying nearly 80% of the total it has been the source of more than 75% of electric power.

Due to its minimal consumption of liquid fuels, China was self-sufficient in crude oil between the mid-1960s (when it produced less than 15 Mt/year) and 1992 when it extracted about 142 Mt, exported 39 Mt of crude oil and refined products, and imported about 28 Mt. Imports remained low, below 50 Mt/year, until 2000; by 2004 they surpassed 100 Mt and by 2015 they were about 335 Mt, making China the world's second largest buyer of oil after the United States and twice as large as Japan (BP 2016). In addition, between 2000 and 2015 China's domestic crude oil extraction rose by nearly a third to just over 215 Mt/year—but even this combination of growing production and rising imports could not prevent the oil's share of primary energy supply from falling from the peak of 22% at the beginning of the 21st century to about 18% in both 2010 and 2015.

Although China was the world's earliest user of natural gas, the country's gas resources have turned out to be relatively limited when compared to other countries with large territories and with extensive hydrocarbon-yielding sedimentary basins. In 2015 Russia had about 16% of the world's natural gas reserves, the United States about 5.5% but China (with the territory only a few percent smaller than the United States) had less than 4% (BP 2016), with most of them located far from the main coastal markets. But a new assessment of potential gas resources raised the previous (2007) total by 158%, including a 127% increase of exploitable resources (China Daily 2016).

But, so far, domestic natural gas production has been only a small contributor to the country's primary energy supply: it rose above 1% of the total only in 1971, and it was just 2% in the year 2000. Subsequent gas consumption rose largely due to increasing imports, first (starting in 2006) by LNG tankers (from Australia, Indonesia, and Qatar; China has now 13 receiving terminals) and then (starting in 2012) by pipelines from Myanmar and, above all, from Central Asia. Three parallel pipelines bring gas from Turkmenistan, Uzbekistan, and Kazakhstan to China's Xinjiang. As a result, gas supplied 4% of all primary energy in 2010 and almost 6% in 2015, still far below the Russian, U.S., or EU shares. In 2014 a long-term deal was signed with Russia to import natural gas from Eastern Siberia (Chayanda field in Sakha, formerly Yakutia) and Kovykta (west of the Lake Baikal) starting in 2018 (Itar-Tass 2014).

But China has the world's largest potential water power capacity, and its development brought its share of the total primary energy supply from less than 2% during the early 1950s to 5% by the late 1980s. Subsequent development of large hydro projects (including Sanxia, the world's largest hydro station on the Chang Jiang in Hubei with installed capacity of 22.5 GW) helped to increase water power's share of the much expanded primary supply to 7% by 2010 and 8% by 2015. Hydroelectricity thus remains much more important than nuclear generation: many bold plans for its development have remained just that, and its share reached only 1% of the total in 2015.

Unlike in all other major economies where the combined shares of crude oil and natural gas are now more than half of all primary energy supply (more than three-quarters in Russia, nearly two-thirds in the United States and Japan, close to three-fifths in the EU countries), China (where oil and gas remained below 25% of the total by 2015) has thus accomplished only the transition from biomass to coal. Moreover, given the magnitude of the country's recent coal dependence (with domestic extraction nearly tripling from 1.38 Gt in the year 2000 to 3.97 Gt in 2013), there is no early prospect for hydrocarbons surpassing coal's contribution.

Although in absolute terms all fuels have been recently consumed at record levels and at per capita consumption rates unprecedented in China's long history, China's relative dependence on coal (with all environmental, safety, and logistics implications such a dependence implies) is also much higher than it was at the outset of Deng Xiaoping's reforms in 1980. At that time coal supplied no more than 55% of all primary energy (including all biomass), while in 2010 it was (again, including all primary energies) nearly 65% of the total (Fig. 3.8). China thus presents an even stronger case of arrested energy transition than does the United States where coal's share (when all fuels are included) had remained fairly stable during the same three decades: in China's case coal's share had actually risen by almost 20%!

To a large part this was driven by the necessities of China's rapid economic modernization, but that process has been also accompanied by excessive growth of industrial capacities (particularly of steel and cement) and capital expenditures on often underused infrastructures (also causing unprecedented levels of air pollution). Eventual reduction of these excesses has been only a matter of time, and the restructuring process had finally begun in 2014: annual growth of coal output slowed down from nearly 10% in 2011 to less than 1% in 2013 and, as already noted, the output

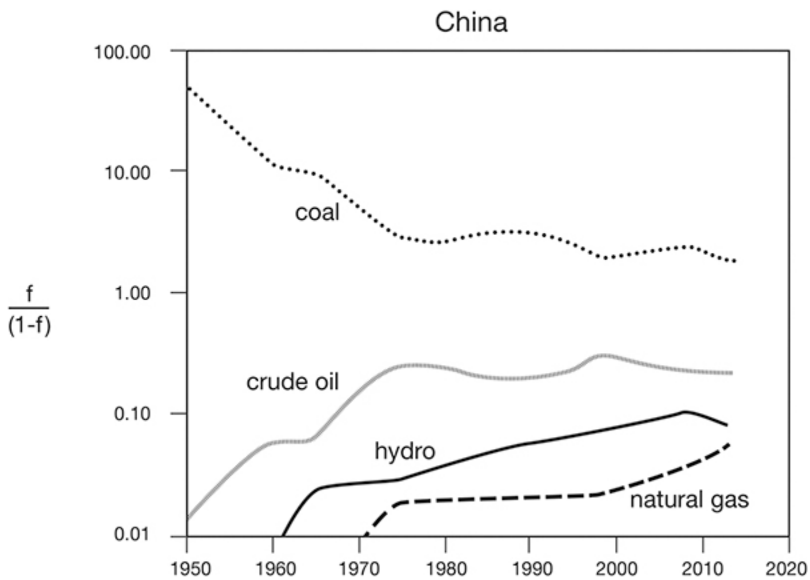

Figure 3.8 Fisher-Pry plot of the primary energy transition in China, 1950–2015. Data points calculated from statistics in Smil (1976), Fridley et al. (2008), China Energy Group (2014), and NBS (2015). Another highly idiosyncratic pattern of a national energy transition marked, once again, by a notable post-1970 stagnation of coal and oil shares.

declined by about 2.5% in 2014 and more than 3% in 2015, and in 2016 a new official plan aims at eliminating 500 Mt of surplus coal capacity by 2020 (Reuters 2016).

Changing Patterns: Commonalities and Exceptions

The shift away from traditional biofuels shows an expected advantage of later starters: it has been accomplished faster by countries where it began more recently than in nations where it started before 1850. Once coal established a foothold in the market by providing at least 5% of all primary energy it took only three decades to claim 50% of the supply in Asia's late-start modernizers (Japan and China), but more than 50 years in the case of vigorous 19th-century modernizers: 55 years in the United States and Sweden. The span was about 70 years for Russia/USSR, a delay attributable to the economic disruptions caused by the 1917 revolution and its long aftermath; otherwise the country would have reached the 50% mark at least a decade sooner. And the 5%–50% rise took more than a century in France and even longer in the UK (Fig. 3.9).

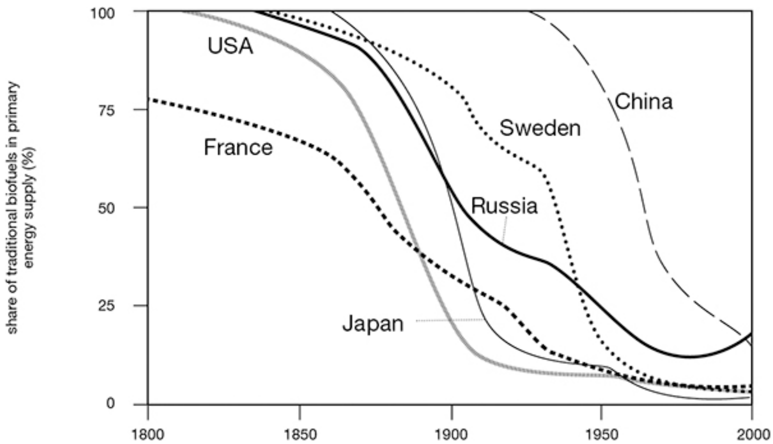

Figure 3.9 Grand transition from traditional biofuels to fossil fuels, 1800–2000. Plotted from data used to construct Figures 3.2 to 3.8.

At the same time, coal trajectories have shown clear national idiosyncrasies. We now have two completed coal extraction histories, for the Netherlands and for the UK (Fig. 3.10). Setting the disruptions caused by economic crises and World War II aside, the Dutch extraction curve forms a blunted bell-shaped curve whose down-slope is steeper than its rise, a consequence of deliberate closure of coal mines following the discovery of Groningen gas. The British curve is entirely sui generis. We cannot accurately reconstruct its centuries-long ramp-up, but its long rise from the early 18th century to the 1913 peak and its subsequent demise are well documented and result in a nearly perfect bell-shaped curve, with 80 years needed to reach the peak once the annual output from deep mines passed 25 Mt (in 1833) and 85 years to lower the output back to 25 Mt (by 1998).

The U.S. coal extraction was in retreat by the end of World War II, but the loss of its two largest traditional markets (railroads and heat for industries and households) was more than compensated by the demand for electricity generation that brought six decades of post-1950 output growth. But now, with natural gas ascendant in electricity generation, there is a high probability that the output of about 1.055 Gt in 2008 might be the all-time peak of American coal production (by 2015 the extraction was nearly 24% lower). China aside, coal's shares in primary energy supply of major economies peaked a long time ago but, at the same time, coal has not disappeared from national balances even in the Netherlands and the UK, the two countries that stopped mining it.

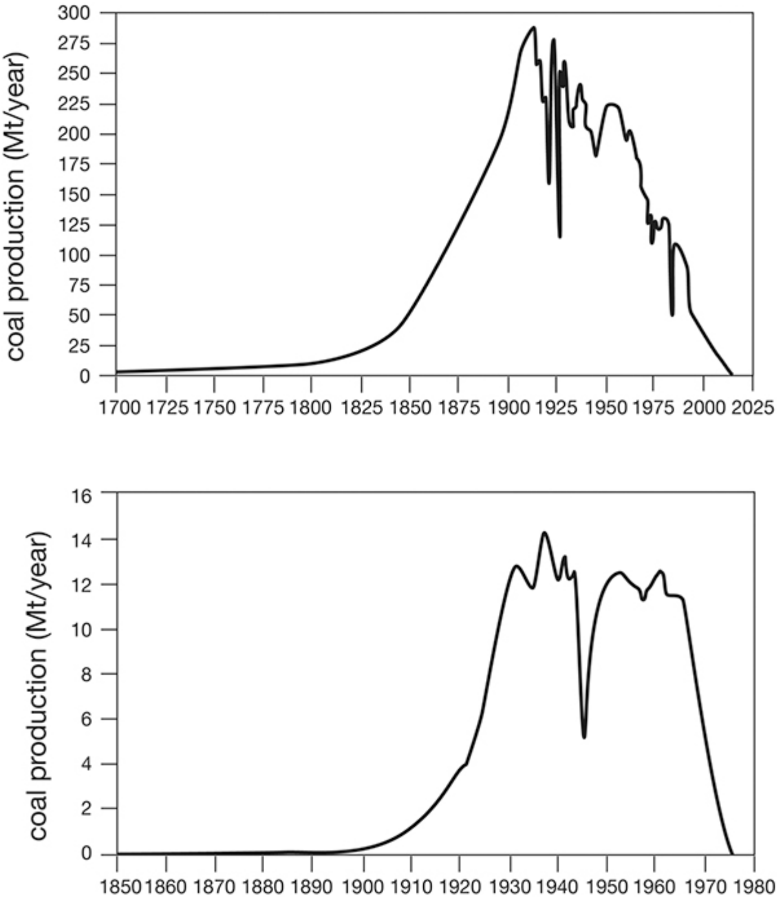

Figure 3.10 Complete curves of coal output in the UK and in the Netherlands. Plotted from data in Starr (2009), DECC (2015), and de Jong (2004).

As already noted, during its last 16 years the British deep coal production was surpassed by imports, and hence coal's share in the UK's primary supply was still at 20% in the year 2000 and just over 12% in 2015. Trajectories of coal shares in such disparate economies as France, the United States, and Japan show several remarkable commonalities: similar rates of fuel adoption, peak shares between 1910 and 1930, and fairly symmetrical declines until the early 1970s followed by slower retreats or even slight gains (Fig. 3.11). Russia and China have followed different paths. Coal shares in Russian energy supply fell as fast as they had risen, and they have been below the Western rates since the 1970s, while China's continuing high dependence on coal is declining slowly, from nearly 80% in 1975 to

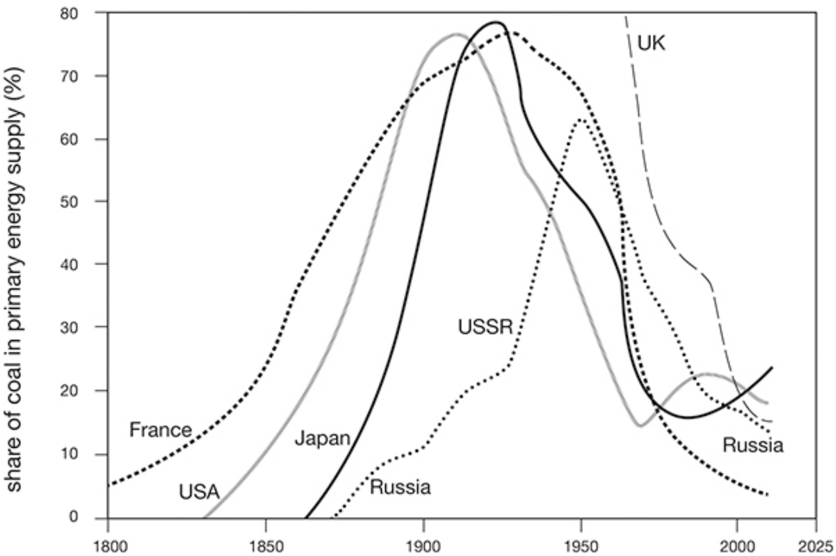

Figure 3.11 Coal shares in primary energy supply of the UK, France, United States, Japan and Russia. Calculated from data in sources listed in this chapter for specific national energy transitions.

65% 40 years later—but with concurrent enormous expansion in absolute terms.

For most economies transitions from coal to crude oil took place only after 1950: they were made possible by inexpensive Middle Eastern oil and by similarly inexpensive transportation in large tankers. The years when crude oil's share of primary energy supply had surpassed coal's contribution in major economies clustered mostly between 1963 and 1972: Japan in 1963, the Netherlands in 1964, France in 1965, Spain in 1966, Germany (Federal Republic) in 1968, and the UK in 1972. There were two classes of notable exceptions to this delayed transition, one including the three large economies (United States, USSR, and China), the other one composed of 20 Latin American states.

The United States and Russia (USSR), the two major economies with large domestic crude oil resources, did not have to wait for the post–World War II combination of cheap foreign oil and cheap tanker shipping to introduce larger shares of crude oil, but the pace of their transitions was determined by a variety of domestics factors. Both in the United States and the USSR natural gas emerged as a relatively early alternative to oil for domestic and industrial heating, while coal kept for decades its dominance in electricity generation. As a result, oil supply surpassed the coal's share only in 1951 in the United States and in 1974 in the USSR. Post-1949 Communist China did not participate in the global economy and hence it remained unaffected by the nearly universal shift to imported oil, and until the 1990s it relied overwhelmingly on its own relatively modest extraction.

In contrast, nearly all of the 20 Latin American countries experienced transition to crude oil about three decades in advance of the industrialized countries of Europe (Rubio and Folchi 2012). In some of these countries (including Mexico and Peru) the switch was sudden. In others (Ecuador, Venezuela) the transition went back to coal before oil finally prevailed, already in 1896 in Ecuador, 1903 in Haiti, 1906 in Nicaragua, 1915 in Mexico, 1918 in Venezuela, 1920 in Cuba, 1922 in Colombia, 1928 in Argentina, and 1940 in Brazil; only in Chile the switch came after World War II, in 1953. This sequence contains the principal explanation of the process (and the expected effects of path dependence): conversions were relatively easy in small countries that were importing both fuels, and they required more time in more advanced economies whose larger markets became more dependent on coal in earlier stages of development.

Transition to natural gas has been considerably slower than the switch to crude oil not only because of the intervening rise in aggregate supply (requiring larger inputs to achieve the same shares) but also due to the necessity to construct extensive infrastructures (pipelines, LNG supply). Again, the United States and the USSR/Russia stand apart due to their massive domestic resources, and smaller economies proceeded to adopt natural gas at a considerably faster pace than countries requiring large imports (and particularly those relying on expensive shipments of LNG). But in about 20 countries the gaseous fuel now supplies more primary energy than crude oil: most of them are major gas producers (and exporters), including Russia, Qatar, Iran, Nigeria, Brunei, Trinidad, UAE, Malaysia, Egypt, and Bolivia, but the group also includes Bangladesh and Pakistan, the two countries with very low energy use.

Finally, some remarks on the transition from low to high rates of average per capita consumption, that is, from preindustrial societies to either postindustrial or heavily industrialized economies. This indicator is much more idiosyncratic than is the sequence of primary energy substitutions because it is strongly influenced not only by the modernization process but also by prevailing climate (in cold-climate preindustrial societies household heating was either the largest category of wood and charcoal use or it was a close second to the demand of small-scale industries) and by population growth. Obviously, all else being equal, slowly growing populations can complete the transition considerably faster than those growing at high rates: China's rapid post-1980 rise in per capita use was greatly helped by the country's concurrent one-child policy (repealed only in 2015).

In 1850 only the UK was far along the industrialization path, with per capita consumption of primary energy at about 90 GJ/year, while the two heavily wooded countries in early stages of industrialization stood far apart: the United States, with about 110 GJ/capita, was ahead of the UK, but Russia's mean was only about 40 GJ/capita, less than half of the U.S. rate and similar to Sweden. Traditional biofuels energizing agrarian Japan and China provided less than 10 GJ/capita. And nation-specific growth rates are much evident during the following 100 years. The U.S. spurt between 1900 and 1910 (from 133 GJ to 189 GJ, more than a 40% gain in average per capita use) was driven by doubled consumption of bituminous coal and more than quadrupled supply of crude oil.

French per capita consumption rate—going up nearly 2.5 times during the latter half of the 19th century, from 18 to 74 GJ—reflected the efforts of an industrial late starter trying to keep up, unsuccessfully, with its more powerful eastern neighbor. In 1850 France was slightly ahead of (at that time still nonunified) Germany, 21 vs. 18 GJ/capita, but by 1900 the united Germany, at nearly 75 GJ, was about 50% above the French rate. Japan's near quadrupling of total primary energy use between 1900 and 1940 left the country at a still low level of nearly 40 GJ/capita but provided enough capacity for temporarily successful wars of aggression against China and the United States.

Only the post-1950 modernization imposed a clear general pattern: 1950s was a decade of strong growth in all modernizing countries, but it was far surpassed by the 1960s when average per capita energy consumption was up by a third in the United States, by nearly half in France, by two-thirds in Sweden, and when it had nearly tripled in Japan (from 38 to 111 GJ/capita). China's remarkable gains in aggregate energy use were set back by rapidly growing population, and it took nearly three decades to double the rate from almost 20 GJ in 1970 to 40 GJ/capita in the year 2000, but the next decade saw a near doubling to about 75 GJ/capita. Given an order of magnitude difference in total populations that was a feat much more remarkable than the Japanese per capita energy consumption growth of the 1960s.

This long-term comparison of per capita gains also indicates that this process is reaching the saturation stage. In most Western countries the slowdown in the growth of per capita primary energy supply (triggered by OPEC's quintupling of crude oil price in 1973–1974) began immediately after the record decade of the 1960s. By the century's end average per capita consumption rates in most mature EU economies were either only marginally higher or basically unchanged compared to 1980; the U.S. rate was 10% lower, while the British 2010 rate was not only lower than in 1970 (150 vs. nearly 170 GJ/capita) but it was almost exactly the same as in 1900. Of course, in terms of useful energy it was at least three times as high, yet another reminder that any simplistic comparison of even accurate gross values is misleading.

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CHAPTER FOUR

Decarbonization: Progress So Far

History of energy transitions might be seen as a process of gradual decarbonization of primary energy supply (Ausubel 2003). Of course, the substitutions of wood by coal and coal by hydrocarbons were not done with any explicit goal of lowering CO_2 emissions per unit of consumed fuel. They were driven by demand arising from the adoption of new energy converters, by profit realized through more concentrated production, by the quest for cheaper transportation and more efficient final energy use, and later (starting only during the 1950s in the UK and 1960s in the United States) also by environmental considerations, above all by the efforts to reduce excessive urban air pollution. Only since the late 1980s have the concerns about the possible impacts of anthropogenic global warming focused on carbon as an undesirable element in modern energy supply and have led to national efforts to introduce low-carbon or no-carbon alternatives and to find international agreements to reduce future greenhouse gas emissions.

But we have been decarbonizing for centuries, ever since coal became an important fuel in late premodern England, and this slow process began to broaden during the late 19th century with the commercial extraction of crude oil and natural gases and with generation of hydroelectricity. All of these trends intensified during the 20th century, particularly since 1950. Moreover, a new ingredient, nuclear fission, was added to the mix starting in the late 1950s, but a number of countries capable of developing or managing nuclear power had deliberately stayed away from that option, or announced its early abandonment, in order to focus on renewable energy supplies.

In this chapter I will first quantify the process of relative post-1900 global decarbonization and then focus on its principal components, the long-running substitutions of coal by hydrocarbons and primary electricity, and the recent contribution of new renewables, both as electricity generated by harnessing wind and solar radiation, and as biofuels produced by conversions of waste biomass or cultivated crop phytomass. I will close the chapter with a review of some failed or highly unrealistic visions of rapid decarbonization and with a closer look at the progress of Germany's *Energiewende*, so far the most ambitious national program of goal-driven decarbonization.

Slow Gains: Relative Global Decarbonization

We can trace the decarbonization of global and natural energy supply either by following the long-term shifts in H:C ratio in fuels or by quantifying carbon emissions per average unit of primary energy. Wood, for millennia the only source of thermal energy, is composed mostly of cellulose (a linear polysaccharide and the biosphere's most common structural macromolecule), hemicelluloses (amorphous and structurally weak biopolymers), and lignin (a complex polymer of alcohols linked to hemicelluloses to provide stem stiffness). Carbon makes up 44.4% of cellulose mass, 45% of hemicelluloses, and between 61% and 66% in lignin (USDA 2010). Carbon content of different wood species ranges from 46%–55%, and 50% is a representative mean for woody biomass that is composed of 25% lignin and 75% of cellulose and hemicelluloses. In contrast, only 4%–6% of wood is hydrogen.

Coals are similarly hydrogen-poor (5% H) and 65% C would be a good mean (the rest being incombustible elements producing ash and moisture), while liquid fuels refined from crude oil have 86% C and 13% H and, obviously, methane (CH_4), the dominant constituent of natural gases, has 75% C and 25% H by mass. Typical atomic H:C ratios are thus 1.4 for wood, 1 for coal, 1.8 for liquid hydrocarbons and 4 for methane, and hence it would appear that replacing wood by coal cannot result in any decarbonization. But it does: H:C ratio of atoms actually subjected to oxidation in wood is much lower because most of them escape as hydroxyl (OH-) radicals during the early stage of combustion. In contrast, different wood species also contain low shares of organics (waxes, resins, oils) whose hydrogen is oxidized during combustion. As a result, true H:C ratio of wood is invariably well below 1.0, typically no higher than 0.5. Burning coal rather than wood thus results in slight decarbonization, and the shifts are more pronounced when moving to liquid and gaseous hydrocarbons.

Average H:C ratio of the global primary energy supply has moved from 0.5 in 1800 to roughly 1.0 in 1900, 1.6 in 1950, and 1.9 in the year 2000; it then dipped slightly to less than 1.8 by 2015 due to China's enormous post-2000 coal extraction (Fig. 4.1). Global decarbonization has been proceeding much slower than anticipated by Marchetti (1985). His plot of the global primary energy H:C ratios (calculated by assuming a very low H:C ratio of 0.1 for wood) pointed to the mean around 3 by 2010 (in reality it was just 1.83), and it indicated the arrival of global methane economy (H:C ratio of 4.0)

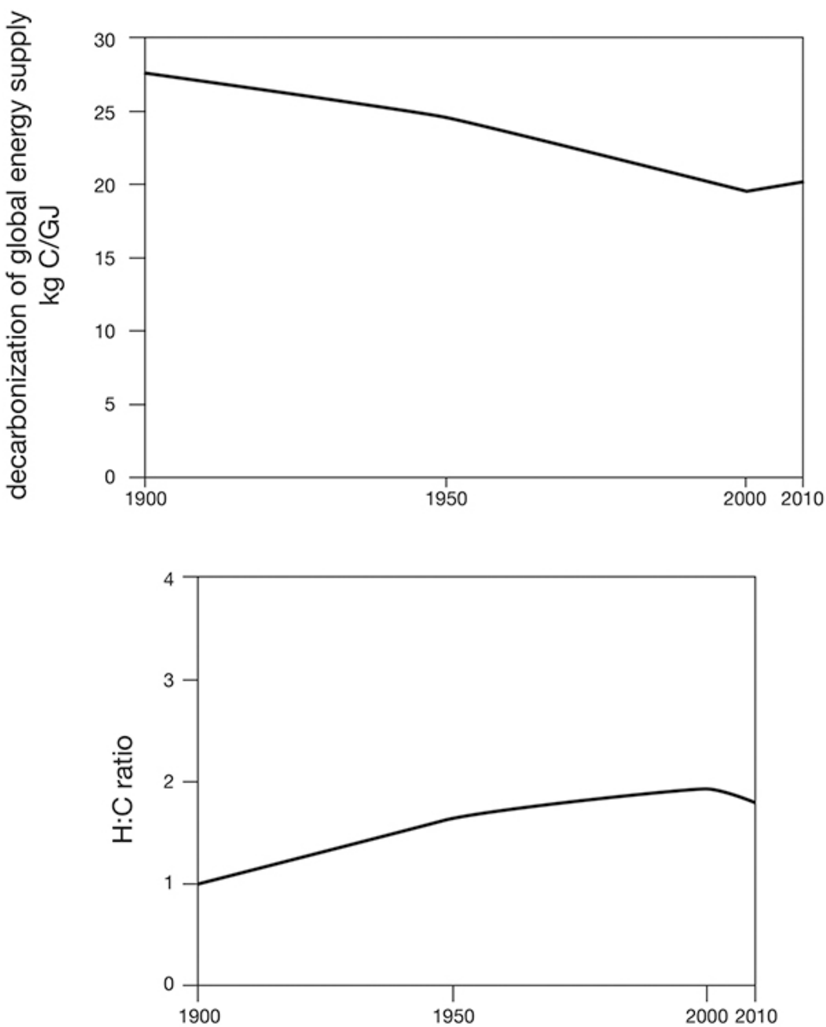

Figure 4.1 Decarbonization of the global primary energy supply (Smil 2015a).

during the early 2030s and hydrogen-dominated system sometime around the end of the 21st century. But the process of global fuel decarbonization has actually stagnated between 1990 and 2015, with coal consumption adding about 17% more energy than did the use of natural gas (BP 2016).

A more conventional way to measure decarbonization is by calculating average carbon emissions per unit of fuel supply. Specific fuel emissions decrease from about 30 kg/GJ of wood to around 25 kg/GJ of good-quality bituminous coal and 20 kg/GJ of liquid hydrocarbons to just 15.3 kg C/GJ when burning pure methane (IPCC 2006). In global terms the average carbon emission rate of fossil fuel supply changed only slightly during the 20th century (given the uncertainties regarding both the energy and carbon totals I am rounding to the nearest unit to avoid the appearance of unwarranted accuracy): from about 25 kg C/GJ in 1900 to 23 kg in both 1950 and 2000, roughly a 10% decline in 100 years. Subsequently, the rising natural gas combustion has more than compensated for expanding coal extraction, and the global rate declined to about 21 kg C/GJ in 2010 and to slightly above 20 kg C/GJ in 2015 (Fig. 4.1).

Inclusion of all modern primary energies has a minimal effect for all carbon rates during the first half of the 20th century, but rising hydro and nuclear contribution lowered the global rate to less than 18 kg C/GJ by the year 2000, for an overall decline of about 28% during the 20th century. At the same time (as I will explain in some detail in this book's closing chapter), it is important to realize that all noncarbon energies require substantial amounts of fossil fuels in order to produce requisite machines, converters, and infrastructures. Finally, inclusion of all primary energies (fossil fuels, primary electricity and traditional phytomass) makes the decarbonization less pronounced due to wood's high specific carbon emissions per unit of energy and its continued importance in global energy supply: that all-inclusive rate fell from more than 27 kg C/GJ in 1900 to less than 22 kg C/GJ in the year 2000 (20% decline) and then close to 18 kg C/GJ by 2015.

Regardless of how it is measured, the pace of relative decarbonization of global energy supply has been very slow, being simply a by-product of shifts undertaken for other (economic, resource availability, technical, air quality) reasons. H:C ratio of global fuel supply during the 20th century was rising by merely 0.6%/year. Measuring the process by average emissions per unit of fossil fuel combustion results in annual 1900–2015 reduction of 0.2%, and expressing it in terms of specific reductions per unit of total primary energy supply (including all traditional biomass) also ends with –0.2%/year for 115 years between 1900 and 2015. As I will show, these decarbonization rates are an order of magnitude slower than they would have to be in order to achieve the desired carbon displacement during the first half of the 21st century.

Inadequate Shifts: Hydrocarbons and Primary Electricity

This slow post-1900 decarbonization has been primarily due to the shift from coals to hydrocarbons in general and to natural gas in particular. Hydroelectricity has been the second largest contributor to the decarbonization of global primary energy, followed by nuclear electricity (although in conversions using straight thermal equivalent for hydroelectricity and a higher value, assuming between 33%–38% equivalent efficiency, for nuclear generation, the latter aggregate for 1960–2000 surpasses the former by about 50%), while even the combined effect of all new renewable conversions (geothermal, wind, solar, biofuels) remains marginal.

Those substitutions of coal that had eventually resulted in massive market shifts began with the replacement of coal-fired steam engines by oil-fired engines and, more importantly, by diesel engines in ocean shipping (starting before 1910), followed by the substitution of steam locomotives by diesels (since the 1920s). Switch from coal-fired heating to oil-fired boilers and later to natural gas furnaces by households, industries, and institutional and commercial users began first in the United States where it was virtually completed by the late 1960s. European coal-fired heating lingered in some countries for up to four decades after World War II before it was replaced by natural gas piped from Groningen, the North Sea, and Western Siberia, and coal stoves and boilers remained important in China (in industries as well as for centralized residential heating in large northern cities) until the beginning of the 21st century.

Such exceptions aside, by the year 2000 coal use in most countries was reduced to just three sectors, electricity generation, industrial heat, and ferrous metallurgy, with coal used to produce metallurgical coke and (in powdered form) directly blown into blast furnaces (Smil 2016a). U.S. electricity generation has recently consumed more than 90% of all marketed coal, and the latest global energy balances show that nearly 60% of all coal is now used to generate electricity (IEA 2015b; USEIA 2015a). Where inexpensive natural gas became available in large volumes coal was replaced fairly rapidly. The most recent demonstration of this substitution is the American gas produced by hydraulic fracturing displacing coal in electricity generation: the two fuels produced, respectively, about 50% and 19% of total generation in the year 2005, but by 2015 the shares shifted to a near equality at 33.1% and 32.6% (USEIA 2016).

Substitution of coal by primary electricity has been generally a much less important form of decarbonization during the 20th century: in both the United States and the USSR expanding hydrogeneration took place alongside the rising use of coal in power plants, and the same has been true about post-1990 China. By far the most effective example of this shift was the French adoption of nuclear generation starting in the 1970s that has reduced coal-fired generation to a marginal level. Obviously, countries that have been deriving rising shares of primary energy from natural gas and from either hydro or nuclear electricity have been decarbonizing considerably faster than the global mean.

The U.S. average (including all primary energies) declined from 24.1 kg C/GJ in 1900 to 15.6 kg C/GJ in 2000, a 35% drop in a century, with the shift toward natural gas as the leading factor. Conversion of the Dutch economy to Groningen gas reduced the country's average ratio quite rapidly from about 23 kg C/GJ in 1960 to roughly 18 kg C/GJ by 1980. The French ratio fell from 26.4 kg C/GJ in 1900 to just 10.1 kg C/GJ in the year 2000, a 62% decline driven mostly by the adoption of nuclear electricity. In contrast, the Chinese rate moved from nearly 30 kg C/GJ in 1950 to about 23 kg C/GJ in 2015, only a 23% drop in 65 years reflecting the country's high dependence on coal.

But these relative decarbonization gains could not overcome the combined effects of the intervening population growth and economic expansion. Dips caused by wars and economic crises aside, global carbon emissions from fossil fuels increased nearly 70-fold during the 19th century—from only 8 Mt C in 1800 to 534 Mt C in 1900—and during the 20th century their total rose to nearly 7 Gt and then, propelled by China's burst of coal extraction, 2.18 Gt C were added in a single decade to reach a new record of 9.16 Gt C (or 33.6 Gt CO_2) in 2010 and about 9.6 Gt C in 2015 (see Fig. 1.3). In China, now the leading emitter, the 2015 emissions (nearly 2.9 Gt C) were roughly 110 times higher than in 1900, and the analogical multiples were more than 60 for Japan and nearly nine for the United States.

But since the 1980s there has been a change in the rich world's growth of CO_2 emissions from fossil fuel combustion: they have slowed down considerably and some countries show a clear plateaux and even slight declines as per capita energy use stagnates or declines. Between 1985 and 2010 the U.S. carbon emissions rose by 20% while during the preceding 25 years (1960–1985) they were up by 55% (CDIAC 2016). Analogical growth rates for Japan are 28% and 393%, for Germany (largely due to the postunification collapse of the former East German economy rather than to the impact of *Energiewende*) decline of 27% vs. growth of 28%. And the growth of emissions in modernizing countries also began to moderate. As a result, the global growth of about 4%/year during the first decade of the 21st century slowed down to just 1% in 2012 and 2013; it was only 0.5% in 2014 and remained at that level in 2015 (PBL 2015).

Slower growth of carbon emissions in affluent countries has been due to a shift toward natural gas and a combination of falling shares of energy-intensive manufacturing, rising efficiency of common energy conversions, reduced energy demand due to population aging, and elimination of older, wasteful processes aimed at improving environmental quality. Contrary to impressions one gets from media reports, so far it has had little to do with the displacement of high-carbon fuels by new noncarbon energies. This is true even in the German case where the new renewables have been making large and much-publicized advances. Between 2010 and 2015 Germany's wind generation doubled and photovoltaic (PV) generation had more than tripled, but coal-fired power plants had actually generated slightly more electricity in 2015 than it did in 2010, while natural gas, the least carbon-intensive fossil fuel, produced 36% less electricity in 2015 than in 2010 (BWE 2016).

This will have to change because even a complete worldwide substitution of coal by natural gas would still leave us with unacceptably large carbon emissions, and the two established noncarbon conversions, hydro energy and nuclear fission, will continue to have a limited impact (I will explain why in this book's last chapter). The choice then comes down to three sources of renewable energies: electricity generated by large wind turbines, by conversion of solar radiation (mostly by photovoltaic cells but also by central solar power plants), and biofuels (for heat, in transportation and also for electricity generation).

A great deal of recent media reporting has created the impression that the diffusion of these sources has been progressing at unprecedented pace while their costs have been exponentially declining and that their contribution already accounts for large shares of not only electricity generation but even of total primary energy demand. Here is a perfect illustration of these misconceptions. In June 2014 a headline of a German news Web site in English boldly claimed that "Germany produces half of energy with solar" (The Local de 2014). That claim was quite misleading. Data from Fraunhofer ISE research institute showed that the peak of solar energy supply lasted for just one hour and that the record share of 50.6% was due to the combination of sunny weather with a public holiday that lowered the normal demand (Fraunhofer ISE 2015).

But the most important error of that headline was that it mistook electricity production (*Stormerzeugung* in German) for total energy use (*Energieverbrauch*). The briefly achieved share was half of electricity production, and electricity accounts for only a fraction of total primary energy. The correct statement (too long for a catchy headline) should have been: thanks to the mandated preferential access of renewable electricity generation to the national grid, electricity generated by PV supplied half of Germany's total demand for one noon-hour on a sunny holiday, while on the annual basis less than 3% of the country's primary energy used in 2014 originated in solar PV (and only about 1% when solar electricity is converted by using its thermal equivalent).

Unfortunately, mistaking electricity generation for total energy supply is a common error. I will cite just another example, from an oil journal: it claimed that Scotland “has been in contention” to be the first country “to produce 100% of its energy from renewable sources by 2020” (Torsello 2016). That would be quite impossible: in 2013 Scotland derived only 13% of its primary energy from renewables (compared to 15% average for the EU), third of its electricity came from nuclear fission, and oil products and natural gas provided 78% of all primary energy (The Scottish Government 2016). Again, the report had failed, inexcusably, to distinguish between electricity generation—for which the government set a 100% renewable goal by 2020—and overall primary energy supply.

Closer looks show that the diffusion of new renewables has seen some fast and impressive technical advances and production gains, particularly in countries where their adoption has received long-term subsidies and preferential treatment by governments committed to “greening” their energy supply. This has been true particularly about wind-powered electricity generation and, to a lesser extent, about PV electricity (although the media attention puts the latter first). At the same time, readily available and accurate capacity and production statistics confirm that the adoption of these new techniques is still in an early stage and that future contributions face many natural limits and technical constraints.

New Renewables: Solar Energy and Wind Electricity

As I stressed in this book’s opening chapter, direct solar radiation is the only renewable energy flux whose magnitude is far larger than any conceivable demand of the 21st century’s high-energy civilization. Three commercial techniques have been exploiting this enormous resource: rooftop water heating, PV electricity generation, and central solar power (CSP) plants. Rooftop water heating is relatively simple and affordable and, thanks to new flat-plate collectors and evacuated glass tubes, is also highly efficient. Recent history of commercial PV energy generation has been an encouraging case of technical progress, and CSP offers at least a partial remedy for the inevitable intermittency of solar radiation.

Water heaters in sunny climates can satisfy moderate household needs without any voluminous hot water storage; elsewhere they can make a substantial contribution. A combined system can provide both space and water heating. About 110 million units of mostly small rooftop heaters have been put in place during the last three decades. Mauthner, Weiss, and Spörk-Dür (2015) estimated that by the end of 2013, solar thermal collectors had an aggregate area of 535 Mm^2, total capacity of 375 GW (70% of it in China, 12% in Europe), and annual output of 314 TWh. These accomplishments imply a high power density of 67 W/m^2 and reduce electricity or fuel bills—but they add up to only about 0.25% of the world's total primary energy supply.

Continuing installations of solar heaters have been overshadowed by the rapid growth of PV capacities, both as rooftop modules for household and commercial use and for large generating arrays. The PV conversions have a long history, but their use for land-based commercial electricity generation began only during the 1990s (Perlin 2002). Edmund Becquerel discovered the conversion of solar radiation to electricity in 1839, and while the first experimental PV cells were made in 1877 practical uses of photovoltaics began only in 1954 when Bell Laboratories made the first silicon solar cells. The era of satellites powered by PV cells started in 1962 with Telstar, but terrestrial applications took off only when PV cells became more affordable during the 1990s (Smil 2006).

Installation of PV cells to generate carbon-free electricity was enabled by government subsidies and by guaranteed long-term feed-in tariffs. In turn, this has led to steadily rising average conversion efficiencies, mass production of modules and their falling unit prices, larger numbers of rooftop units, and impressive growth in the size of largest solar parks: Germany was the early leader on all of these accounts, later joined by the United States and China. In 2015 the best research-cell efficiencies were as follows: emerging techniques (organic, perovskite, and dye-sensitized cells), 10.6–12.6%; thin films, 13.6%–23.3%; crystalline silicon cells, 21.2%–27.6%; and multijunction cells, 31.6%–44.4% (Fig. 4.2).

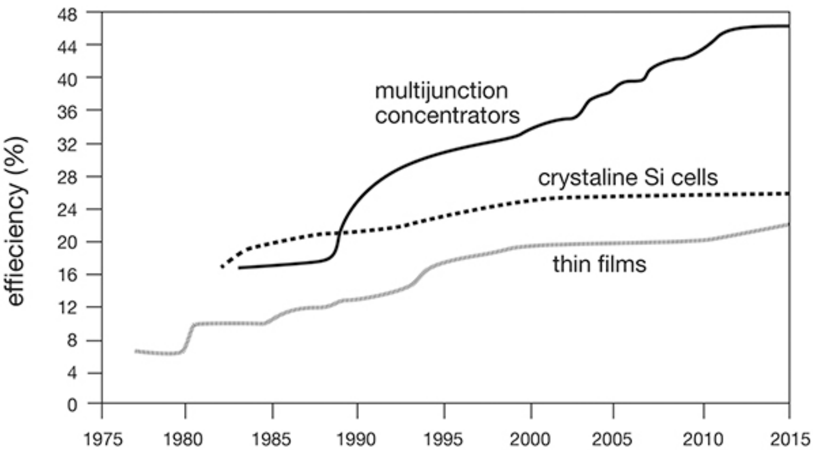

Figure 4.2 Best conversion efficiencies of PV cells (NREL 2015).

Actual field efficiencies of PV cells have been much lower. Nominal efficiency of crystalline silicon PV modules has been increasing by about 0.3% a year, from about 11% in 2000 to 16% in new installations in 2015, with peak performance just above 20%; in thin-film modules the efficiencies range from 6%–11%, with peak levels at 12%–13% (Wirth 2015). When deploying PV cells with efficiency of at least 10%, peak power densities of PV modules are 80–100 W/m^2 during a few midday hours; with 15% efficiency the rate would rise to 120–150 W/m^2, while annually averaged power densities would be, depending on the location, as low as 10 W/m^2 (in cloudy midlatitudes including Atlantic Europe and the Pacific Northwest) and as high (in the U.S. Southwest, Middle East) as about 40 W/m^2 (Smil 2015a). All of these rates are far higher than the averages for any other form of renewable energy in similar settings.

Reductions in the unit costs of solar installations have been substantial: in Germany the decline was 90% between 1990 and 2015, from €14,000/kW$_p$ (peak watt) to €1,300/kW$_p$, an annual reduction rate of 9% (Fraunhofer ISE 2015). Modules now make up about half of the cost, balance of the system (including inverters) the rest. Energy return on invested energy is high, with payback times of less than a year in the best subtropical locations, up to 2.5 years in cloudier climates, and lifetime energy return (after 20 years) could be commonly 15- to 20-fold. Most of the early capacity growth was in Europe (by 2014 more than 50% of the installed total) and particularly in Germany (20% of the global total in 2014), but now both the highest module production and the highest annual increments are in China (REN21 2015).

Exponential growth of globally installed peak capacities (100 MW$_p$ reached in 1992, 1 GW$_p$ in 2000, 40 GW$_p$ in 2010) reached 177 GW$_p$ in 2014 (this translates into an average annual compound growth of 34%), with Germany China and Japan having the largest totals, respectively about 38, 28 and 23 GW$_p$, making Germany the per capita leader (IEA-PVPS 2015). But PV generation has relatively low capacity factors: the global, as well as the U.S. and Chinese, mean in 2014 was just 12%; even in sunny Spain some projects average no more than 16%, and the best performance in Arizona is about 25%. As a result, the total 2014 PV output of 186 TWh (compared to just 1 TWh in the year 2000) was still no more than 0.8% of global electricity generation.

In 2015 national shares of PV generation in total electricity output ranged from 8.9% in Italy and 5.9% in Germany to 3% in Japan, 0.9% in the United States, and 0.7% in China. And even when converted at the rate of 9.5 MJ/kWh (as BP does), PV generation added just 0.4% of the world's 2015 primary energy consumption, while the IEA and UN conversion (also used in this book) would have it at a mere 0.15% of total primary energy supply. This is a perfect illustration of how reporting that concentrates on rapid annual growth rates of a technique in its early stages of diffusion makes it appear more consequential than it actually is.

In contrast, wind-powered electricity generation has already made a much greater impact. Small, isolated generators of the 1920s were eliminated by the extension of electric grids and the interest in harnessing wind came back only in the early 1980s, after the second round of OPEC's oil price rise. The first modern wind power wave began, thanks to tax credits, in California. In 1985, when the credits expired, the United States had a bit more than 1 GW of installed wind capacity (mostly in small, 40–50 kW, machines) and California's Altamont Pass (637 MW) was the world's largest wind farm but its capacity factor was just 10% (Smith 1987).

During the 1990s all major advances in exploiting wind energy took place in Europe: typical turbine ratings increased to 500–750 kW, the first 1-MW machines were introduced in Denmark, which was also the first nation with offshore installations. In relative terms Denmark is the world leader, with total capacity rising from 2.417 GW in the year 2000 to 5.03 GW in 2015 and with wind generation (11.03 TWh in 2015) supplying 42% of Danish electricity (DWIA 2015). Germany used to be the world leader in absolute terms, with capacities rising from 6.1 GW in 2000 to 45 GW by the end of 2015 and with wind generation (85.4 TWh in 2015) share rising to just over 13% of the total (BWE 2016). American wind-generating capacity rose from 2.55 GW by the end of 2000 to 74.4 GW in 2015 when China added nearly 33 GW to become an undisputed leader with 129 GW, but the wind-powered generation (at 186.3 TWh) was only 3.3% of China's total.

Turbine size has continued to increase, and in 2015 the largest machines were rated at 8 MW for offshore and 7.5 MW for onshore installations, while record-size wind farms were offshore London Array at 630 MW, and onshore Alta Wind in California at 1.32 GW (CEC 2016; London Array 2016). Worldwide capacity rose from 1 GW in 1985 to 17.3 GW at the end of the year 2000, 198 GW in 2010 and 370 GW in 2014 (REN21 2015). Wind-powered electricity generation is now far ahead of solar conversion in terms of unit size, typical project capacity, total capacity, capacity factor, and actual generation. Declining costs made wind turbines a preferred competitive choice for new capacity additions in many windy locations.

Average capacity factors have been improving, but in 2014 the mean values were still only 16% in Germany (31% in the United States) and nearly 24% worldwide as wind turbines produced about 760 TWh of electricity, less than 4% of the global total. In 2015 national shares of wind-generated electricity ranged from about 50% in Denmark, 22% in Portugal and 18% in Spain to nearly 14% in Germany, 4.5% in the United States and just over 3% in China; for the latter two countries wind shares were roughly five times higher than for PV. Integration of these intermittent sources of energy into modern electric grids is more demanding than when dealing with natural gas-fueled turbines, now the leading addition of new fossil-fueled capacities, whose output is available, almost instantly, on command. As long as the output of intermittent conversions remains low (less than 10% of the total), integration problems remain fairly manageable; as the shares of variable input rise, steps must be taken to manage those short-lived high peaks while assuring sufficient reserve capacities for cloudy and calm periods that, in some places, can last for weeks.

Germany was the first country to encounter these challenges. Wagner (2012) pointed out that the use of renewable energies did not bring any large-scale displacement of thermal power, with capacity savings of less than 10%. German data are clear: in the year 2000 the country had 84.2 GW of fossil-fueled generating capacity, in 2014 that total actually rose by about 4% to 87.5 GW—while the combined capacity of renewable generation rose from 6.2 GW to 84.8 GW, almost perfectly matching that of fossil-fueled generators (Fig. 4.3)! The obvious question to ask is how rational it has been to expand the total capacity by 61% in order to produce less than 9% more of electricity?

Subsidies, technical advances, and declining unit costs have led to steadily expanding wind and PV generation capacities, but the gains have been heavily concentrated in a small number of nations: in Germany, China, Japan, Italy, and the United States for PV; in China, the United States, Germany, India, and Spain for wind. At the same time, when their importance is assessed in terms of their shares of the global electricity generation, they are still only marginal contributors (their combined share was just above 4% in 2015) and, obviously, they remain even more marginal in terms of total primary energy supply (combined share below 2% in 2015).

Modern Biofuels: Electricity and Liquids

I have already explained how during the 20th century the relative decline of traditional biofuels in the global primary energy supply went along with substantial absolute increases of their consumption, and how Marchetti's (1977) mechanistic transition scheme had completely failed to capture these trends. Although their relative importance is now lower than ever (about 7% of all primary energy), total harvest of biofuels remains near a record level of about 40 EJ/year, an equivalent of nearly one Gt of crude

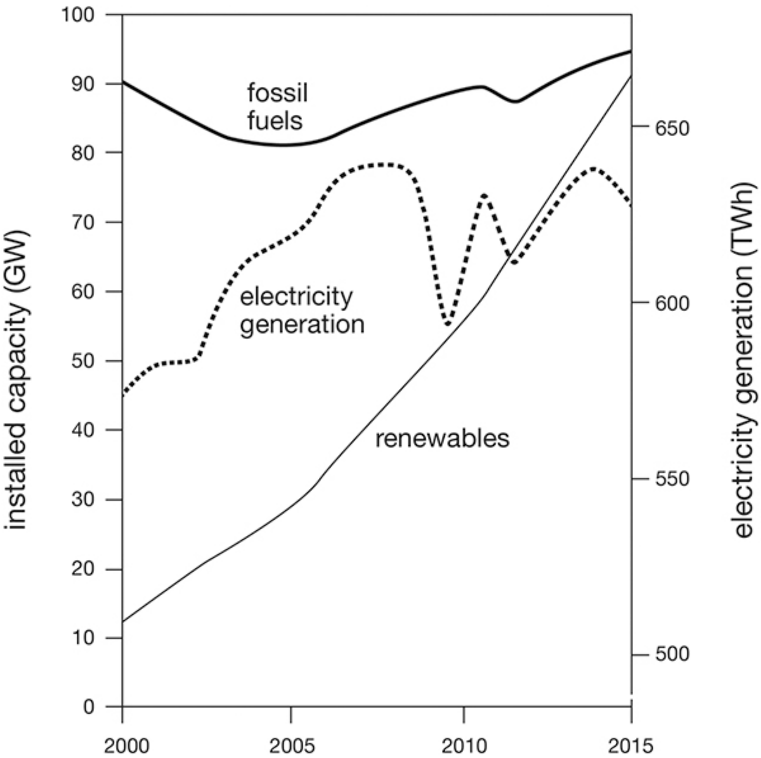

Figure 4.3 Installed capacity in Germany's fossil-fueled and renewable generation, 2000–2015, and total electricity generation. Plotted from data in BWE (2016) and Fraunhofer ISE (2016).

oil. Some of these harvests are truly renewable (with wood harvested from well-managed small woodlots); others cause destruction of trees and shrubs in dry subtropical woodlands and deforestation in wet tropics.

Environmental impacts of excessive phytomass harvesting and health consequences of inefficient biofuel combustion are two main reasons why these traditional uses should be further reduced, and eventually eliminated. Progressing modernization has replaced them by commercial fossil fuels and by electricity, but in a world reducing its dependence on fossil energies their remaining supply should come in the form of modern varieties. More importantly, modern liquid biofuels are the only practical option (assuming there will be no early hydrogen economy) to supply the world's large, and growing, transportation demand by renewable energies as well as to produce heat and generate electricity in a predictable manner (made possible by stores of solid or liquid fuels).

The new biofuel industry includes five distinct conversion streams: burning woody phytomass (pelletized for higher combustion efficiency and obtained from logging wastes, and from harvesting of natural forests and fast-growing tree plantations) to generate heat and electricity for industrial uses or for public consumption; fermentation of ethanol from food crops, mainly from sugar cane and corn; production of biodiesel derived from a variety of oil crops; production of cellulosic ethanol from crop residues and wood waste; and fermentation of organic wastes (and energy crops) to generate biogas (for heat and electricity generation).

Commercial use of wood wastes was by far the largest modern conversion of phytomass before the establishment of new bioethanol, biodiesel, and biogas industries—and in most countries it still keeps that primacy. In 2014 in the EU, despite the promotion of other renewables, woody phytomass contributed 10 times more primary energy than PV solar and 4 times as much as wind-powered electricity generation as it accounted for 44% of all renewable energies (Eurostat 2015b). Even in Germany wood supplied nearly a third of all renewable energies, in Sweden 53%, in Finland 80%. Similarly, in the United States woody phytomass was still the largest contributor to modern biofuel conversions in 2015, accounting for 22% of all renewable energies, nearly twice the country's exceptionally large and subsidized ethanol production from corn (USEIA 2016).

While wood keeps its traditionally dominant position, its conversions have become more efficient. Efficiencies close to 90% can be achieved in circulating or bubbling fluidized bed boilers (Khan et al. 2009). By 2014 modern phytomass heat capacity rose to nearly 399 GW, and more than 400 TWh of electricity are now generated from woody phytomass burned mostly as pellets, now also widely traded on international market (REN21 2015). Gasification can convert biomass to substitute natural gas (>95% CH_4) with overall efficiency of up to 70% (Aranda, van der Drift, and Smit 2014). Gas that contains up to 17 MJ/m^3 and can be used to generate electricity could be produced with even higher (80%–85%) efficiencies (Worley and Yale 2012). Using wood harvested from natural forests—as is now done not only in many tropical countries but also in one of Europe's last remaining primary forested regions in Romania's Carpathian Mountains where illegal logging has been common (Norman 2015)—would not reduce overall carbon emissions.

The obvious way to expand wood-based energy conversions is to harvest wood from fast-growing tree plantations. Productivity of the most intensively cultivated plantations (receiving supplementary fertilization and irrigation) is limited by inherently low efficiency of photosynthesis. Fast-growing trees (willows, poplars, eucalypti, leucaenas, pines) yield only

0.1 W/m^2 in arid and northern climates and up to 1 W/m^2 in the best temperate stands, where typical harvests (about 10 t/ha) prorate to about 0.5 W/m^2 (Smil 2015a). Tropical plantations do better: typical yields of Brazilian eucalyptus were 12 t/ha in 1980 and 21 t/ha in 2011 (CNI 2012). Wood grown in a highly productive tropical plantation (20 t/ha) will be converted to heat with power density no higher than 1.2 W/m^2 and to electricity with power density of 1 W/m^2. Securing GW-scale supplies for modern megacities and industries would demand expansive cultivation of fast-growing monocultures accompanied by well-known environmental impacts (biodiversity loss, nutrient leaching, soil erosion).

Solid biofuels dominate global energy use of phytomass, but liquid biofuels have attracted most of the recent attention because they provide the main alternative to liquids refined from crude oil. Experimental use of automotive ethanol goes back to the 1920s, but post–World War II commercialization was delayed by the availability of inexpensive gasoline. Interest returned only after OPEC's first oil price rise in 1973–1974 with Brazil's sugar cane–based ProÁlcool program in 1975, and with the U.S. corn-based ethanol in 1980 (Basso, Basso, and Rocha 2011; Bressan and Contini 2007; Solomon, Barnes, and Halvorsen 2007). In the year 2000 the United States produced 50 GL and Brazil 26 GL of ethanol; by 2015 the U.S. output reached 55 GL and Brazil produced more than 27 GL. In the United States up to 10% of ethanol (by volume) is blended with gasoline or it is used in flexible-fuel vehicles (up to 85% ethanol), while the Brazilian blend contains 25% ethanol and 75% gasoline and the country has a growing fleet of vehicles running on pure ethanol.

The United States and Brazil now account for about 85% of the global crop-based ethanol production, with the EU, China, and Canada producing nearly all of the rest (REN21 2015). Such a highly skewed production pattern is not surprising. Although both cane and corn are the photosynthetically most efficient C_4 plants—average harvests are now close to 11 t/ha for the U.S. corn and about 70 t/ha for the Brazilian sugar cane (FAO 2016)—and although the latest fermentation processes convert the feedstock with almost 40% higher efficiency than during the 1970s, ethanol production from Iowa corn yields only about 0.25 W/m^2 and from Brazilian sugar cane about 0.41 W/m^2 (Crago et al. 2010; Smil 2015a).

Such low power densities mean that only countries with abundant farmland and with surplus food production can divert a significant amount of their agricultural resources from food and feed. Brazil has been using almost 60% of its sugar cane harvest to produce ethanol, and since 2011 the United States has been diverting between 37% and 43% of its large annual corn harvest for the production of ethanol. And yet in overall energy terms American ethanol has been displacing less than 10% of the country's annual motor gasoline consumption (9.8% in 2014). Obviously, even the farmland-rich United States could not ever run all of its transportation on corn-based ethanol.

Devoting 40% of its main crop to ethanol has been a highly questionable choice for the United States as it perpetuates an extensive monoculture whose major environmental impacts—nitrate leaching and formation of dead zone in the Gulf of Mexico, and depletion of the Ogallala aquifer—result from high application of nitrogenous fertilizers and supplementary irrigation in the Corn Belt. Studies have also shown that replacing gasoline by corn-based ethanol may actually increase overall carbon emissions due to land use changes (Searchinger et al. 2008). Brazilian sugar cane, a perennial grass (but usually replanted after five harvests to keep high yields) is a better choice because of its superior yields and also because its endophytic nitrogen-fixing bacteria eliminate the need for nitrogen fertilizers and it does not need irrigation.

Liquid biofuel with the greatest promise is ethanol made by enzymatic hydrolysis of phytomass high in cellulose and hemicellulose, that is, any woody matter and crop residues (mostly cereal straws), and also by using intensively cultivated switchgrass, reed canary grass, miscanthus, and the giant reeds (Singh 2013). After years of exaggerated promises, commercial production of lingo-cellulosic ethanol finally began in 2015 at the world's first two large plants, one in Iowa using corn stover (corn leaves and stalks) the other in Brazil using cane bagasse (stalks after the expression of cane juice). Their combined annual capacity will be about 150 ML or a mere 0.005% of current global demand for transportation fuels. But power densities of this conversion will not be any higher than for those based on starch or sugar: even very high grass yields (15 t of dry matter/hectare) and ethanol yields of 330 L of ethanol/t of grass (Schmer et al. 2008) would produce cellulosic ethanol with power density no higher than about 0.4 W/m^2. Again, large areas would be required to displace higher shares of refined oil fuels.

In contrast to ethanol fermentation, biodiesel output remains low. The fuel is produced by transesterification of plant oils, that is, by reacting triglycerides with alcohol in the presence of a base catalyst (Gerpen 2005). This process converts up to 97% of oil into biodiesel, and rapeseedis the most commonly used plant oil. Rapeseed has about 40% oil, which means that nearly 39% of the harvested crop can end up as fuel. Rapeseed yields vary between 2–4 t/ha, and the average EU harvest produces only 0.12 W/m^2, power density inferior to that of crop-based ethanol. U.S. production of biodiesel (soybean-based) has been close to 5 GL, an order magnitude smaller than that of ethanol. In 2015 Brazil (using soybeans) produced about 4.1 GL, and Germany and France (using mostly rapeseed) produced, respectively 2.8 and 2.4 GL. These four top producers accounted for about 60% of the global output.

Low power densities of biodiesel production based on rapeseed or soybeans will limit the extent of possible fuel substitution. For example, nearly 220 Mha of rapeseed would have to be planted to supply the EU's diesel demand of roughly 260 GW, while the union's arable land adds up to only about 103 Mha (Eurostat 2015c). And the highest power density option—basing the production on oil extracted from the mesocarp of oil palm, with oil yields per hectare five times those of soybeans and three times those of rapeseed—entails large-scale tropical deforestation as extensive oil palm plantations displace natural rain forest (UCS 2011).

In 2015 the combined output of bioethanol and biodiesel was equal to about 75 Mt of crude oil, while the world's land, air, and water transportation consumed about 2.4 Gt of crude oil. A 10-fold increase of 2015 production would still supply just a third of the current demand, and it would run into many economic and environmental problems because even those countries that may have enough land or waste phytomass to support major expansion do not share the exceptional circumstances that allowed the United States and Brazil to make their advances. There is also a critical consideration of the energy return on investment.

While PV cells and wind turbines will return 15–20 times the energy that was needed to make them, early production of corn ethanol entailed a net energy loss or a very small gain, and more recent practices return less than two units of energy for every unit of fossil fuels and electricity invested (Blottnitz and Curran 2007; Hammerschlag 2006). Depending on yields, soybean-based biodiesel returns between 2.5 and 5.6 units per unit invested. High energy cost of farming and processing inputs required to maintain high crop yields mean that about a quarter of the EU's rapeseed-growing area would produce biodiesel with a net energy loss (Firrisa 2011). That we cannot run economies on negative-energy basis is obvious, and the fundamental question to ask is if we can run a large segment of global energy supply with very low (<5) energy returns.

The least important contributor to new biofuel production has been the generation of biogas. This conversion was originally pioneered on a small scale in rural areas of China and India to produce cooking and lighting gas for rural households from animal, human, and crop wastes (Smil 1976, 1988). More recently it has been used on a large commercial scale to produce gas for electricity generation. Germany has the largest national biogas program: in 2015 it had just over 8,000 biogas plants whose output supported 4 GW of installed generating capacity to produce 27.8 TWh (Wagner 2015). But nearly 80% of their feedstock does not come from livestock excrement or crop wastes but from the cultivation of energy crops, above all corn, and hence any substantial expansion of this conversion would affect food and feed cultivation. Again, overall power density of this energy production is very low; in terms of marketed electricity it amounts to slightly above 0.2 W/m^2 (Smil 2015a).

National Trajectories: Aspirations and Accomplishments

In the closing section of this chapter I look at goals and achievements of decarbonization efforts that have been unfolding in several countries. I will pay particular attention to the developments in Germany, the country whose *Energiewende* is the boldest deliberate attempt at accelerated energy transition aiming eventually at a complete decarbonization of primary energy supply. National substitution goals are usually stated as shares of particular energy supply to be provided in future years, typically those ending in zero or five, and usually they are not set as legally binding targets. Aspirations are expressed in formal and informal forecasts and scenarios produced by governments, industrial associations, nongovernmental organizations, and universities.

Robust optimism (or, less charitably, naïve expectations) and a remarkable unwillingness to err on the side of caution is a commonality shared by an overwhelming majority of those goals, promises, and aspirations. This, of course, is *nihil novi sub sole*. Recent anticipations of a fairly rapid and comfortingly smooth coming transition to renewable energies have had quite a few precedents going back to the aftermath of the two energy "crises" of the 1970s when the OPEC-driven increases in oil prices convinced many people that the end of the hydrocarbon era and mass embrace of renewables were imminent. As we know, that did not happen, and hence it is instructive to review some of those notable forecasts and plans whose timing has already expired (or is to end soon) and contrasting them with actual performances: it makes for sobering comparisons.

In 1976 Amory Lovins envisaged that by the year 2000 a third of America's primary energy will come from "soft" conversions, that is, overwhelmingly from small-scale decentralized harnessing of renewable flows (Lovins 1976). A year later the InterTechnology Corporation (1977) suggested that by the year 2000 solar energy could provide 36% of America's industrial process heat, and Sørensen (1980) put the share of America's energy coming from renewables in 2005 at 49%, with biogas and wind each at 5% and decentralized PV generating 11%. Actual share of new renewables in America's 2005 primary energy supply was less than 3%, with biogas supplying less than 0.001%, wind 0.5%, and photovoltaics less than 0.1%.

I have already noted how the Swedish plans of the late 1970s envisaged the country energized solely by domestic and renewable sources (including willow plantations) by the year 2015, and a 2006 ministerial promise to make Sweden (without any nuclear help) the world's first oil-free country by 2020 (COI 2006). The first aspiration failed: by 2015 Sweden was still importing a third of its primary energy while nuclear electricity remained its single largest domestic source, and the country is not deriving a large share of its energy from willows. Making Sweden an oil-free society by 2020 is also a promise that has reached too far too fast—but the report's closer reading reveals more realistic goals (COI 2006). They include a 20% increase in overall efficiency of energy use, reduction of gasoline and diesel use in transportation by 40%–50%, and cutting the use of refined fuels in industry by 25%–40%. "Oil-free" would then 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. Volvos and flights to Thailand are thus safe!

By far the most ambitious energy transition challenge for America was presented in 2008 by the country's former Vice President. Al Gore's fundamental premise was 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." He was confident that he had an effective solution (Gore 2008, 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. . . . The quickest, cheapest and best way to start using all this renewable energy is in the production of electricity.

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," a goal he thought to be challenging but "achievable, affordable and transformative." He was wrong. 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% from "new" renewables, that is, wind, geothermal, and solar (USEIA 2015b). Eliminating carbon-based electricity according to his plan would have required replacing 71% of the 2008 generation originating in the combustion of fossil fuels. But if the country were to end up only with renewable electricity generation, then the repowering should also affect the nuclear stations whose operation emits no carbon but fissionable isotopes are not renewable: then the replacement need would rise to just over 90% of the 2008 generation.

Because of different capacity factors new generators would have to have higher installed capacity than the old ones. In 2007 the net summer capacity of the U.S. fossil-fueled stations was about 740 GW, and they generated 2.88 PWh with an average capacity factor of about 44% (73% for base-load coal-fired stations, 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 adequate HV interconnections) 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 in all power plants built in nearly 60 years 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. Moreover, it would also require writing off in a decade the entire fossil-fueled electricity generation industry, 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. In reality, during the seven years between 2009 and 2015 the United States added about 50 GW of wind and 20 GW of solar capacity, or about 10 GW of new renewables a year compared to 150 GW/year that would have been required in order to "repower" the country in a decade. The fact that actual annual additions have been running at less than 7% of the needed rate should alone suffice to demonstrate how unrealistic the original "achievable, affordable" plan was.

Gore's repowering plan was actually preceded by a more modest, but still very ambitious, plan advanced by T. Boone Pickens, a Texas oilman and a former corporate raider, in 2008. His 10-year energy plan for America had an appealing cascading simplicity. Pickens wanted to fill the Great Plains with wind turbines whose output would replace electricity produced by burning natural gas. The freed natural gas would be used to run efficient and clean natural gas vehicles while the substitution would create new massive domestic aerospace-like industry bringing economic revival to the depopulating Great Plains, cutting U.S. oil imports by more than one-third and putting the country on a better fiscal foundation.

Pickens outlined the plan to the Congress and promoted it with a $58 million advertising campaign to rally public support (www.pickensplan .com). Pickens saw America's addiction to oil, especially with 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 have required building more than 100,000 wind turbines, connect them to large cities with at least 65,000 km of transmission lines, and convert 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 at least another $200 billion in order to construct the requisite high-voltage transmission lines to connect those giant wind farms to densely populated coastal regions.

The Grand Energy Transition (GET) plan proposed by Robert Hefner, a life-long natural gas explorer and producer, amounted basically to the second part of the Pickens Plan, but with some other questionable provisos (Hefner 2009). Hefner believed that America's gas reserves are perhaps even larger than the country's remaining minable coal deposits, and his plan called for retrofitting and converting half of the U.S. vehicle fleet to natural gas by the year 2020. He also believed that this would not be a difficult conversion: given the existing natural gas grid some 63 million homes with more than 130 million vehicles would need only a convenient home-fueling appliance. According to Hefner this conversion would cut the oil imports by about 250 Mt/year (in 2008 imports were nearly 640 Mt), trigger some $100 billions of private investment, and add about 100,000 new jobs.

Al Gore's organization (wecansolveit.org) went on to publish prayer-like advertisements in U.S. magazines 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"—but soon it disappeared. Gore's 2008 appeal was removed from the World Wide Web, and the wecansolveit.org domain became available for sale. Pickens first acknowledged that his grandiose plan had 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 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 and O'Grady 2009, 1). But even his own project that was planned to be the world's largest 4-GW $4.9 billion wind farm near Pampa in Texas was abandoned. And no steps were even taken to make Hefner's GET even a partial reality.

I must note just one more failed American dream: Google's plan to repower America was released in October 2008, shortly after Gore's challenge. Google's *Clean Energy 2030* called for "weaning the U.S. 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 transition rested 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 to keep the overall demand flat at the 2008 level. And, finally, raising the sales of 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 agreed that keeping the nationwide electricity demand flat at the 2008 level by 2030 and raising the average car performance to 45 mpg were technically eminently doable goals. But 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 was a goal whose achievement was based on some unrealistic assumptions. The Google plan proposed 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 pointed out (correctly) that such rapid buildups of electricity-generating capacity have precedents: 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% to18%. But both comparisons refer to much larger converters (unit sizes of 10^1–10^3 MW) whose capacities are much easier to expand than those of wind and solar units. I was not at all surprised when Silicon Valley's supposedly transformative energy foray failed. In November 2011, just three years and one month after launching its *Clean Energy 2030*, Google abandoned the project and two engineers who worked on it admitted that "We felt that with steady improvements to today's renewable energy technologies, our society could stave off catastrophic climate change. We now know that to be a false hope" (Koningstein and Fork 2014).

Again, *nihil nove sub sole*: exaggerated appraisals of the new renewables are just the latest demonstration of two errors of judgment that are common during the early stage of technical advances. The early hype error overestimates the pace and extent of their adoption and their near- and midterm impact, and the replacement hype error sees them as swift and inevitable winners of the unfolding substitution process. In reality, diffusions of these new techniques do not proceed at uniformly fast rates; they encounter complications and setbacks and even after considerable periods of acceptance new machines and conversions will often coexist with long-established ways.

Given the repeated failure of exaggerated promises it is only fair to ask: are today's mandated shares of renewable energies and performance forecasts equally unrealistic? Jefferson (2008, 4116) gave a reasoned answer: "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 renewable technologies are pushed nationally with insufficient regard for their cost, contribution to electricity generation, transportation fuels' needs, or carbon emission avoidance." Keeping this in mind I now turn to recent plans that set their specific energy transition goals for 2020 and whose completion, with only a few years left to go, can be assessed with confidence.

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, 20). By 2013 (the latest all-EU count available) the share was up to 11.8%, and the continuation of the 2005–2013 gains would bring the total to no more than about 15% by the year 2020: achieving the set goal thus looks increasingly unlikely. But will not Germany, the policy's most determined promoter, achieve its goals as it pursues its much-publicized *Energiewende*?

In German *die Wende* can mean a gradual turnaround as well a sudden U-turn, and before its association with energy its most common use was in the latter sense, describing a swift demise of East Germany in 1989, a true U-turn. In contrast, *Energiewende* must be a protracted process—and yet many enthusiastic proponents in Germany, as well as many foreign observers, have made it a paragon of rapid decarbonization (Buchan 2012; Gielen et al. 2015; HIS 2014). The policy has deep roots in German infatuation with anti-industrial naturalistic-romantic-*völkisch* beliefs (so conspicuously absent in either of its two populous neighboring states, in France and Poland!), and its proximate beginnings go to the year 2000, with the Renewable Energies Law (*Erneuerbare-Energien-Gesetz*) adopted in order to subsidize increased generation of renewable electricity. This quest for decarbonization had intensified and was made even more challenging in 2011 when the Fukushima disaster led the German government to a hastily concluded decision to shut down all nuclear power plants by 2022 (in 2010 they produced 25% of Germany's electricity).

New rules favor renewable sources: producers of electricity generated by solar radiation, wind, and biogas (produced by the fermentation of crops) receive guaranteed fixed payments for 20 years—and renewably generated electricity was given preferential access to the national grid. When wind or solar electricity is available, the grid must absorb its intermittently spiking output even if that requires reducing (or even shutting down) the operation of thermal power plants burning fossil fuels. This has had the intended effect: by the year 2015 the share of renewable generated electricity (including hydro and all biomass) reached 30% of the German total, and a gloomy country where typical annual insolation is about 20% lower than in Seattle has become the world's leader in PV generation. Wind generation has also expanded rapidly, from less than 2% to more than 13% of total electricity output (BWE 2016). But a closer look reveals many corrective perspectives.

First, as significant as the shift in electricity generation has been, it has not been as radical as it is commonly portrayed: most notably, between 2000 and 2014 the mass of poor-quality *Braunkohle* (lignite) burned to generate thermal electricity did not decline (it was up by nearly 3%) while the volume of natural gas, the cleanest and the least carbon-intensive fossil fuel, had actually decreased by about 10% (BWE 2016). Second, *Energiewende* remains overwhelmingly *Stromerzeugungwende*, a shift in electricity generation rather than in total primary energy supply: in 2000 fossil fuels supplied 83.7% of all German energy; in 2015 the share was down just 4.3% to 79.4% (BWE 2016; Fig. 4.4; Appendix B).

Because of lower overall primary energy use the 2000–2015 decline of fossil fuel consumption was about 12% in total energy terms, but France, Germany's neighbor that has not had any deliberate decarbonization policy, reduced its reliance on fossil fuel by about 18% during the same period. And while wind and solar electricity generation get most of the news coverage, in 2014 they contributed only 22.4% to all primary energy derived

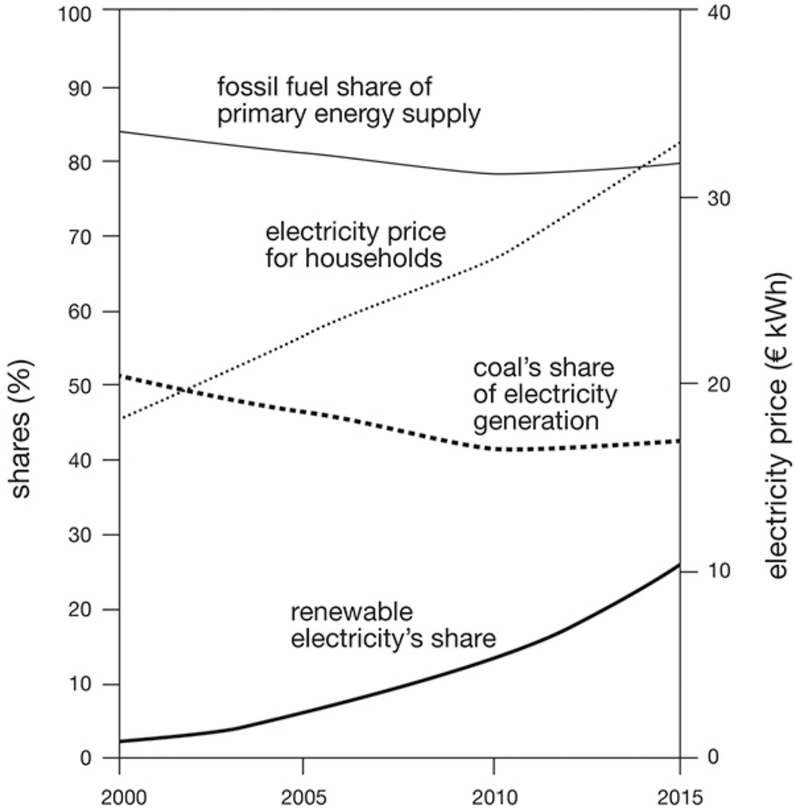

Figure 4.4 *Energiewende,* 2000–2015, in four revealing graphs: electricity's share generated from new renewables (wind, solar, and biomass) nearly 22 times up from 1.19% to 26%; electricity generated from coal down 16% from 50.5% to 42.2%; share of fossil fuels in primary energy supply down by just 5% from 83.7% to 79.4%; and cost of household electricity nearly 80% up from € 0.18/kWh to € 0.32/kWh. Plotted from data in BWE (2015).

from renewable sources: biomass, which accounted for 30% of Germany's renewables in 1990 rose to about 60% by 2014 (AGEB 2015). Most of that was domestic wood and wood pellets for electricity generation, but in order to meet its post-2020 green targets Germany will have to start importing biomass, a dubious enterprise that causes environmental impacts in the source areas (now mainly the U.S. South) and requires diesel fuel for intercontinental shipping.

Third, the rising reliance on wind and solar electricity generation has been costly, for many households burdensome. Germany now has the most expensive electricity among the EU's major economies: in 2014 households paid 48% more than in the UK, 73% more than in France and 2.1 times as much as in Poland (Eurostat 2015d; Fig. 4.4). In September 2013, *Der Spiegel*, Germany's leading weekly, entitled its report on new energy poverty "How electricity became a luxury good" (*Spiegel* 2013), and in 2014 the rising cost of German electricity created record numbers of people (350,000 households) disconnected from the grid for failing to pay the bills, and much larger numbers of customer (6.3 million) were threatened with such an action (Schultz 2015). Large industrial enterprises have been exempt from these rising prices, a practice that Europe's Competition Commissioner called an inadmissible subsidy (Dohmen, Pauly, and Traufetter 2013).

The challenge for the operators of large coal-fired power plants has been obvious: substantial (and not always well predicted) shares of their electricity become useless on windy and sunny days when renewables, with their preferential access to the grid, supply large portions of the demand for brief periods of time. That forces coal-fired stations to idle—but they must maintain sufficient capacities to cover any shortfalls during cloudy and calm days and during Germany's gloomy winters. But they, and not PV and wind, keep supplying the largest share of the country's electricity: 42% in both 2010 and 2015 (BWE 2016). Suddenly spiking renewable electricity flows have also created problems with the grids in neighboring countries that might be facing overloads of their transmission capacity.

Meanwhile the government subsidies for renewables continue to rise, and in 2013 a former minister of the environment, Peter Altmeier, told the *Frankfurter Allgemeine Zeitung* that the eventual cost may reach €1 trillion:

> *Das alles kann dazu führen, dass sich die Kosten der Energiewende und des Umbaus unserer Energieversorgung bis Ende der dreißiger Jahre dieses Jahrhunderts auf rund eine Billion Euro summieren könnten.* (All of this can lead to the cost of *Energiewende* and of the restructuring of our energy supply to be around one trillion euros by the end of the 2030s). (FAZ 2013)

Finally, the principal goal of *Energiewende* is to accelerate the decarbonization of Germany's energy supply. But between 2004 and 2014 the country's CO_2 from electricity generation declined by 5.4% (Umwelt Bundesamt 2016)—while during the same period American emissions from electricity generation decreased more than twice as fast, by 12.9% (USEIA 2016). America's no-target, no-mandate, essentially market-driven energy transition has been thus a more effective decarbonizer than the highly touted *Energiewende!* And by 2015 the official German target of reducing 2020 CO_2 emissions at least 40% below the 1990 level looked increasingly unrealistic: in 2014 they were 27% lower, but there was no reduction during the five years between 2009 and 2014, and the average for 2004–2014 was just 9 Mt/year. In order to achieve the 2020 goal this reduction rate would have to be tripled to 27 Mt/year (BWE 2015).

Renewables at 18% of total primary supply by 2020 are also unlikely. Succinctly, *Die Zeit* labeled this gap between green promises and actual performance *Schmutziger Irrtum*, dirty nonsense (Drieschner 2014). And yet so many people prefer to ignore these facts because they undermine the dominant simplistic narrative of *Energiewende* as an admirable, magic path toward greenness: many proponents of that forced shift refuse even to consider (pace Hans Christian Andersen's wise tale) that the new king of what *The Economist* called "a quasi-planned economy with perverse outcomes" (The Economist 2014) might not be fully clothed. But once all the vested-interest bureaucracies are in place, there is no end to new targets.

In 2010 the German federal government adopted an *Energy Concept for an Environmentally Sound, Reliable and Affordable Energy Supply* with specific targets for 2030 and 2050 (FMET 2010). I will review these targets, together with a number of other national goals for specific renewable sources or for combined renewable shares and with some recently outlined deep-decarbonization pathways in this book's closing chapter. There I will also contrast these aims and scenarios with carbon emission maxima compatible with preventing tropospheric temperature rise above 2°C and with more realistic trajectories informed by the past energy transitions.

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CHAPTER FIVE

Looking Ahead: Possibilities and Constraints

A long and complex history of energy transitions supports some generalizations, but it also provides many instances of exceptional achievements. Moreover, as is always the case with long-term perspectives, even the most robust and conservatively stated conclusions based on careful examination of available evidence may have only limited 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 unfolding energy transition—but it may also be because of the possibility of an unprecedented and persistent commitment to a rapid change.

My interpretation of the analyzed record and my understanding of the current technical capabilities and global commitment to act, and to persist, confirm that the lessons of history should not be dismissed by arguing that we face an unprecedented situation: although specifics have differed, that has been case with every past transition. On that basis, we are justified to conclude that many relatively rapid shifts are possible on national scales (and especially for smaller and less populous economies) and that partial transformations of electricity systems in some capable countries can proceed at relatively fast rates. At the same time, we must remember that changing the sources of electricity is much easier than changing the makeup of primary fuel supply, and that energy transitions on the global scale—and that is the only scale that ultimately matters as far as decarbonization and prevention of an excessive temperature rise is concerned—remain inherently protracted affairs.

As demonstrated by many plans and forecasts reviewed in the last section of Chapter 4, propensity to offer unrealistic "visions," to set excessively ambitious goals, and to discount known difficulties (to say nothing about ignoring the existence of unanticipated complications) shapes the perceptions of what is possible and achievable. Too many people who do not have requisite scientific and engineering understanding mistakenly accept such unrealistic opinions and goals as realistic outlines of what lies ahead and as the best practical precepts to follow. And many people who appreciate challenges and complexities of the unfolding transition have a benign view of unrealistic goals and excessive promises, seeing them as possibly helpful inspirational tools. I disagree as I continue to promote critical appraisals and stand ready to be pleasantly surprised as some of my insufficiently optimistic assessments may be surpassed by new realities.

And while the unfolding energy transition will share many general traits with the past shifts in primary energy supply, we must also understand that the process of restructuring the modern high-energy industrial and postindustrial civilization on the basis of nonfossil, that is, overwhelmingly renewable, energy flows will be much more challenging that was replacing wood by coal and then coal by hydrocarbons. I use the qualifier "overwhelmingly" in order to leave room for a possibility of substantially increased nuclear electricity generation—although (as I have already noted) the combined challenges of risk perception, public acceptance, permanent waste storage, and nuclear weapons proliferation do not make any early vigorous and widespread renaissance very likely.

Amid all of these uncertainties one thing is fairly assured: today's forecasts, targets, scenarios, and visions of a new energy world will turn out to be no less faulty than our past predictions and goals. With these lessons in mind I will review some recently prominent long-term goals and forecasts made by governments, international energy institutions, and companies. But we are facing an even greater (and fundamentally more important) gap than the one between uncritically enthusiastic goals and likely realities: in order to keep the average tropospheric temperature below 2°C the mass of allowable future CO_2 emissions is considerably smaller than the total that would be released even if today's aspirations for a relatively rapid transition to noncarbon energies were fully realized. And this challenge is made even more difficult by insufficiently appreciated indispensability of fossil fuels: it is the disparity between how little room for additional CO_2 emissions we have left if we are to limit the extent of global warming to a manageable level, and how much we depend on several critical fossil fuel uses that have no readily available alternatives.

There are some options for their gradual replacement but none that could be deployed on desirable scales in a matter of just a few decades. Smelting of iron ores in blast furnaces to produce cast iron, production of cement, and synthesis of ammonia are the three most important cases in this indispensable category. Just to be absolutely clear: by indispensable I do not mean that there is no conceivable prospect of doing away with this dependence but that the combination of the scale at which these materials are now produced (10^8–10^9 t a year), of enormous capital invested in the requisite long-lived supply and conversion facilities, of high quality of final products, and of their affordable availability precludes any rapid switches to alternatives, and that the global transition to low-carbon, and eventually even no-carbon, steel, cement, ammonia, and plastics will be a multigenerational process.

New renewables offer some highly desirable and technically and environmentally preferred solutions, but they also have drawbacks and face limits that are complicating their mass adoption, limiting the pace at which they can displace established sources and, in not a few instances, their mass-scale adoption would exchange one set of environmental impacts for another amalgam of long-term concerns about further encroachment on the biosphere's finite structural and functional boundaries. At the same time, it is obvious 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.

Every kind of energy transition could be accomplished faster, supported at a lower cost, and a new supply pattern could be perpetuated with lower overall impacts if we would not have to reckon with excessive energy consumption, now a common phenomenon embodied not only in mansion-type houses and SUVs but also in mass tourism (including cruising to nowhere and flights to subtropical and tropical beaches) or surfeit of throwaway personal electronics. As yet, there is no 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 future deep and protracted disruptions of existing production/consumption arrangements will help to accelerate the coming energy transition.

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. In this chapter I review first recent predictions and goals and then contrast the limited room for further carbon emissions (imposed by the need to limit the extent of global warming) with some indispensable (in near- to medium-term) uses of fossil fuels. I close the chapter by some musings on the nature of technical innovations and the process of energy advances, on remarkable inertia of energy systems and some of their particular components, and on numerous categories of surprises affecting their evolution. All of these factors are shaping the extent and determine the pace of unfolding energy transitions. I will emphasize that, in the long run, we need much more than just a fundamental shift in primary energies and dominant prime movers if we are to reconcile a decent quality of life for some 10 billion people with the preservation of irreplaceable biospheric functions.

Long-term Forecasts: Past Failures and New Visions

Repeated futility of long-term energy forecasts, on the national level as well as on the global scale, has been well documented (Craig, Gadgil, and Koomey 2002; IRGC 2015; Smil 2003), and some of the recent instances regarding the progress of renewable energies were reviewed in Chapter 4. What has been so remarkable about so many energy forecasts and targets is that they not only missed their goals by large margins but that they ended up as complete failures. There is not a single commercial breeder reactor operating anywhere (they should have been dominant by now), the world is still consuming nearly 3 Gt of traditional biofuels (none should have been consumed by this time), no nuclear explosives have been used to stimulate production of natural gas or to "excavate" canals, and the world is not about to run on hydrogen (NRC 2004; Rifkin 2002). Excavating the cemeteries of failed energy forecasts reveals that excessive performance expectations are the norm, not the exception.

But the opposite sentiments, fear and panic, also have been in evidence. Their most dependable post-1973 expression has been the recurrent concern about runaway oil prices: as recently as 2013 they were forecast to surpass $200/barrel! Perelman (1981), just after OPEC's second round of crude oil price increases, forecast perennial energy supply problems during the 1980s and 1990s, accompanied by a high degree of social conflict and disorder. Instead, crude oil prices remained relatively low and remarkably stable for the remainder of the 20th century, and since 2013, instead of rising above $200, they fell below $30/barrel. And the 1990s witnessed a (still insufficiently appreciated) peaceful demise of the USSR, the world's most militarized empire, and remarkable economic expansion in the United States and China, all in total contradistinction to Perelman's dystopian futures.

This dichotomy of visions continues. During the past two decades the concerns arrayed at one end of the spectrum (worrisome if not quite catastrophist) included not only the much publicized predictions of an imminent global peak of oil extraction but the peak of everything (Heinberg 2007), with logically associated end of global development as we know it (Kearns 2014) or even with the slide to the postindustrial stone age (Duncan 1996). On the other hand, there has been no shortage of unrealistic scenarios outlining rapid and easy transitions to a noncarbon world. The conclusion reached by a systematic examination of energy forecasts for the United States is applicable to long-term forecasting in general: it showed that the key failure was a systematic underestimation of uncertainties, above all the importance of surprises unaccounted for by their models (Craig, Gadgil, and Koomey 2002).

Unfortunately, most long-term forecasts continue to be made as if such uncertainties had no place in determining the final outcome. This is even more remarkable given the number of recent discontinuities—ranging from the deepest post–World War II recession in 2008 and 2009 to falling oil prices of 2014–2016—whose consequences have many worldwide implications. With this in mind, I will review some important long-range global and national forecasts, goals, and scenarios, most of them extending to 2030 and 2040. As far as I know, nobody has outlined a vision of a future noncarbon world that would be more extreme, and that would be realized far faster than any previous energy transition in history, than Jacobson and Delucchi (2009).

To supply the world with 100% renewable energy (electricity and electrolytic hydrogen), they envisage 3.8 million 5-MW wind turbines, 40,000 300-MW central solar plants, 40,000 300-MW solar PV plants, 1.7 billion 3-kW rooftop PV installations, 5,350 100-MW geothermal plants, 270 new 1.3-GW hydro stations, 720,000 0.75-MW wave devices, and 490,000 1-MW tidal turbines. And all that, they claim, faces no technical or economic barriers! Fictional nature of these visions is easily demonstrated by noting the up-scaling needed to achieve those goals. When compared to 2015 the overall installed capacities would have to go up 30-fold for wind, 100-fold for geothermal power, and 500-fold for tidal power—and in addition we would have to build 40,000 new large (300 MW+) PV plants and nearly 50,000 new central solar plants, as well as more than 700,000 wave-conversion projects.

Moreover, the incredible expansion rates (1–5 of orders of magnitude) in just 15 years would have to be accompanied by unprecedented extensions of high-voltage transmission and by the creation of an entirely new, hydrogen-based society (even when leaving aside such minor problems as converting all jetliners to hydrogen or using hydrogen to smelt all iron ore in just 15 years!). Comments sent to the *Scientific American* had immediately exposed the delusionary nature of this poorly thought-out academic exercise. Briggs (2009) concluded that "As a physicist focused on energy research, I find this paper so absurdly poorly done that it is borderline irresponsible. There are so many mistakes, it would take hours of typing to point out all of the problems. . . ."

But this has had no effect on Jacobson who continues to promote a rapid transition to "100% clean, renewable energy" (The Solutions Project 2016). There is perhaps no better way to highlight how utterly unrealistic such proposals are than to cite the expectations of recent decarbonization studies published by the Deep Decarbonization Pathways Project (DDPP) that has been convened under the auspices of the Institute for Sustainable Development and International Relations and the Sustainable Development Solutions Network (DDPP 2015). Individual studies in this series have been prepared by national teams in order to outline scenarios leading to the highest practically conceivable decarbonization by 2050—and even those do not show complete demise of fossil fuels by 2050.

China has been the world's largest investor in renewables—in 2014 more than 70% ahead of the United States (Chu 2015)—but given the size of its energy demand, its future economic growth, and its current dependence on fossil fuels, its primary supply cannot be transformed rapidly. The deep decarbonization study concluded that primary energy demand could rise by about 60% between 2010 and 2050, with coal, oil, and gas supplying nearly 60% of the 2050 demand, with coal still at least 25% of the total (Teng et al. 2015). For the United States in 2050 the most aggressive decarbonization scenario would cut the carbon emissions by about 80%, but it would still leave fossil fuels with 17% of final energy use, while the high nuclear scenario would have 58% of the 2050 supplied by fossil fuels (Williams et al. 2014). Similarly, the official goals for the adoption of nonfossil energies in Sweden and Germany, the two most enthusiastic proponents of renewable conversions, confirm that multidecadal transitions are unavoidable.

The latest Swedish goal was announced in November 2015 as the government reserved SEK 4.4 billion in its 2016 budget to start putting Sweden in the trajectory that should make it "one of the world's first fossil-free welfare countries" (Government Offices of Sweden 2015) by 2050. Even if we assume that the goal will be reached as far as the domestic combustion of such fuels is concerned, can any country in the global economy be fossil fuel–free as long as most other countries continue to rely on such energies? Sweden that would burn no oil within its borders would require the Swedes to do without any imports that come as air cargo or are carried by container vessels and bulk cargo ships because it is very unlikely that the global transportation will stop burning liquid fuels by 2050. Or would they reload all imports from the EU on trucks fueled by biofuel before they reach Swedish shores?

As already noted, in 2010 Germany's federal government adopted an *Energy Concept for an Environmentally Sound, Reliable and Affordable Energy Supply*, and its specific targets for 2030 and 2050 goals are as follows (FMET 2010). By 2020 renewables are to supply at least 35% of all electricity and 18% of all primary energy, while greenhouse gas emissions should be reduced at least 40% below the 1990 level. The analogical goals for 2030 are, respectively, at least 50%, 30%, and 55%, and in 2050 they should reach at least 80%, 60%, and reduction of CO_2 emissions of at least 90%–95% (Fig. 5.1).

Since 2010 it has become obvious that if the targets for 2030 and 2050 are to be achieved, or at least closely approached, much more will be needed than the continuation of recent practices. In any case, it is worth stressing that even *Energiewende*'s complete long-term success would mean that 40% of Germany's primary energy would still come from fossil fuels by 2050, confirming the multigenerational dimension of energy transition for even

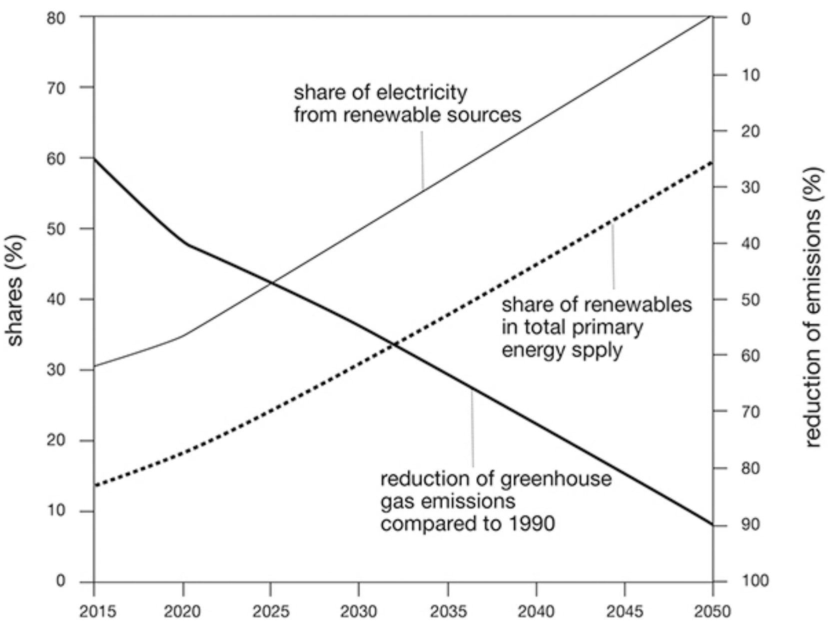

Figure 5.1 Targets for German shares of renewable electricity generation, renewable primary energy supply, and greenhouse gas emissions until 2050 (FMET 2010).

the fastest deliberately policy-driven shift. Germany has been unique in setting up so many goals for different time periods: most of the renewable targets defined by more than 160 countries apply only to electricity generation or to one of its specific modes, most commonly wind or solar (IRENA 2015b; REN21 2015).

Among the countries that set the overall goals for renewables in primary energy supply in 2030 the shares are just 10% for Nepal, 11% for South Korea, and 18% for Ukraine. EU has the target of at least 27% of gross final energy consumption, binding at the EU level but not at national levels. The United States has no official target, but in August 2015 President Obama's proposed Clean Power Plan would raise the share of renewables to 28% of electricity-generating capacity in 2030 while reducing CO_2 emissions by 32% compared to 2005 (White House 2015). As for the total energy supply, the U.S. Department of Energy anticipates essentially saturated demand and slow, gradual transition. Modest growth of energy supply (0.3%/year) until 2040, improved conversion efficiencies, and shift to natural gas should keep the U.S. CO_2 emissions below their 2005 level, while the total renewable share of electricity generation would rise from 13% in 2013 to 18% in 2040 (mostly in hydro and wind) in its reference scenario and to 22% in the case of high oil prices (USEIA 2015g).

Finally, it comes as no surprise that long-term forecasts by international energy institutions and by the world's largest energy-producing companies do not envisage any radical shifts by 2040, only continued reduction of shares supplied by fossil fuels and rising, but still secondary, importance of renewables. In its annual outlook ExxonMobil (2016) sees coal undergoing the greatest relative decline (from 26% in 2014 to 20% in 2040), natural gas would go from 22% to 26%, crude oil from 34% to 32%, nuclear from 10% to 8%—and fossil fuels would still account for 78% of the total supply by 2040. Hydro would go from 2% to 3%, and all other renewable energies would double their overall share, but that would still leave them at only 4% by 2040. OPEC's *World Oil Outlook* has both coal and oil at about 25% in 2040 with natural gas at 28%, nuclear at 6%, hydro at 2.5%, biomass at 9.5%, and other renewables at 4.3%, with fossil fuel share almost identical to Exxon's expectations at about 78% (OPEC 2015).

For the year 2030 the International Energy Agency prepared two scenarios, one reflecting the submitted Intended Nationally Determined Contributions (INDCs) toward reduced carbon use, the other one to meet the goal of staying below 450 ppm CO_2 (IEA 2015c). The INDC scenario has fossil fuels generating 56% of all electricity in 2030, compared to 42% in the 450 scenario, but the difference for the global primary energy mix would be much smaller, with, respectively, 76% and 69% coming from fossil fuels, compared to about 80% in 2015 (recall that IEA's share of fossil fuels is lower than in BP's accounts, as the former primary energy total also includes all traditional biofuels).

For 2040 IEA offers four scenarios (IEA 2015d). Its central forecast is the New Policies Scenario (NPS) reflecting actual steps as well as many pledges made in 2015; the Current Policies Scenario (CPS) considers only the policies enacted as of mid-2015; a Low Oil Price Scenario (OPS) looks at the effect of lasting low oil prices; and the 450 Scenario (450) conforms to a trajectory that would limit the rise of average global temperature to 2°C above the preindustrial levels after 2100. There are substantial differences between CPS and NPS on one hand and 450 on the other, but relative reductions are not that large: by 2040 the global primary energy demand according to the NPS is less than 10% smaller than for the CPS while 450 is about 23% lower.

But even under the IEA's 450 scenario fossil fuels supply 60% of the global energy demand by 2040, compared to 75% under the NPS and 79% under the CPS. Biofuels would be the leading renewables under the 450 scenario, supplying 15% of all demand in 2040, followed by other new renewables with 10% and hydroelectricity with 4% for the total of 29% compared to 17% under CPS. Once again, long-term projections by the world's leading energy-monitoring and forecasting institution do not indicate anything but gradual transition from fossil fuels to renewables unfolding at a rather measured pace. Two key considerations should be addressed at this point.

First, what is the total allowance for additional fossil fuel–derived CO_2 emissions compatible with limiting the average tropospheric temperature rise to no more than 2°C? That total is impossible to pinpoint, but it is definable within fairly narrow limits, and it would be the key determinant of our actions if that temperature limit would be the paramount guide of the world's energy policy. The second concern focuses on the opposite reality, on those dependencies on fossil fuels that are either truly indispensable in the short term (10–20 years) or that would require uncommon efforts to be completely replaced over longer (20–40 years) periods.

Climate Change Challenge: How Much More CO_2 Can We Emit?

Broad global consensus signaled by the Paris COP 21 meeting in November 2015 aspires to limit the rise of average tropospheric temperature to no more than 2°C, and preferably to just 1.5°C (UNFCCC 2015). If we were to adhere to this goal, then there are only two options that would allow us to keep burning fossil fuels for decades to come, and do so at rates that would be limited only by the prevailing demand and by the availability of economically recoverable resources: we would have to resort to mass-scale carbon capture and storage (CCS)—or we would have to engage in geoengineering projects aimed at cooling the planet.

As of 2015 there was no shortage of carbon capture and storage proposals, plans, and scenarios (NRC 2015; Williamson 2016). After years of exaggerated promises, there were finally 15 fair-sized CCS projects in operation and 7 under construction with the combined annual CO_2 capture capacity of about 40 Mt (Global CCS Institute 2016). The new CCS industry calls them "large-scale," and while some of them are still mostly experimental, others are a part of commercial industrial operations. There were also 9 projects in advanced planning stages and 12 in earlier stages of development. If all of them were built, the grand total of CO_2 sequestered annually by 2020 would be about 77 Mt CO_2 a year—an equivalent of about 0.2% of total 2015 emissions. This comparison alone puts the challenge of any effective CCS into proper perspective: even if a 10-fold scale-up of these existing and planned efforts were to be accomplished during the 2020s, we would be removing still only a few percent of all emissions.

And the prospect for any geoengineering projects large enough to make a real difference is far dimmer. Again, there is no shortage of suggestions, plans, and scenarios but, unlike with the incipient commercialization of CCS, no actual deliberate geoengineering steps have been taken to reduce the incoming radiation, to increase the planetary albedo, or to maximize carbon sequestration (Keith 2013; Morton 2015; Srbulov 2014). Moreover, it is highly unlikely that we will soon have either a clear global agreement that would license nations with requisite technical capacities to proceed individually with assorted alterations of the Earth's radiation balance or that a global facility would be set up with multinational funding in order to undertake consensual planetary manipulations on behalf of the entire humanity.

Once we conclude that we are either unable or unwilling to resort to CCS on sufficiently massive scale (that would mean annual removal of at least 10 Gt of CO_2, more than 100 times the capacity of projects operating and planned in 2015) or to prolonged alterations of planetary radiation balance, then the only way to limit the tropospheric temperature rise is to restrict the future combustion of fossil fuels and hence to keep the resulting CO_2 emission below the allowable limit. That cumulative maximum (when set with 90% confidence) amounts to just 730 Gt C, and when defined at 66% confidence level it goes up to about 1,000 Gt C. In either case it would apply if we were to take into account only the warming impact of CO_2; once we also consider non-CO_2 contributions the available budget at 66% confidence level declines from about 1,000 Gt C to 790 Gt C.

Between 1750 and 2015 CO_2 emitted from the combustion of fossil fuels added up to about 550 Gt C, which means that we should not (at 66% confidence level) emit more than about 450 Gt C or that the "allowance" is as small as 240 Gt C (IPCC 2013). This means that even if we were able to stabilize CO_2 emissions at the 2015 rate of about 9.5 Gt C, we would exhaust the lower allowance in just 25 years, and the fossil fuel era would come to the end by 2040. The higher limit would give us about 47 years of emissions at the 2015 level, but in reality we would have to adhere to some gradual reduction of annual emissions, and any number of scenarios can be proposed how we could burn the allowance at a gradually declining rate. For example, reducing 2015 annual emissions by 10% per year would give us more than 60 years before we would run out of the 240-Gt C allowance.

In any case, adhering to the limits required by the 2°C temperature cap would end the fossil fuel era in a matter of decades. **In reality, the challenge is even greater because CO_2 emissions are expected to rise—and do so even if all the national promises pledged at the Paris COP 21 meeting were completely fulfilled. The adoption document noted "with concern that the estimated aggregate greenhouse gas emission levels in 2025 and 2030 resulting from the intended nationally determined contributions do not fall within least-cost 2°C scenarios but rather lead to a projected level of 55 gigatonnes in 2030," which would mean "that much greater emission reduction efforts will be required than those associated with the intended nationally determined contributions in order to hold the increase in the global average temperature to below 2°C above pre-industrial levels" (UNFCCC 2015, 3).**

Emissions of 55 Gt CO_2 (15 Gt C) by 2030 would be roughly 50% higher than in 2015. Lower rates of the global economic growth could reduce this increase significantly, but emission declines without any specific interventions are unlikely. Could this be turned around? Do we have solutions to pursue aggressive decarbonization that would combine already established techniques with innovations that may be seen on the verge of mass-scale commercialization? Could our ingenuity and determination allow us to displace all fossil carbon in just a few decades? Answering these questions in a realistic manner requires us to assess the existing options (regardless of their current cost, adoption, or acceptance) and then to separate theoretical possibilities from those likely commercial advances that could make a relatively rapid (within a few decades) and substantial difference (claiming appreciable market shares) on the global scale.

But before getting to such appraisals I must introduce a major consideration that will complicate any quest for rapid decarbonization: the extent to which we rely on specific fossil fuels, not only as energizers of major industrial processes but also as excellent feedstocks, in order to mass-produce materials whose ubiquitous uses truly define modern civilization—and the fact that we do not have either any noncarbon processes and feedstocks or any suitable non-carbon-based substitute materials that could be deployed both rapidly and on requisitely large scales. The only practical and immediately effective options are to minimize the use of such materials—by further relative dematerialization (reduced mass per unit, or per unit of performance) and eventually achieving absolute reductions in uses—and to maximize their reuse and recycling.

Indispensable Fossil Fuels: Steel, Cement, Ammonia, and Plastics

Inexplicably, most analyses contemplating the shift from fossil fuels to renewable energies ignore the indispensable roles played by high-quality coal and by several kinds of hydrocarbons as critical raw materials or energizers (or both) of leading industrial processes that produce key materials whose mass-scale deployment defines modern economies and enables unprecedented numbers of people to enjoy a high quality of life—and that cannot be made on such large scales by any readily available commercial alternatives that would operate without fossil carbon. None of those materials is more important than steel, the leading metal in modern infrastructures and the dominant component of industrial products ranging from pipelines to oceangoing vessels, from cars to agricultural machinery, and from machines used to make other machines to an enormous assortment of professional and household tools.

Almost 30% of global steel (and much higher shares in some countries, about 60% in the United States, 75% in Spain) has been made recently by recycling the scrap metal in electric arc furnaces. That process, now energized mostly by electricity generated by the burning of fossil fuels, could eventually run entirely on electricity originating from renewable conversions. But about 70% of all steel (in absolute amounts it has been recently about 1.1 Gt/year) continues to be made in basic oxygen furnaces by decarburization of cast iron (by reducing its carbon content from around 4% to usually less than 1% C) that is produced in blast furnaces. These furnaces are charged with sintered or pelletized iron ore, flux (limestone or dolomite to carry off the impurities), and metallurgical coke produced by pyrolysis (destructive distillation) of coking coal, typically at rates of 300–450 kg/t of hot metal (Smil 2016a).

Coke (virtually pure carbon with 31 GJ/t) has two indispensable roles in blast furnaces. First, its oxidation produces the reducing gas (CO, whose reaction with iron oxides yields elementary iron) and energizes the smelting process by generating temperature (1538°C) required to liquefy the metal. Second, coke's strength and porous structure make it possible for the furnace to run as a counter-current reactor: it creates the permeability that allows the ascent of heat and reducing gases and descent of slag and metal. In order to reduce coke demand, modern blast furnaces get injected (through their tuyères) with powdered coal, with typical amounts around 200 of coal/kg of hot metal. Production of metallurgical coke required about a billion tonnes of coal in 2015 and no noncarbon alternative is commercially available for this key industrial process. The two carbon alternatives—using a variety of fossil fuels in direct iron reduction processes, and charging blast furnaces with charcoal—account for relatively small shares of global iron smelting and cannot be rapidly scaled-up to produce a billion tonnes of iron a year.

Various processes of direct iron reduction are the only commercialized class of fossil carbon alternatives. Direct reduction techniques, dominated by the MIDREX process, have fallen far short of early hopes for their rapid success. In 1980 they produced only 1% of the primary metal, in 2015 less than 5% (WSA 2015). They use mostly natural gas (reformed to yield CO) as the reductant, but they also derive CO directly from coal, petroleum coke, or from heavy refinery residues processed in a gasifier or from coke oven gas. Direct iron reduction broadens the choice of reductants but still requires fossil carbon—while relying on nonfossil carbon would have profound technical, economic, and environmental consequences.

Charcoal (also virtually pure carbon) is an excellent reductant, it was the only choice to smelt iron ore during the precoke era, its use persisted in many countries well into the 20th century, and it is still important in Brazil. But charcoal is too fragile: its compressive strength is only one-quarter of that of typical metallurgical coke at 1,000°C (Emmerich and Luengo 1996; Haapakangas et al. 2011). That is too low to support heavy ore and flux charges in tall blast furnaces: charcoal would get crushed and could not maintain the porosity required for ascending gases and descending hot metal, eventually causing the collapse of charged materials and the end of the smelting process.

Consequently, charcoal use limits the height (and volume) of blast furnaces to about 8 m (no more than 400 m^3); in contrast modern blast furnaces are taller than 30 m, and their internal volumes range up to 5,000 m^3, offering unprecedented economies of scale. Switching from coke to charcoal would thus require closure of large, modern furnaces, mass-scale construction of smaller units, and inevitably higher production costs—even if requisite wood supply for charcoal production could be secured. But such a massive switch would necessitate establishment of extensive plantations of fast-growing tree species, their mechanized harvesting, and more efficient ways of large-scale charcoaling—and still result in inferior productivities and significant negative environmental impacts.

The only commercial-scale charcoal-fueled smelting is in Brazil where the fuel is used to produce about a third of the country's pig iron (Uhlig 2011). Brazil's practices offer no template for global up-scaling. About a third of all wood comes from illegally harvested rain forest (responsible for about 15% of the Amazon's deforestation), the rest from eucalyptus plantations, and charcoaling is primitive (with no by-product recovery, efficiency of only 25%, and with large uncontrolled emissions of NO_x, SO_x, benzene, methanol, phenols, naphthalene, and polycyclic aromatic hydrocarbons) resulting in hazardous working conditions (Kato et al. 2005).

Using the same practices to produce all iron in 2015 would consume at least 3 Gt of wood—compared to roughly 2.3 Gt of wood harvested for lumber and pulp (FAO 2016). Charcoal-fueled iron smelting operating at the 2015 level would thus require a 2.5-fold increase of global commercial wood harvest, and if the production were to be concentrated mainly in the tropics it would necessitate more than a 20-fold increase in the global wood trade (shipping charcoal would be associated with larger losses of that friable fuel). With average yields of 15 t/ha just over 200 Mha, or slightly more than half of Amazon basin, would be needed to secure that wood.

But this could be dismissed as an excessively pessimistic scenario because the need for large charcoal output would improve wood yields and conversion efficiency. High-yielding eucalyptus clones could produce 25 t/ha (Pfeifer, Sousa, and Silva 2012), and charcoaling in continuous retorts could be 35%–40% efficient (Rousset et al. 2011): this could produce the needed wood from about 125 Mha. But nontropical charcoal would be needed in order to reduce further risks to tropical rain forests, and it is unrealistic to expect sustained harvests of 25 t/ha in all environments: long-term yields may be only 10–15 t/ha in plantations of hybrid poplars, pines, or willows (Smil 2015a). Even when ignoring the higher cost of charcoal-based iron smelting, developing a global industry handling 3 Gt of wood a year harvested from more than 100 Mha is not a scaling challenge for a decade or two.

The Technology Roadmap Research Program of the American Iron and Steel Institute defines an ideal future ironmaking process as one that eliminates all coke and coal and uses low-quality iron ores to produce enough metal (5,000–10,000 t/day) to supply existing steel mills (AISI 2010). The roadmap's best no-carbon or low-carbon alternatives are suspension reduction of iron ore concentrates, molten oxide electrolysis, and paired straight hearth furnace. The first method, known as Novel Flash Ironmaking, would be the most effective: it would reduce fine iron oxide concentrates sprayed into the furnace chamber by natural gas, syngas, hydrogen, or their combination (AISI 2014). Hydrogen use would cut CO_2 emissions by 96% compared to traditional ironmaking. An evaluation of these innovative techniques concluded that hydrogen reduction and electrolysis would become economically attractive by the middle of the 21th century (Fischedick et al. 2014), confirming the fact that the combination of high efficiency, high productivity, and longevity of blast furnaces (some campaigns last more than 20 years) make it very difficult to displace them.

Cement comes next in terms of the total mass of fossil fuels used to produce common materials. Its production relies mostly on coal and petroleum coke whose combustion is responsible for only about 35% of CO_2 emitted by the industry; most of the gas is released during calcination from heated $CaCO_3$ (IPCC 2001). Global CO_2 emissions from cement industry rose from about 1% of the total produced by fossil fuel combustion in 1950 to more than 5% in 2015 (CDIAC 2016), and there are several options for their elimination or reduction. Novacem proposed to eliminate calcination emissions by using magnesium silicates instead of limestone. Licht et al. (2012) favor a new solar thermal electrochemical process that would emit no CO_2 and reduce energy consumption. Calera plans to make $CaCO_3$ from sea water mixed with CO_2 emitted by fossil fuel combustion (Calera 2016). And Vance et al. (2015) would recombine CO_2 captured from calcination with calcium hydroxide to recreate limestone, and this would also reduce energy use by about half.

In 2012 the intellectual rights of insolvent Novacem were sold to Calix, an Australian company that has been developing its own process of CO_2 separation and capture in cement production (Tickell and Macalister 2012). By 2015 none of these proposed techniques has been available for commercial use and given the industry's global size—recent output of more than 4 Gt/year, or about the same mass as the total of extracted crude oil, consuming an equivalent of more than 500 Mt of coal—it is obvious that, again, no energy transition in this key industrial sectors can be accomplished in one or two decades.

Similarly, no rapid retreat from the prevailing practices can be expected as far as synthesis of ammonia, the first step in producing all modern nitrogenous fertilizers, is concerned. Haber-Bosch process of ammonia synthesis, invented in 1909 and commercially introduced in 1913, still dominates the production (Smil 2001; USGS 2016). The process now relies on methane, both as a feedstock (to yield hydrogen) and as a fuel for energy-intensive combination of nitrogen (derived from air) and hydrogen to form

NH_3 whose further processing makes various solid and liquid nitrogenous fertilizers, now dominated by urea.

The world now produces about 175 Mt of NH_3 (80% used by fertilizer industry, the rest in many chemical processes) whose synthesis consumes annually about 5% of natural gas extraction. There is a well-established alternative for synthesizing nitrogen fertilizers that relies on high-temperature electric arc to oxidize atmospheric nitrogen and then to convert the resulting NO to NO_2 and HNO_3, but it is predicated on an uninterrupted supply of inexpensive electricity. That is why Norsk Hydro was the only company to support it, between 1911 and 1991, in its Rjukan plant powered by electricity produced by water diverted from a waterfall (Norsk Hydro 2015).

Finally, annual production of more than 300 Mt of plastics—energy-intensive materials that need typically between 80–150 GJ/t to synthesize (Smil 2014)—depends on liquid and gaseous hydrocarbons (mostly methane and ethane) for its feedstocks and energy. There are alternatives as some plastics are already produced on small scale from cellulose, starches, and ethanol, but these options are not ready to be deployed rapidly on mass scales. Moreover, overall environmental impacts of sourcing raw materials and synthesizing new compounds may make new bioplastics no less problematic than the standard hydrocarbon-based compounds.

A recent claim of synthesizing polyethylene furandicarboxylate from 2-furan carboxylate (Banerjee et al. 2016), praised for opening a new route toward the production of polymers that uses CO_2, is a good example of these limitations. The route via 2-furan carboxylate is new, but the compound is made by oxidizing furfural that must be derived from such pentosan-rich phytomass as corn cobs (30% by weight), cereal straws (24%–30%), and sugarcane bagasse (25%), all of which have competing uses including animal feed, recycling to maintain soil and organic matter, and fuel to energize sugar extraction or ethanol fermentation. Current furfural yields have been around 50% but can be improved to more than 60% (Mai et al. 2014). In any case, careful appraisals of reliably available raw material supply would be needed before setting up mass-produced plastics based on furfural.

My calculations show that in 2015 global production of steel, cement, ammonia, and plastics emitted about 1.9 Gt C, or nearly 20% of the anthropogenic total. Growing demand for these commodities will negate most (or all) reductions due to steady efficiency gains stemming from technical advances (typically 1%–2%/year). This increased demand will be especially important for the development of Asia's (above all India's) and Africa's urban, industrial, and transportation infrastructures and for the expansion of their food production. About 75% of the global population increase during the next five decades will be in Africa and India where typical per capita consumption of energy and materials is still only a fraction of China's recently achieved averages.

Inevitably, this continuing dependence on fossil fuel will also affect new renewable energy conversions. For example, my calculations (Smil 2016b) show that if by 2030 wind-generated electricity were to supply 25% of the global demand (and do so with a high average capacity factor of 35%), the installation of 2.5 TW of new wind turbines would require about 450 Mt of steel (not counting the metal for towers, wires, and transformers and new high-voltage transmission links) whose production (at 35 GJ/t) would consume more than 600 Mt of coal. Production of plastic turbine blades would consume the equivalent of about 90 Mt of crude oil.

Similarly, Wilburn (2011) calculated that if the United States were to derive 20% of its electricity from wind turbines in 2030 annual consumption rates required to achieve this goal would include nearly 7 Mt of concrete, 1.5 Mt of steel. 0.3 Mt of cast iron, 40,000 t of copper, and 380 t of the rare-earth element neodymium. Additional fossil energy would be needed to produce diesel fuel for trucks and heavy construction machinery used to transport and erect the machines and for lubricants to keep them operating. And while a well-sited wind turbine could return all of this embodied energy in less than a year, all of it will be in the form of intermittent electricity—while specific fossil fuel energies will be needed to produce, install, and maintain the machines.

Continuing dependence on fossil fuels will exert a moderating effect on the pace of global decarbonization, but many promoters of new renewables have stressed the features of the unfolding transition that appear to be well suited to accelerate its process. Wind turbines and PV modules are already priced competitively in many settings; their modularity facilitates upscaling; in the early stages of their diffusion they may pose no, or only minimal, problems of integrating their generation into existing grids; their cleanliness and safety of operation is a strong asset; and the spin-offs from the quest for their improved performance benefit the entire energy system.

But does this mean that diffusion of new renewables, be it on national or global scales, has been proceeding faster than the adoption of the established energy conversions? Do they constitute a new class of energy innovations more akin to the ascent of modern electronics than to the diffusion of steam turbines? I will show that the latter is not true. And I will also show that our existing energy systems are massive, complex, and strongly embedded in the fabric of modern civilization, and they will not be rapidly transformed by new energies. Finally, I will stress the limits of our understanding due to inevitable surprises.

Pace of Transitions: Innovations, Inertia, and Surprises

I must address first an important notion of accelerating technical advances because this expectation has greatly influenced the opinions about the speed of decarbonization. The notion of generally accelerating pace of technical innovation has been driven primarily by some admirable advances in computing capacities—but 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 20th 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 and Meyer 2003, 2).

And—as attested by the existence of Accelerating Innovation Foundation, Center for Accelerating Innovation and the Institute for Accelerating Change—Kurzweil's is hardly an isolated belief. Many people believe that the new renewables, much like the new information and communication techniques whose rapid growth has been driven by steadily rising capabilities and steadily falling prices of microprocessors, will diffuse at rates far surpassing the past transformations of energy supply. If true, the lessons from past historic transitions would be irrelevant and the world's energy supply could be completely decarbonized in just a few decades.

Moore's Curse

Gore made the analogy between the two classes of these modern techniques quite explicit: "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, 6). There are two fundamental problems with this unfortunate comparison. Steadily rising performance of microprocessors (chips) has hardly anything to do with declining prices 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 a few percent of the total value of a finished microprocessor.

That phenomenal increase in microchip performance (and hence a huge drop in cost per unit of operation) has been overwhelmingly due to the crowding of 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 2 years. For five decades the Moore's law has stood the test of time—or Intel's efforts have made it a self-fulfilling prophecy (Intel 2015). That relentless progress is finally slowing down (Waldrop 2016), but it 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 (Fig. 5.2).

Microprocessors have made energy supply and use less expensive, more reliable, and more efficient, but their use has not changed the fundamental parameters of the established techniques: advances in energy extraction, harnessing, and conversion have not been governed by rapid doublings of performances. Even after doubling Moore's average doubling period 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. 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

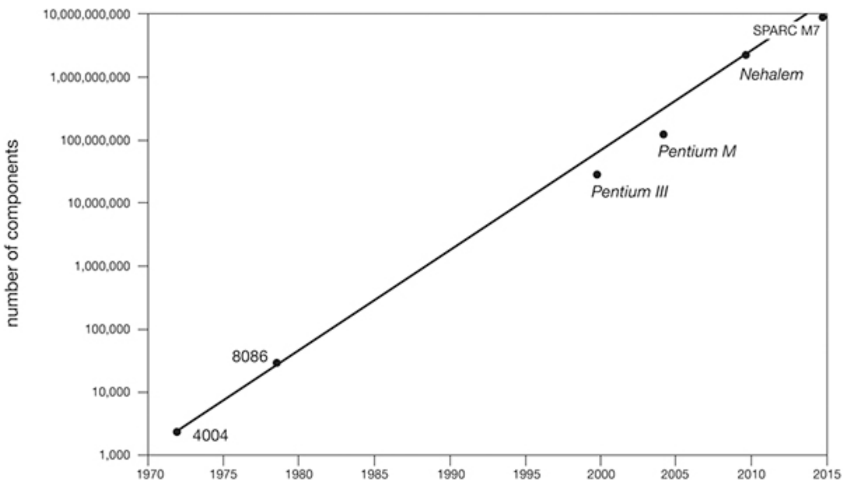

Figure 5.2 Moore's law. Plotted from data in Intel (2007) and Waldrop (2016).

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 few decades (Smil 2006; Yeh and Rubin 2007).

Efficiency of thermal electricity generation, now the source of some 80% of global electricity, rose annually by about 1.5% during the 20th century when comparing steam turbogenerators, and by 1.8% when comparing the best steam turbogenerators of 1900 with combine cycle gas turbines of 2000—but capacity of typical turbogenerators has been stagnant since the early 1970s and U.S. statistics show that average annual improvements of nationwide power plant heat rates were just 1% between 1950 and 1980, and merely 0.2% between 1980 and 2015 (USEIA 2016). Energetic, material, and transportation fundamentals that enable the functioning of the modern civilization and that circumscribe its scope of action are improving steadily but slowly: performance gains range mostly between 1%–3% a year, as do the long-term declines in cost of those essential inputs.

Quotidian innovations outside of the microchip-dominated world of information and communication do not obey Moore's law; their progress is an order of magnitude slower. 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 6-fold between 1950 and the year 2000, while gas turbines in flight increased their maximum power roughly 10-fold in 25 years, from de Havilland Ghost engine with the thrust of 22 kN in 1945 to Pratt & Whitney's JT9D with the thrust of 210 kN certified in 1969 (Smil 2010a).

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 does this conclusion—based on the advances of long-established, and hence obviously mature, techniques—apply to the new renewables? Is not the comparison of new renewable conversions and microchip performance at least partly valid? The best way to answer these questions is to focus on the three most promising new energy conversions, on wind-driven and PV electricity generation and on the production of liquid biofuels.

Commercialization of large wind turbines has shown notable capacity advances. 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). Fifteen years later the highest capacity reached 4.5 MW, and in 2014 Vestas introduced its 8-MW machine. This means that the maximum capacities of the largest wind turbines have been increasing by more than 11% a year. But such rate of growth for energy converters is not at all unprecedented during an early stage of technical innovation: during the identically long spell of 28 years, between 1885 and 1913, the maximum capacity of steam turbines increased from 7.5 kW to 20 MW, averaging annual growth of 28% (Fig. 5.3).

And while average conversion efficiency of steam turbines has been rising along with their growing capacities, the best conversion efficiencies of

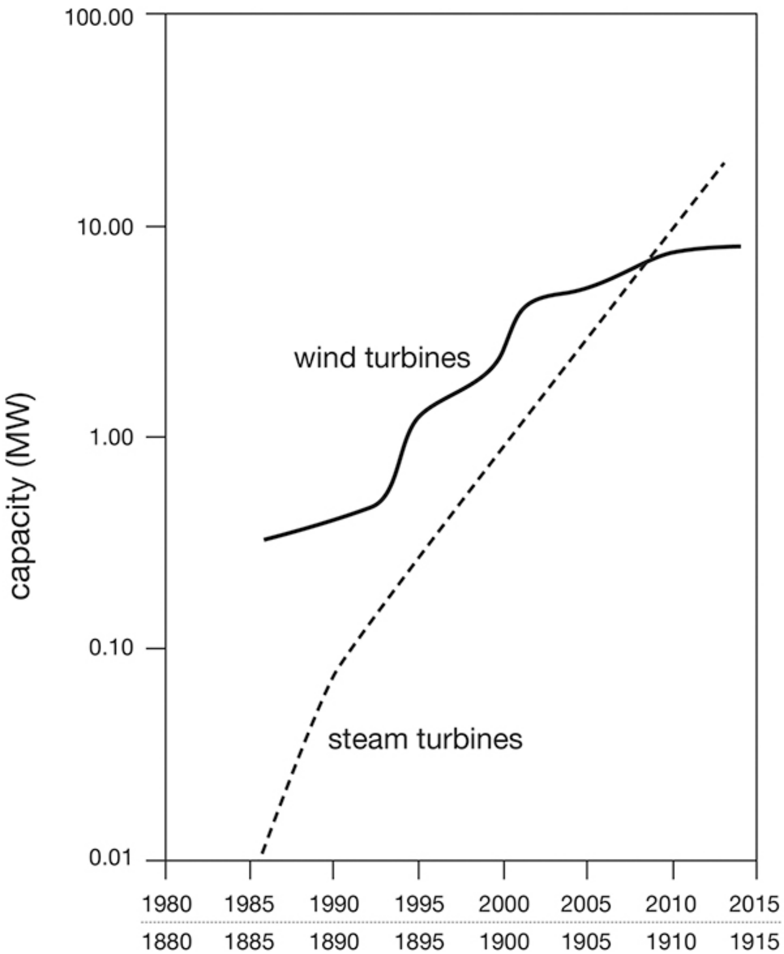

Figure 5.3 Growth of wind turbines (1986–2014) and steam turbines (1885–1913). Plotted from data in Smith (1987), UpWind (2011), MHI Vestas Offshore Wind (2016), and Smil (2005).

wind turbines have remained largely unchanged (around 35%). Moreover, neither they nor the maximum capacities will undergo several consecutive doubling during the next 10–20 years: we will not see a 32-MW turbine in 2022. European Union's UpWind research project has been considering designs of turbines with capacities between 10–20 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 2011; Fig. 5.4).

Hendricks and Hassan (2008) argued that building such structures is technically possible because the Eiffel tower had surpassed 300 m already in 1889 and because we build supertankers and giant container vessels whose length approaches 400 m, and assemble bridges whose individual elements have mass more than 5,000 t. Such comparisons are categorical mistakes because none of those steel tankers or bridges is vertical and none is surmounted by massive rotors. Economies of such giant turbines are also questionable (UpWind 2011). That is mainly because the weight stresses are proportional to the turbine radius (making longer blades more susceptible to buckling) and because the turbine's power goes up with the square of its radius while the mass (turbine's cost) goes up with the cube of the radius. In any case, doubling the machine's power output is not a simple scaling problem (Hameed and Vatn 2012).

But even if we were to see a 20-MW machine as early as 2020 this would amount to a bit less than a tripling of the maximum capacity in a decade,

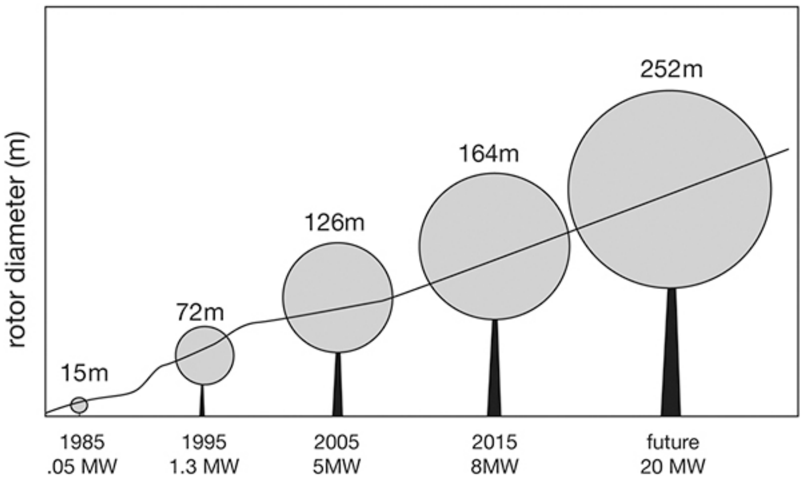

Figure 5.4 Increasing rotor diameter of the largest wind turbines compared with a diameter of a 20-MW machine. Adapted from UpWind (2011).

again hardly an unprecedented achievement: for example, average capacities of new steam turbogenerators installed in America's thermal stations rose from 175 MW in 1960 to 575 MW in 1970, more than a threefold gain in a decade. 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 flowing past it, 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 amounts to 16/27 or 59% of wind's total kinetic energy (Betz 1926). Consequently, it will be impossible even to double today's prevailing wind turbine efficiencies in the future.

Looking ahead, we must be concerned about the declining performance of wind farms. Hughes (2012) found that the normalized load factor for British onshore wind farms declined from about 24% during the first year of their operation to 15% at age 10 and 11% at age 15, while the fall for Danish farms was smaller, but still significant, from a peak of 22% to 18% at age 15. Staffell and Green (2014) examined nearly 300 UK wind farms and found that the turbines lose 1.6% of their output per year as their average load factors fall from 28.5% for new machines to 21% at age 19; this lowers the output by 12% over a 20-year lifetime and increases levelized cost of electricity by 9%. And in order to assess long-term performance and longevity of offshore wind farms exposed to humid air laden with sea-salt aerosols, we will have to wait to accumulate sufficient operating record.

Efficiencies of PV cells have been improving slowly. Since the mid-1970s annual growth rates of the best conversions in research laboratories for single-crystal, nonconcentrating cells and thin film cells—calculated from data in NREL (2016)—have averaged, respectively, just 1.6% and 3.8%. This means that the commonly deployed cells have required 18–44 years to double their efficiency. Moreover, since the mid-1990s there have been no gains for single-crystal nonconcentrator cells and only very small improvement for the best thin films, and efficiency doubling for these two designs is impossible (Polman et al. 2016). Monocrystalline Si cells have already reached near-complete light trapping, their further carrier management (conversion to efficiently collected electrical carriers) is limited, and hence their record efficiencies can improve only by a few percent. Only new designs for multijunction concentrator cells could eventually lift the maximum laboratory efficiencies. But such record performances will not become quotidian field realities anytime soon: IEA anticipates maximum field efficiencies of 21%–25% for 2030 (IEA 2010).

One of the most persistent arguments about the supposedly unprecedented achievements of solar PV has been to point out steadily declining prices of newly installed residential systems. When measured in constant 2013 $, the U.S. decline was from $12/W in 1998 to $4/W in 2014 (Feldman et al. 2015), that is, an average drop of 6.8%/year. But, once again, such gains are not unusual in early stages of new energy systems. During the early years of the 20th century the U.S. thermal electricity generation in coal-fueled plants had experienced slightly higher price drops: average price is available since 1902 (USBC 1975) and after it is adjusted for inflation its annual decline during the next 18 years was 8.7%, and the rate would be even higher if data were available for earlier years, from 1892 or even from 1882, the very first year of commercial electricity generation.

As for the biofuels, fundamental physical and biochemical limits restrict the growth of yields, be they crops or plantation trees, to small annual increments. During more than 50 years since the early 1960s, average annual global yield gains for the three crops that have, so far, dominated conversions to liquid biofuels, have been 2%/year for corn (doubling in 35 years), 1.6%/year for soybeans (doubling in about 44 years), and just 0.6%/year (doubling in 117 years) for sugar cane (FAO 2016). U.S. corn, the world's highest yielding grain crop, has not done much better, with harvests improving by 2.2%/year between 1950 and 2015 (USDA 2016). The only way to boost the global means would be by extending much improved agronomic procedures and guaranteeing optimal nutrient and water supply and pest protection in low-income economies. Even if, improbably, such efforts were to double the rate of yield gains, average harvests of corn and soybeans would not double in less than 16–22 years.

Ethanol yields from corn fermentation have been improving at an even slower rate, from 0.36 L/kg in 1984 to 0.5 L/kg in 2014 (in U.S. measures from 2.4 to 3.36 gallons per bushel), an average gain of just over 1%/year (NCGA 2014). Fast-growing trees show similar rates of yield improvement. For example, intensively cultivated pines in the U.S. Southeast now yield 13.3 t/ha compared to 5 t/ha for natural slash stands in 1950 (Wann and Rakestraw 1998); that translates to an annual yield gain of 1.5%. Moreover, high productivities in southeastern hardwood plantations are confined to narrow site conditions or require costly inputs (Kline and Coleman 2010). I am not citing any comparisons for algae grown for energy because their cultures have yet to be commercialized on a substantial scale.

Finally, large annual increments in installed capacities of wind and solar electricity generation (both globally and in some countries) have attracted particular attention and have been often seen as spectacularly unique achievements. But these additions have not been unprecedented either in terms of installed capacity or of actual generation. Between 2000 and 2015 global wind turbine capacity rose from 17 to 432 GW (roughly 25-fold), and wind electricity generation increased from about 30 to 830 TWh (28-fold gain due to improving capacity factors). Analogical data for PV solar show rise from 1.3 to 233 GW and from 1 to 243 TWh (REN21 2015). High annual growth rates of these renewable conversions—22% for wind and 37% for PV generation—are not uncommon for new techniques in early stages of their market penetration, and the absolute production gains are not unprecedented.

In 1981, 15 years after the world's nuclear reactors produced 30 TWh (in 1966), fission generated 836 TWh, a slightly higher absolute increment than has wind between 2000 and 2015. An American comparison shows that the country's wind generation rose 40 times between 2000 and 2015 (from 5.6 to 190.9 TWh), but during a similar early stage of its development nuclear generation increased much faster, roughly 70-fold during the 15-year period between 1965 and 1980, from 3.6 to 251.1 TWh (USEIA 2016). This is not surprising given the fact that average units in nuclear stations have power two orders of magnitude larger than average wind turbines.

And if decarbonization is the key goal of the unfolding energy transition then hydroelectricity has done more in that regard than solar and wind generation combined: between 2000 and 2015 annual electricity generated by those two new renewable modes rose by about 1.05 PWh, but during the same period new hydroelectric capacities added 1.24 PWh of noncarbon electricity. And, as already noted, these gains in wind and solar electricity generation are often mistaken for the shifts in total primary energy supply, an inexcusable error that greatly exaggerates the importance of new renewables. In 2015 the two renewable modes produced about 0.7% of global primary energy and accounted for 0.6% of the U.S. primary supply.

Moreover, the growth of new renewables during the next 15 years will not replicate the growth rates of the past 15 years, as important technical imperatives and environmental limitations will exercise their influence. As with all expansions, the future growth rates will moderate. For example, between 2010 and 2015 the world added about 212 GW of PV capacity for a 7.7-fold increase, but the IEA forecasts additional 312 GW for 2015–2020, merely a 1.3-fold increase. And we must also consider that besides wind and PV there is no other new generation technique that can be seen as a major near- to midterm contributor at multi-GW scale. The conclusion is clear: any expectations that the future performance gains of wind and solar electricity generation and liquid biofuel production will resemble the post-1971 record of packing transistors on microchips merely demonstrate the spell of Moore's curse, an unfortunate categorical mistake that takes an exceptional performance as a general norm of coming technical innovations.

Inertia

The second key reason why the rise of microprocessor performance 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 needed to extract, harness, process, transport, and convert energies—and that this reality is inevitably reflected in considerable inertia of these complex technical systems. The same phenomenon is, of course, commonly encountered in economic affairs where the consequences of past managerial and organizational decisions and the extent and operation of existing production, trade, and marketing arrangements strongly influence the way ahead. Economists—for whom inertia, a perfect physical description, or a lock-in appeared to be too simple terms—prefer to call this path dependence.

The phenomenon can reflect highly rational choices (reliability and low cost of well-established techniques) as well as less rational preferences and attachments whose persistence works against new solutions (such as preferring inefficient incandescent lights rather than efficient fluorescent lights emitting in less pleasing parts of the spectrum). In complex energy systems the most important inertial considerations are not only the cost of existing set-ups but also their scale and complexity, as well as the predictability and reliability of prevailing arrangements. As a result, modern energy systems are very much unlike the modern microprocessor industry.

Production of microprocessors is a costly activity, with the fabrication facilities costing up to $5 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 chip-making facilities. Intel, whose share of the global microprocessor market remains close to 80%, has only 10 fabrication facilities (7 in the United States, one each in Ireland, Israel, and China), 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 production, delivery, and consumption of fossil fuels and primary electricity. 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 hydroelectricity-generating plants, HV transmission and distribution lines, and gasoline and diesel filling stations constitute the world's most extensive, and the most expensive, web of energy-intensive infrastructures that now spans the globe, with many of its parts expected to serve for decades.

Its individual components number in thousands (large coal mines, large thermal power plants, large oil and LNG tankers), tens of thousands (large power transformers; there are more than 10,000 hydro stations and about 50,000 oilfields worldwide), and hundreds of thousands (filling stations), and its worldwide networks extend over millions of kilometers. For example, the United States alone has about 300,000 km of oil pipelines, nearly 4 million km of natural gas pipelines (including small-diameter distribution lines), and the North American high-voltage transmission grid has surpassed 700,000 km (Harris Williams 2014).

These infrastructures are present in high densities in all affluent nations, and modernizing countries are building them as rapidly as they can. If only 5% of the world's cumulative material deployment were used in the energy sector, then energy embodied in its materials is equivalent to at least 15 Gt of crude oil (Smil 2014). And even when assuming that the capital investment required to put in place the global fossil fuel–based energy infrastructure averaged to just 2% of the cumulative gross world product, the creation of the entire system had consumed at least $25 trillion (in 1990 international dollars) during the 20th century (IEA 2014a; Maddison Project 2015). Could we expect that the world will simply walk away from these infrastructures before the investments will be amortized and produce rewarding returns?

Certainly the most impressive recent example of this lock-in is China's coal-based quest for modernity. Between 2000 and 2014 China added about 700 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, UK, Italy, and Spain) by 2006 (USEIA 2016). Even by using a very conservative cost average of $1,000/kW, this construction spree represents (including the associated coal-mining capacities) investment in excess of $1 trillion, and the plants are built to operate for at least 30–35 years in order to recover their cost and to make profit. Will the Chinese suddenly terminate most of this brand new investment and write off hundreds of billions of dollars in order to turn to renewable electricity conversions that cannot be operated with similarly high-capacity factors?

But the infrastructural arguments cut 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 more than 17 TW in 2015, 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.

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 fieldwork but also for local transportation.

Inertial reliance on the first mechanical prime mover is perhaps 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: 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 2010a). 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 160 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 2015 the aggregate count of these machines approached 1.5 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 the so-called Dies-Otto engine that combines its standard (sparking) operation with that of a (nonsparking) 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. Two comparisons suffice to illustrate the magnitude of up-scaling that would be necessary to make electric cars a substantial contributor (accounting, say, for at least 10% of new vehicles sold, or in operation). In 2015, the record year for U.S. car sales, only 0.6% of all vehicles bought were plug-in electrics (WSJ 2015) And while global cumulative sales of pure electrics and plug-in electrics surpassed one million units before the end of 2015, that was still less than 0.1% of the 1.2 billion passenger cars on the road (BNS 2016; Shahan 2015). Obviously, a massive scaling up effort is required before electric cars become a major feature of the auto market.

Technical breakthrough of another alternative, the fuel cell–powered drive, was prematurely touted as imminent during the late 1990s. New models are now available (most notably Toyota's Mirai), 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—although gradual advances in metallurgy, precision manufacturing, and control engineering made it much larger and much more efficient: the top efficiencies now surpass 40%, the highest unit capacity is 1.75 GW, and the position of steam turbines as the world's most powerful stationary prime mover is solidly entrenched. These machines, installed in fossil-fueled and nuclear stations, now generate more than 70% of the world's electricity, and there is no converter of a similar capacity, efficiency, and reliability in sight. And there are also no prospects for any near-term replacement of gas turbines used in flight: they have dominated global air transportation since the 1960s, and the best we could do is to raise their efficiency.

Our reliance on those indispensable prime movers that were 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 for internal combustion engines. 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.

Surprises

History of energy transitions makes it clear that many unexpected discontinuities have strongly affected the economic viability, public acceptance, and governmental support of new energy sources and new conversion techniques, and, as a result, they have changed, or even reversed, their adoption or diffusion rates. The most prominent examples of discontinuities that have been encountered in the past 50 years and that have had far-reaching influence on the course of unfolding energy transitions include at least seven classes of recurrent phenomena (their order does not imply any ranking).

The first class includes unpredictable shifts in energy prices. The second one is a relatively sudden emergence of major new consumers on the global energy market. The third one is 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. The fourth category includes effects of long-term environmental implications of energy use. Unprecedented economic crises are the fifth, and fiscal mismanagement, whose painful effects can be postponed but not averted, the sixth discontinuities. Finally, there is a recurrent eagerness of governments to support fashionable solutions whose long-term impact turns out to be limited or nonexistent. Here are some prominent illustrations of these seven discontinuities, going back to the 1960s.

Unexpected and unprecedented rise of world crude oil prices between 1973 and 1981 (from around $2/barrel to as high as $38/barrel in monies of the day), followed by their precipitous fall (monthly mean as low as $11/barrel in July 1986) was the main reasons for the fact that the 1979 peak level of global oil consumption was not surpassed until 1994, 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. Price spikes of 2006–2008 and 2012–2014, and price declines of 2008–2009 and 2014–2016 had many worldwide consequences for the development of fossil fuels and for the adoption of new renewables.

China is the best example of a new major and rapidly growing consumer of energy whose entry into the global market for fuels has had a strong effect on prices. 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 in just over a decade the country would become a major oil importer and a veritable factory for the world? And in 2006, many years before it was expected, it became the largest emitter of greenhouse gases and in 2009 also the planet's largest energy. Looking ahead, India (whose population will soon surpass that of China) 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 2015 about 25 GJ/capita in India vs. just over 90 GJ/capita in China). At the same time, can we exclude the possibility that India may surprise us by doing much worse than expected?

Nuclear electricity generation is not the only prominent example of a rather sudden loss of faith in a new technique that was seen 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 Colorado oil shales (whose small-scale exploitation dates to the 1920s) that was to save the United States: the Energy Security Act of 1980 funded a new massive industry to produce two million barrels of oil from the Rocky Mountain shales by 1992, but the project fizzled out rapidly and was completely abandoned in 1985 (Uslaner 1989). Two decades later we were assured that within a decade fuel cells would routinely energize our cars. Stock of Ballard Power Systems of Burnaby, BC, a major developer of hydrogen-powered fuel cells, topped C$160/share in early 2000—but in early 2016 it was worth less than C$2/share, and the company had abandoned any further development of hydrogen-fueled propulsion, and it survives by selling fuel cells for forklifts and stationary units used for backup electricity generation (BPS 2016).

In 1965 there were no concerns about acid deposition, a process that has been going on for a century; by 1980 acid deposition was the dominant environmental worry in both Western Europe and North America (Smil 1997). That concern now hardly registers in the West as the combination of flue gas desulfurization and switch to low-sulfur fuels, above all to natural gas, has greatly reduced its effects. And although the emissions of SO_x and NO_x have reached new heights with China's massive expansion of coal combustion, acid deposition in East Asia has been completely overshadowed by the worries about global warming.

Little has to be said about the impact of sudden, massive (and now global) economic dislocations. The economic downturn that began in 2008 was 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 (still underway in 2016, eight years after the crisis began in the fall of 2008) has derailed many energy targets and expectations. Fiscal mismanagement (whose extent and depth eventually comes to limit the actions governments and consumers can make) is 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, nearly 3.5 times the country's 2015 GDP (FRB 2016). Low interest rates have made these levels of debt bearable, but they will not last forever.

Energy developments have been also greatly affected by the subsidies granted by governments to entire energy industries or to specific energy conversions (IMF 2015). These expensive interventions have ranged from hard-to-justify persistence—with tens of billions poured into fusion research since the 1950s—to unpredictable support and granting of credits for industries that a few years later are scaled down or withdrawn as the initial enthusiasm turns into widespread doubts. Consequently, there is nothing new in subsidies extended to establish and then to expand renewable electricity generation or the production of liquid biofuels from energy crops (Alberici et al. 2014; Charles and Wooders 2011; Steenblik 2007; USEIA 2015h). But the last example also shows the fickle nature of such support: U.S. ethanol mandates were first enacted in 2005, expanded in 2007, and then scaled back in 2015.

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, new orders stopped abruptly in 1978 (and only a handful of new ones followed eventually), and there is not a single operational LMFBR.

Realistic Anticipations: More Than a Great Transition

Recent advances in the adoption of new renewable energy conversions, particularly large annual increments in installed capacities of wind and solar electricity generation, have been impressive at the global level and even more remarkable in a few countries promoting accelerated decarbonization, with new capacities and outputs doubling in as few as three or four years. But, as I have shown, those growth rates have not been unprecedented when compared to some notable new conversions in the past. And, contrary to commonly shared impressions, new renewables still supply only a very small share of the global primary energy demand.

When wind and solar electricity are converted to joules by using electricity's thermal equivalent (3.6 MJ/kWh), then these two sources contributed just 0.03% of all primary energy in the year 2000 and about 0.75% in 2015; after adding all modern biofuels, the shares for all new renewables are 0.13% in the year 2000 and 1.3% in 2015. When converting wind and solar electricity by average rate of thermal generation (as BP does), the shares for all renewables rise to roughly 0.6% in the year 2000 and to about 3.3% in 2015. In the United States wind turbines and PV cells generated just over 5% of all electricity in 2015, compared to less than 0.2% in the year 2000 (USEIA 2016). But that translates (even when converting, as the USEIA does, primary electricity at about 11 MJ/kWh) to less than 2.5% of all primary energy, while modern biofuels added about 2.2%, leaving the total of new renewables still below 5% (all renewables, including wood, waste biomass, and hydro reached about 10%).

Excessive optimism (or, less charitably, naïve expectations) and a remarkable unwillingness to err on the side of caution have characterized too many past and recent forecasts, goals, and aspirations regarding the rate of decarbonization in general and future adoption of new renewables in particular. And, unfortunately, looking for better appraisals by performing quantitative forecasts based on the best available data may be problematic. Given all of these uncertainties and surprises, it is prudent not to use the past performance of renewable conversions 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—are processes that inevitably follow progression described by s-shaped (sigmoid) growth curves. These curves are distinguished by their slow initial advances followed by a period of rapid rise, an eventual inflection point, and declining increments leading towards saturation. For technical advances Wilson (2012) uses the terms *formative phase* (many smaller-scale units experiencing only small increases in unit capacity), *up-scaling phase* (concurrent growth of unit capacities and numbers of units), and a *growth phase* (when large numbers of larger unit capacities are adopted). 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 have followed other confined-growth functions 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 (in the 20th century that was characterized by growth amounting to an order of magnitude in a decade); this exponential growth continues until the energy source reaches what they call a "materiality," typically around 1% of world energy mix. The second law describes how after materiality the growth changes to a linear rate, and a resource or a conversion settles at a long-lasting market share. This is nothing else but an alternative description of a ubiquitous growth process, of the fundamental limits within which new resources and new conversions can be adopted—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 be a variant of a growth curve.

Constructing individual curves is not easy even for well-documented innovations because the dates—be it the timing of invention, onset of widespread diffusion, or the eventual market dominance—are arguable and complete transitions differ widely among the countries. Just to give one of many possible examples, Fouquet (2008) dates the British transition from steam to electricity between 1821 (Faraday's experiment with primitive electric motor) and 1950 (139 years) as the time span from invention to dominance, and between 1920 and 1950 (30 years) from diffusion to dominance. But other dates could be chosen instead of 1821 because electricity was not invented in a particular year, and commercially generated electricity was first available only in 1882: the 1880s or even 1890s (when all ingredients of a modern system fell into place) might be a more defensible date for starting the diffusion phase.

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 have a much stronger (nearly exponential) initial growth phase and a much higher inflection point than the latter (Fig. 5.5). 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.

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 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%

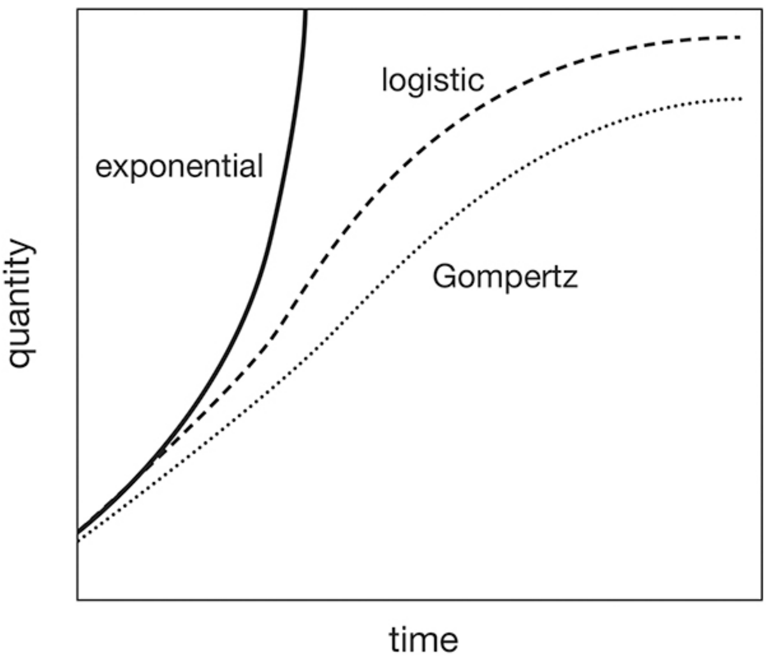

Figure 5.5 Comparison of logistic, Gompertz, and exponential growth curves.

above the 1986 level. Consequently, we have to wait until after a great deal of growth or adoption process will have been completed before we can get on a firmer quantitative forecasting ground. Given the fact that most of the 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 would still be dominated by fossil fuels not only in 2025 or 2030 but even by the middle of the 21st century. To paraphrase what I wrote in this book's preface, a world without fossil fuel combustion is desirable, it will be eventually inevitable, and we should work to accelerate its arrival—but the process will be costly and it will take time as well as extraordinary commitment.

A major part of the challenge is that our choices of noncarbon energy conversions are relatively limited. Realistic appraisals of the road ahead require us to set aside those noncarbon energy sources whose overall theoretical potential may be considerable but whose harnessing has, so far, provided only locally (or regionally) notable contributions, relegating them to negligible global importance and leaving no clear indications of any additional early technical breakthroughs that would elevate them to major contributors in the near future (I must stress that this judgment does not apply to what might be possible in 50 or 80 years).

These conversions include not only ocean waves and currents and ocean thermal energy conversions (a perennial favorite of science and engineering news writers, so far with no profitable, not even medium-scale, commercial deployment) but also to geothermal generation of electricity (supplying a mere 0.3% of the global 2015 output). And it will come as a surprise (or as an unacceptable conclusion) to many promoters of those energies that this judgment must be extended also to the two established ways of primary electricity generation, to hydro energy and to nuclear fission, that are now much larger contributors to noncarbon primary energy supply than all new renewables put together. Here is why.

Environmental impacts of large hydro energy projects have transformed their reputation from formerly desirable options to a highly questionable, and even fiercely opposed, form of renewable energy (Goldsmith and Hildyard 1984; International Rivers 2015; Tortajada, Altinbilek, and Biswas 2012). Even if all potentially suitable sites were to be developed (a most unlikely possibility given the constraints due to mass population displacements and environmental impacts), their electricity generation would 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), but Russia has no need to develop the remaining sites while tapping Congo's huge potential depends above all on political stability that has eluded that part of Africa for three generations.

And the construction of large hydro stations has not only essentially ceased in nearly all affluent countries but there has been, as already noted, some significant dismantling of smaller and medium-sized projects. Combination of high capital costs and environmental concerns has, with China's notable exception, slowed down their construction in African, Asian, and Latin American countries that have most of the remaining undeveloped sites. Hydroelectricity's share in the global generation has declined slightly between 1990 and 2015 (from about 19% to 17%), and it is most unlikely that during the next two decades it would rise above 20%.

Similarly restrained outlook applies to nuclear generation. Many of its long-standing proponents extol its advantages, and the cause has gained many new advocates, including some of the fission's formerly resolute opponents. But in order to assess fission's likely contribution to any near-term shift away from fossil fuels, we do not need to undertake a thorough analysis of its advantages and drawbacks; we just have to look at the composition of the industry's existing capacity (largely aging plants scheduled for closure) and at its immediate prospects (projects under construction) and contrast it with the coming primary energy needs in order to conclude that fission will make a relatively minor contribution to the world's future primary energy supply.

In January 2016 the global nuclear capacity reached 382.5 GW in 439 reactors in 28 countries, and in 2015 fission produced 11% of all electricity compared to nearly 18% in 1996. In 2016 66 reactors were under construction, and they will add 70.3 GW new reactors, but by 2030 more than 70 older (and smaller) reactors will shut down, and even when assuming that most planned projects would go ahead the total capacity is expected to reach 543 MW in 2030—and IEA's *World Energy Outlook 2015* expects about 630 GW in 2040 when fission would provide 12% of all electricity, a marginal gain compared to 2015 (IEA 2015d; WNA 2016b). In terms of primary energy that would be only about 5% of the 2040 supply, clearly not a decisive transition factor.

This means (leaving aside the most unlikely early and rapid commercialization of fusion) that the future decarbonization will have to rely primarily on three kinds of new renewables, on solar- and wind-powered electricity generation and on production of biofuels. As I have shown, assessments of their prospects have been often excessively optimistic—but we must be careful not to succumb to the opposite extreme of unjustifiable pessimism. Keeping their limits in mind, we must acknowledge that all of these energy sources have their inherent strengths, all of them have seen improving performances (lower costs, rising efficiencies, higher load factors, greater reliability), and all of them should make steadily greater contributions to the global energy supply.

Solar and Wind Electricity

Direct conversions of solar radiation deserve special attention because this enormous flux has several advantages that, besides its unmatched magnitude, set it apart from other renewable energy flows. No other renewable energy conversion works with power density even close to that of the solar flux. Lack of moving parts is a distinct operational advantage for PV, as is its high safety (on any scale). Fthenakis and Kim (2011) studied material and energy flows in four commercial PV designs and concluded that the PV cycle is much safer than conventional energy sources both in terms of statistically expected and possible maximum consequences.

Given the history of continuing efficiency gains of PV generation it is only a matter of time when typical conversion efficiencies will be surpassing 20% and when power densities in the sunniest locations will approach, and top, 30 W/m^2. Opportunities for distributed PV generation abound. Of course, many roofs are poorly suited, or entirely unsuitable, for such installations due to excessive pitch (>40°; on the other hand, the slope should be at least 15° for self-cleaning), suboptimal orientation and shading by surrounding buildings or trees, and many roofs are unavailable due to the presence of heating, air conditioning, and ventilation equipment. Still, at least 20% of all roofs can be suitable in cool climates and 25% in warm and arid climates, while the shares for commercial buildings should be at least 60% (Denholm and Margolis 2007).

Concentrating solar power projects already offer higher overall conversion efficiencies, and many of them could be integrated with other no-carbon or low-carbon sources to generate steam during the nights or during periods of higher demand (Azcárraga 2013; Fig. 5.6). America's largest CSP project, Ivanpah Solar Electric Generating System (SEGS) in the Mojave Desert in San Bernardino county in California, has installed capacity of 392 MW_p and expected annual generation of 1.079 TWh, implying the average capacity factor of 31% (BrightSource 2016). And 110-MW Crescent Dunes CSP in Nevada, operating since February 2016, will be able to

Figure 5.6 Two central solar power plants near Seville in Andalusia, Spain. Photo available at https://en.wikipedia.org/wiki/List_of_solar_thermal_power_stations#/media/File:PS20andPS10.jpg

generate for up to 10 hours after sunset (SolarReserve 2016). In suitable locations CSP may be the best option for future electricity generation.

Other solar gains will come from new materials and from new arrangements (Bagher 2014; Lewis 2016; Oxford PV 2015). Perovskite cells have been receiving much attention, and so have low-efficiency inexpensive organic cells. Flexible PV films are the most promising cheaper alternatives to be used as common wall and window covers: shading and suboptimal angles of irradiation will always limit their efficiency, but a low cost would justify their installation to reduce energy cost of buildings. New production methods could double the efficiency of low-cost cells (SLAC 2015), and flexible floating solar power plants on lakes or quiet ocean bays could provide new locations that would also reduce reservoir evaporation and algal growth (Kyocera 2016).

Countries with windy climates can generate not just 20% but 30%, and exceptionally even 40%, of their electricity using large wind turbines (Zubi, Bernal-Augustín, and Marín 2009). Obviously it helps if a country (Denmark being the best example) has relatively small electricity demand and is already well connected to neighboring countries that have adequate capacity to absorb the wind-generated surpluses and cover the need during calm periods. Typical load factors have been increasing thanks to taller towers and better turbine designs, and the best way to raise them substantially (above 35%) is by setting up large wind farms offshore. But, as with every energy converter, wind turbines will soon reach their practical maxima. Sandia National Laboratories have been designing a 50-MW turbine whose rotor blades would be stowed and aligned with the wind direction at high wind speeds (SNL 2016). But even 50 MW would be a small capacity compared to steam turbogenerators—and before we build machines with rotors longer than 200 m we have to step up first from 8 MW to 15 MW and 20 MW, and neither machine will be rotating anytime soon.

A common complication for tapping both solar radiation and wind is the necessity of constructing new transmission links, particularly in large countries where the most suitable resources are concentrated far from major load centers. American wind and solar radiation are perfect examples: windy North Dakota is 2,600 km from New York (in European terms more than the distance between Paris and Moscow), and sunny Arizona is 2,000 km from cloudy Seattle. The need for new long-distance high-voltage links is particularly great in the United States, the only major country without a true nationwide grid, but in 2015 the work began on a transmission superstation in New Mexico that will be able to transfer up to 20 GW (Tres Amigas 2016).

The United States now has about 320,000 km of HV lines, and at least 65,000 km of new high-capacity lines would be needed in order to integrate substantial shares of wind-generated electricity from the Great Plains and solar electricity from the Southwest, and aggregate cost of these extension would surpass $100 billion (Smil 2011). This task is made even more challenging by decades of low investment in the nation's transmission: between 1999–2009 demand grew by 20% and transmission by only 3% (APS 2011). Real costs are bound to increase (not least because of the resistance to new lines), and there is also a lengthy regulatory approval process that takes many years even before new projects can begin. And linking more efficient offshore wind farms to national grids has its own problems, ranging from higher construction and transmission costs to increased maintenance and lower durability of components set in extreme environment.

And any intermittent source of electricity faces inevitable challenges of a smooth integration into a national or multinational grid. Many studies analyzed and simulated the requirements and behavior of electricity grids operating with larger shares of variable renewable electricity (APS 2013; Apt and Jaramillo 2014; JPM 2015). Assessment of the U.S. situation found that winds are systematically underpredicted during periods of light winds and overpredicted when there are strong winds, and that better predictions and changing operations of power plants and improved siting of renewable capacities would help when up to 30% of all electricity came from variable sources (Apt and Jaramillo 2014).

An analysis of Germany's future electricity supply concluded that (even after assuming that the total demand would be reduced by 25% as anticipated by *Energiewende*) surpluses arising from wind and solar generation would be less than 45% of deficits when integrated over the entire year, and even if Germany's planned expansion of wind and solar would generate 80% of electricity over the course of the entire year, **backup thermal capacity needs would be practically *unchanged vs. current levels*, given low wind and solar power during winter months: thermal *generation* would drop sharply, but not thermal *capacity*** (JPM 2015). Energy storage would only partly mitigate that need, and the direct cost of *Energiewende* (using 2015 costs) would be 1.9 times the current system. Another analysis by the Potsdam Institute for Climate Impact Research found that integration costs (dominated by the additional cost of backup thermal power) in systems with high levels of intermittent sources can be up to 50% of generation costs (Ueckerdt et al. 2013).

And as the shares of installed solar capacities rise in some countries above 10% of the total (in Germany it was about 20% in 2015, but it generated just 6.5% of all electricity), their most efficient use will necessitate a greatly expanded storage. Its installation has already begun in both Germany and California. The German program (started in May 2013) is limited to small PV systems (up to 30 kW), and it subsidizes up to 30% of the price of storage connected to new or existing PV modules, while California's three major utilities will have to buy 1.325 GW of storage capacity by the year 2020 (California Public Utilities Commission 2016). At the same time, there are no immediate prospects for impressive practical breakthroughs either for massive compressed-air or other grid-scale storage.

Biofuels

All long-term forecasts show biofuels as the largest sources of renewable primary energy, and hence a realistic assessment of their potential is particularly important because their future mass-scale production would not be able to avoid many undesirable environmental impacts: keeping them to manageable levels would inevitably exert major limits on their use. Although there is a very large theoretical potential for biomass from fast-growing trees and high-yielding grasses grown on the currently unused land, such mega-planting schemes would fail without requisite water and macronutrient supply and without keeping in check all the pests feasting on extensive monocultures; they would also reduce biodiversity, enhance soil erosion, and possible exacerbate, rather than moderate, climate change (Field, Campbell, and Lobell 2007).

A wishful assessment put the future biomass contribution at 365 EJ (nearly equal to all fossil fuels today) and the maximum potential by the year 2050 as high as 1.442 ZJ, more than three times the total global energy use in 2015 (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, 56)—but they use them anyway as the foundation for their meaningless claims. IPCC (2010) estimates have been also unrealistically high, with the upper limit of phytomass potential of as much as 400 EJ by 2050 (compared to about 550 EJ of total global primary energy supply in 2015). But the report conceded that such a level could not be achieved without sophisticated land and water management and without large worldwide plant productivity increases: in their absence biomass expansion could lead to major regional conflicts between energy and food, water and biodiversity.

Supply constrained to residues and organic waste use and to cultivation of bioenergy crops on marginal/degraded and poorly utilized lands could be about 100 EJ in 2050 (IPCC 2010). But even that may be too high: only careful assessments based on local needs for residue recycling. 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 removed for fuel. In any case, gathering and transporting bulky residues to a centralized processing facility is energy-intensive, and it becomes uneconomical beyond a restricted radius; in turn, this supply constrains the throughput of a biorefinery.

While combustion of phytomass would yield the highest amount of useful energy, we will not see the families in densely packed high-rises of Hong Kong, Mumbai, or São Paulo burning wood in efficient small stoves. The most realistic option is the conversion of wood to electricity in large stations located near major plantations because the production of liquid or gaseous fuels would further lower the already low overall power density of phytomass-based energy system and require even larger areas of woody plantations and hence more land and more fertilizer and insecticide applications. And because the greatest opportunities for large-scale cultivation of trees for energy are available only in the tropics, any massive phytomass cultivation would also require voluminous (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 nutrient constraints. Nonleguminous 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 growth. Extending such plantations to an area slightly larger 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 energy that we now extract in fossil fuels. 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 fuel's annual ethanol yield would be less than 5% of the global gasoline demand in 2015. Even if America's entire corn harvest was converted to ethanol, it would produce an equivalent of less than 25% of the country's recent annual gasoline consumption.

And the proponents of massive biomass harvesting ignore a worrisome fact that modern civilization is already claiming a fairly high share of the Earth's net terrestrial primary productivity (NPP), the new phytomass that is produced in a year and that is dominated by woody tissues in tropical and temperate forests. Several studies (Haberl et al. 2007; Imhoff et al. 2004; Rojstaczer, Sterling, and Moore 2001; Vitousek et al. 1986; and Wright 1990) concluded that human actions are already appropriating between 20%–32% of the Earth's NPP as food, fiber and feed, pulp, timber and fuel, as grass grazed by domesticated animals and as deliberately set fires. My detailed systematic account of harvesting the biosphere showed that about 17% of the global NPP was taken out of the nature every year during the 21st century's first decade (Smil 2013a).

Moreover, human phytomass harvests are very unevenly distributed, with the highest shares already in excess of 60% in East Asia and to more than 70% in Western Europe, and with local rates even higher in the most intensively cultivated and the most densely populated regions of Asia (China's Jiangsu, Sichuan, and Guangdong, Indonesia's Java, Bangladesh, the Nile's delta). Whatever the actual (and impossible to pinpoint) global share of harvested NPP might be, it is already so high that it does not leave enough space for any future doubling that might be required following a complete elimination of fossil fuels.

Harvest claiming 40%–60% of NPP, and hence above 80% or even 90% in many regions, would leave too small a share of photosynthetic output to support the lives of millions of other species. Proponents of mass-scale biomass use ignore the fact that the Millennium Ecosystem Assessment (2005) concluded that essential ecosystemic services that underpin the functioning of all economies have been already modified, reduced, and compromised to a worrisome degree. And Edward Wilson (2016), in his latest examination of the state of the biosphere, has called for setting aside half of the planet in order to save the rest of life, a goal utterly incompatible with any mass-scale phytomass harvesting.

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. Starting in 2009, Exxon investigated this option by sponsoring the work at Craig Venter's Synthetic Genomics to develop algae-derived biofuels (Service 2009). By 2013, after spending more than $100 million, it realized that significant challenges must be overcome in order to mass-produce algae-based biofuels and refocused its attention on long-term basic research (Herndon 2013).

Overconfident boasts of gene manipulators about soon-to-come feats of algae producing gasoline have been always suspect. As always, 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 by 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 and on providing adequate nutrients: naturally, a great deal of energy would be required to operate such high-throughput cultivation. 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.

I feel strongly that the recent proposals of massive biomass energy schemes are among the most regrettable examples of wishful thinking and inexcusable ignorance of ecosystemic realities and necessities. Modern phytomass fuels—produced overwhelmingly by converting organic wastes and wood from plantings grown on nonagricultural land, not from carbohydrate- or oil-rich energy crops or from cutting down natural forests—should be an important ingredient of low-carbon energy supply, but any realistic assessment of their environmental demands and impacts and of the challenges and costs of their mass production should carefully consider their limits, including their long-term potential to increase carbon emissions.

All of these realities make it clear that in order to achieve its intended goal—a relatively rapid decarbonization of the global energy supply—the unfolding energy transition must go much beyond changing energy sources and abandoning long-established energy conversions in favor of new techniques. Improved conversion efficiencies are imperative: it would be much easier and much more affordable to source rising shares of energy demand from limited renewable flows if that aggregate demand would be reduced in significant ways. Even Germany's *Energiewende*, which recognizes the need for higher efficiency, should put more stress on it (EEP 2013).

Our belated quest for higher energy efficiencies started in earnest during the late 1970s, and it has brought some impressive gains. In 2010 energy use in affluent countries was about 20% higher than in 1974, but it would have almost doubled without the savings realized by efficiency investments (Bishop 2015). Even after nearly half a century of trying, the opportunities for further gains remain excellent because some components of that drive were interrupted or suspended for indefensibly long periods of time—the U.S. CAFE standards for passenger cars were frozen between 1985 and 2010—while many other efficiency gains have been completely negated by increased demand. Flying is perhaps the best example of this process: specific kerosene consumption of new jet engines (per seat-kilometer) was halved between 1960 and 2010, but during the same time the airline traffic (total passenger-kilometers) had expanded more than 30-fold (Smil 2010a; Fig. 5.7).

Because of the still ubiquitous opportunities for further efficiency improvements, the pace of these advances should not be any slower

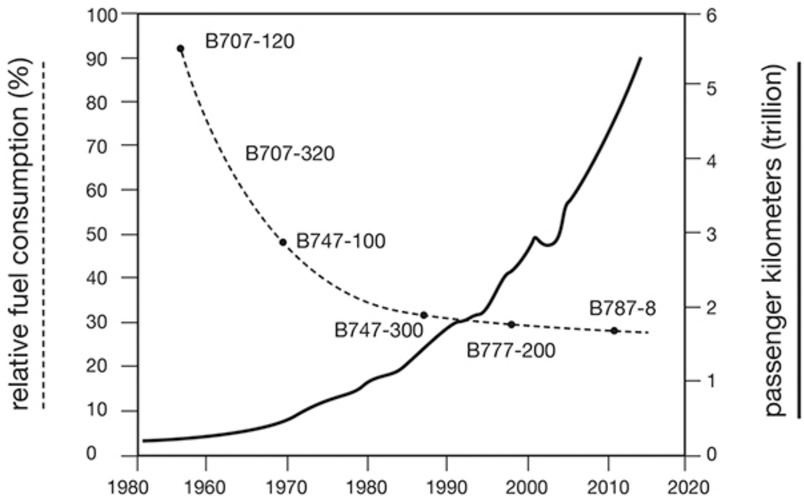

Figure 5.7 Increased efficiency of jet flight (fuel consumption per seat) and increased traffic volumes (passenger-kilometers per year). Plotted from data in IPCC (1999), Smil (2010a), and Boeing (2015).

during the coming 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). McKinsey assessment concluded that, globally, energy efficiency represents about 40% of the greenhouse gas reduction potential that can be realized at a rewarding cost (McKinsey 2010). Cost-effective opportunities to avoid new energy supply mean that energy efficiency should be always seen as the first source in energy transitions.

But if we were serious about not surpassing 450 ppm CO_2 and keeping the warming to 2°C, then even the highest practically achievable efficiencies combined with realistically rapid shifts in primary supply would not suffice. On a planet whose population will be soon approaching 10 billion we will also need some realistic limits on absolute levels of energy and material consumption: atmosphere responds only to aggregate greenhouse gas emissions, not to a specific decline of emissions per consumed joule of energy or an energy-intensive material. Per capita use of energy must go up in scores of low-income countries in order to bring them a decent quality of life. But because fossil fuels will continue to supply most of the rich world's energy use in the next few decades, it is particularly important to see the moderation and eventual cessation of per capita energy growth in the EU, North America, and Japan.

Fortunately, in some countries this process has been underway for some time, and higher efficiencies have been only part of the reason: aging populations and saturated markets have been the other key factors. Per capita use of primary energy is now about 10% lower in North America than it was in 1980, and by 2015 it was about 15% down in the EU compared to just 10 years ago (USEIA 2016). Given the EU's stagnating population that has translated into reduced absolute consumption. At the same time, real declines in affluent countries have been lower than indicated by national statistics because of the economic globalization: significant shares of Asia's (above all China's and South Korea's) soaring energy use has gone into production for exports to rich countries.

What should be done and what benefits it would bring if our efforts would be successful was well summarized by Bill Gates in his call for accelerated energy innovation:

> It is hard to overstate the impact that clean, affordable, reliable energy will have. It will make most countries energy-independent, stabilize prices, and provide low- and middle-income countries the resources they need to develop their economies and help more people escape poverty—all

> while keeping global temperatures from rising more than 2 degrees. I am optimistic that the next 15 years can bring the big breakthroughs we need to accomplish all of these things. This is a fantastic opportunity. It is also an unmistakable challenge. Humans have changed their energy diets before, but never as rapidly as we need to today. Moving this fast is unprecedented, which is all the more reason to start now. (Gates 2015)

Given Gates's optimism have not I been unduly pessimistic rather than realistic? No, because Gates's optimism is predicated on a massive increase in the requisite energy research and development: even in the United States this critical component of modern civilization receives a fraction of monies going into health care, and an order of magnitude less than is claimed by military R&D. Changing that could accelerate global decarbonization even without such early "miracles" as developing inexpensive solar chemical cells using sunlight to make liquid fuel or deploying solar paint (that would make any surface a silent electricity generator) in conjunction with superior batteries.

What if a combination and interaction of steady and eventually substantial gains (that would be far from revolutionary, and not at all in category of energy miracles) would transform many parts of the energy system (PV efficiency, battery density, fuel cell cost, productivity of algal biofuels, etc.) in ways that would allow us to build new production and consumption arrangements that could deliver a unit of useful energy with only half of today's energy, material, and capital expenditures? And what if we were to do that within a single generation (20–30 years)? Simply put, the future of the global energy system is inevitably circumscribed by many physical and metabolic realities, but it is not foreordained: our commitment and our choices can shape it in many important ways.

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CHAPTER SIX

Recapitulations

This book has several goals. In Chapter 1 I tried to make sure that all readers (and particularly those whose interest in energy matters is of a recent origin) appreciate the basic properties and complexities of modern energy systems, including major resources, conversions, uses, infrastructures, and impacts. This is important because, contrary to a common view that reduces energy transitions to changes of fuel base (oil replacing coal, biofuels replacing oil) or shifts in generating electricity (wind power replacing electricity produced by burning coal), those processes are only parts of a dynamic whole, some of whose components are transforming rapidly while others remain surprisingly inertial.

As a result, some of the long-established, gradually progressing energy transitions—declining energy intensities, gradual decarbonization of global energy supply, rising share of electricity in the final energy use—will continue regardless of successes or failures of specific energy sources and conversions. Much less appreciated, but no less important, will be the continued relative dematerialization of industrial products that lowers the embodied energy of infrastructural and consumer items. Concerns about global warming will intensify the unfolding gradual decarbonization, and there are three major reasons why its pace should accelerate even in the absence of any specific targets: increasing supplies of natural gas; rising efficiency of electricity generation (combined cycle turbines), passenger cars (improved engines, continuing diffusion of hybrids and electrics), and household energy uses (LED lights, better appliances); and new wind-driven and PV electricity generation.

Chapter 2 offers a long-term historical perspective by surveying 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. Revealing quantifications of these long-term shifts in resources and prime movers show that 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 any preordained primary energy transitions are concerned: such simplistic deterministic models do not reveal the future. Time required for capital mobilization, technical advances required to enable large-scale resource extraction and conversion, and for putting in place extensive infrastructures needed to bring energies to their global markets constrain the rise of individual fuels or modes of electricity generation and limits the pace of their maturation and adoption. But on national scales there are notable exceptions and departures from generally expected norms, and unpredictable economic, social, and political changes can affect even what appeared to be the strongest trends.

Development of two major noncarbon resources offers excellent illustrations of unpredictable shifts. Who would have guessed during the 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 (Devine 1995), and the World Bank would be reluctant to lend money for new hydro projects (Goodland 2010). And there was nobody who predicted in 1965—when nuclear generation was on the verge of large-scale expansion and expected to take over most of electricity generation by the century's end—that just two decades later fission would be commonly seen, at best, as a dubious proposition, at worst as a regrettable error.

And the history of prime movers reveals, again, incremental ascents with decades elapsing between technical breakthroughs and claiming of significant market shares. Moreover, those remarkably persistent machines that have been with us for more than 100 years (gasoline and diesel-fueled internal combustion engines, electric motors, steam turbines) or for more than 70 years (gas turbines) are not in any precipitous retreat. That is either because there are no equally efficient and reliable alternatives (steam turbogenerators in large-scale base-load electricity generation, gas turbines in flight) or because the substitutes cannot take over rapidly. Electric cars are the best example in the latter category: of course, they rely on the prime mover that was introduced in the late 1880s, and their operation will depend on steam turbogenerators or gas turbines that will continue to produce most of the world's electricity for decades to come.

Chapter 3 focuses 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 indefensible 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 Dutch coal mining, from a highly idiosyncratic and swiftly changing evolution of Japan's energy use to America's orderly sequence of fuels during the first half of the 20th century followed by a surprising post-1960 near-stasis of the primary energy makeup.

These national examinations offer some obvious lessons. Small, resource-rich, or affluent, countries can do what large, resource-poor and low-income nations cannot replicate (Dutch or Kuwaiti experience holds no lessons for India or Ethiopia). National commitment to a large-scale technical transformation can make a real difference (French nuclear power is the best proof of that). Coal (mostly for electricity generation) remained important in the United States but is now yielding to natural gas; it has seen enormous post-2000 increase in China but is now also showing the first signs of eventual retreat. Refined liquid fuels that are used to energize 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 nonfossil energy system.

Chapter 4 opens with the assessment of surprisingly slow, relative advances of global decarbonization. The next two sections look at the recent transitions to wind and PV electricity generation and to the use of modern biofuels. The chapter closes with a review of some notable examples of national transition targets and deconstructs some extreme scenarios outlining shifts to renewable energies. I also take a closer look at Germany's *Energiewende*, the most ambitious accelerated transformation of an entire energy system in a large modern economy. In Chapter 5 I stress the futility of long-term energy forecasts and contrast the constraints imposed on the transition process by the quest for limiting the rise of average global tropospheric temperature to less than 2°C with the importance of fossil fuels for the production of some key industrial materials and services. Then I review how innovation, inertia, and surprises will continue to affect the unfolding energy transitions, and in closing I offer some realistic comments about the likely advances and limits of leading renewable energy conversions.

As with all technical innovations, a definite judgment regarding long-term capability and reliability of new renewables is 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 properly their reliability and their true life-time costs. We will be able to do this 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 dependability and productivity will be particularly critical for massive offshore wind farms, for large PV and CSP projects in desert environment, for extensive plantations of fast-growing trees, and for mass-scale conversion of cellulosic phytomass to liquid biofuels.

Reality, particularly when combined with inevitable impacts of future discontinuities and surprises, is the best argument against any simplistic judgments about the future worth and importance of techniques that are still in early stages of their development. Trying to envisage in some detail the global energy system of 2100, or even that of 2050, is an exercise bound to mislead. Just think of describing the status of energy supply in 2015 from the vantage point of 1980, when oil prices reached unprecedented highs, when advanced economies were in deep economic recession, when China was still a poor Maoist economy, when global warming was not on top of anybody's list of global concerns, and when nuclear fission still seemed like the best long-range energy option. And the uselessness of the 2100 scenario, equivalent to envisaging the energy realities of 2015 from the perspective of 1930, is all too obvious without any additional comments.

In the absence of real understanding, 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, 195, 197). But energy supply remained abundant during those two decades and prices were at historical lows: as always, informed concerns are essential, exaggerated fears are counterproductive.

At the same time, uncritical embrace of questionable promises is hardly helpful. Renewable energy enthusiasts do not sufficiently recognize the challenge of converting the existing (and in many key aspects more than 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 that already house more than half of humanity. A number of smaller windy or sunny, and interconnected, countries can reach high shares of renewable electricity generation rather rapidly, but even their astounding progress would count for little in the quest to limit future warming if the overall level of carbon emissions keeps rising or is falling too lowly. In a global civilization faced with an environmental challenge whose local origins have global consequences, the global scale is the only one that matters.

And global imperatives are clear. Decentralized energy provision, the holy grail of true green believers, is fine for a farmstead or a small town, but we still have no technical means to make a reality for large cities and even less so for megacities (such as today's Tōkyō, Shanghai, Mumbai, or Cairo) where nearly half of the world's population will live in during the second half of the 21st century. An even greater (and curiously ignored) challenge will be the replacement of fossil fuels used as energizers and feedstocks of key industrial products including iron, cement, nitrogenous fertilizers, and plastics. Some alternatives are already available, more of them will become commercial in the future, but the global scale of the existing demand (>1 Gt of steel, >4 Gt of cement, >100 Mt of fertilizer nitrogen, >300 Mt of plastics) makes it impossible to eliminate the carbon-based foundations of these industries in a matter of two or three decades.

Given these realities it is not at all surprising that the actual advances of renewable conversions have not been exceptionally rapid. As with many phenomena in early stages of their growth, global wind and solar electricity generation has been growing rapidly, with average annual gains of, respectively, about 22% and 37% between 2000 and 2015. But after a quarter century of development (1990–2015) they contributed no more than 0.75% of the world's primary energy in 2015 (or 1.9% when using BP conversion rate), and after adding modern biofuels all new renewables claimed 1.7% (or nearly 3.3%) of all primary supply in 2015. Jefferson (2008), reviewing the growth of renewables until 2006, called this rightly a very poor performance, but the contrast is not so surprising given the magnitude of the global switch from fossil to renewable energies.

In relative terms the share of new renewables (electricity generated by wind, solar radiation, and biomass combustion and liquid biofuels) had increased by an order of magnitude 25 years, from about 0.17% in 1990 to 1.7% in 2015, growing at an average annual rate of 9.2%. That is a fast but not an extraordinary pace of gaining a market share during the early stage of expansion. Under relatively primitive technical circumstances coal was gaining at a rate of more than 5%/year between 1850 and 1870; crude oil gains averaged more than 9%/year during 1870–1890, and natural gas gained its global market share at 7%/year between 1920 and 1940. These gains were also slowed down by the necessity to develop new distribution infrastructures, while in most cases the renewably generated electricity has been readily fed

into the existing grid, and liquid biofuels could use the existing network of filling stations.

And in absolute terms primary energy added by new renewables has been only a small fraction of the total added by fossil fuels. In 2015 their consumption was 160 EJ above the 1990 level, while the combined contribution of new renewables was about 8 EJ above their very low 1990 level: during the 25 years since 1990 the world added 20 times as much energy in fossil fuels as it did in the new renewables. Renewable advances have been, obviously, better as far as electricity is concerned, but even in that case the aggregate share for wind and solar generation reached only 4.5% of the 2015 total, and nearly 2% were produced by combustion of biofuels.

Even the fastest conceivable adoption of noncarbon energies will fall far short from eliminating fossil fuel combustion by the middle of the 21st century. Forecasts done by governments, institutions, and companies see the fossil fuel supplying more than 70% of the world's primary energy by 2040, and even the scenario that would limit CO_2 concentrations to 450 ppm (2°C) anticipates at least 60% share for coal and hydrocarbons. That scenario has the highest share for all renewables (including hydro and all biomass): 29% in 2040 compared to 13% in 2013. None of the published forecasts and scenarios puts new renewables (wind, solar, and modern biofuels) at more than 15% by 2040, and IEA's CPS and NPS have all renewables accounting for 25% of the total. Even when assuming that the new renewables will reach 5% of the global primary supply by 2020 and then 15% by 2040, that growth would be in line with the pace of previous substitutions.

Perhaps the main reason why so many people have a mistaken impression about the pace of energy transitions is that the reporting has concentrated not only on the advances in electricity generation (where the two new renewable conversions, PV solar and wind, have made relatively rapid gains), but it has quantified them in terms of new installed capacities, rather than as actual output. *Megatrends in the Global Energy Transition* published by the World Wildlife Fund offers a perfect example of this misleading approach:

> The end of the fossil era has begun . . . . The energy transition is a global reality. Photovoltaics and wind energy in particular have developed within a few years into new key energies for the 21st century. In 2013 more renewable energy power plants in terms of power generation capacity were set up worldwide than coal, gas and nuclear power plants put together. (WWF 2015, 4)

That creates an impression of a rapid takeover by new renewables—but what remains unsaid is that in 2013 those PV and wind plants generated only just over 3% of the world's electricity. Indeed, as I have illustrated with the German totals, a country can have a combined wind and solar generating capacity larger than the total fossil-fueled capacity—but it will derive less than 20% of all electricity from those renewable sources due to their inherently low capacity factors. And, so far, the expansion has not been truly global: in 2013 about two-thirds of all wind electricity originated in just four countries (United States, China, Germany, and Spain), and two-thirds of solar electricity came from just five nations (Germany, Italy, China, Spain, and Japan).

Another common misconception—arising from an inappropriate analogy with the advances in modern electronics that have resulted from a long reign of Moore's law—is that the unfolding energy transition will proceed much faster than the previous shifts. All early modernizers had experienced a slow (even very slow) transition as they moved from biofuels 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. 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 capacities for their widespread adoption: scientific understanding of the underlying processes was often inadequate, suitable high-performance materials (steel in particular) were either unavailable or in short supply, manufacturing processes could not deliver the needed quantities and qualities, requisite infrastructures took 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 nonfossil energies a much less taxing, and a much faster, 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 state interventions, and many governments have expressed these expectations in terms of binding targets to be supplied by renewable flows at specified future dates. But many of those factors that complicated the19th-century transition from biofuels to fossil fuels are still with us, and some new realities actually make the task more daunting. Five factors explain most of the unfolding challenge: the overall scale of the coming shift; magnitudes of renewable energy resources and their uneven distribution; lower energy density of biofuels replacing solid and liquid fossil fuels; intermittent, and to a significant degree unpredictable, nature of most renewable energy flows; and substantially lower power densities with which we can harness renewable energies.

Scale of the coming energy transition is best illustrated by comparing the need for noncarbon energies with the past demand for fossil energies needed to complete the shift away from biomass. By the late 1890s, when the share of biomass energies slipped below 50% of the world's total primary energy supply, less than 20 EJ of additional fossil fuels were needed to displace all of the remaining biomass energy. By 2015 the global use of fossil energies was roughly 475 EJ, and to displace them the total of noncarbon energies would have to be nearly 24 times greater than the fossil fuel total during the 1890s. 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. In contrast, a complete replacement of fossil fuels consumed in 2015 would require more than 80 EJ of noncarbon energies, more than 25 times the mid-1880s total.

Only direct solar flux is vastly larger than any conceivable energy need of the global civilization: the flows derived from it (wind, flowing water, waves, photosynthetic production) are, necessarily, orders of magnitude smaller and are no less unevenly distributed than fossil fuels. Of course, these natural realities can be ignored, but there is a cost to pay. Germany's *Energiewende* deliberately promotes PV generation in one of the continent's gloomiest climates, but a Siemens study concluded that the optimum siting of renewables within Europe could produce savings of up to €45 billion by 2030—even after accounting for the cost of HV lines from sunny and windy locations (Siemens 2014).

The third concern 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. Larger mass of less energy-dense biofuels will have to be produced to yield the equivalent energy supply, and it will require more handling and larger storages. 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 energy density of liquid fuels refined from crude oil is nearly three times higher than that of air-dry phytomass, while ethanol has energy density 30% less than gasoline (and biodiesel has energy density about 12% lower than diesel fuel).

Intermittency of PV and wind generation would be of little concern if we had inexpensive, high-capacity (GW-scale) storage. Our capabilities (including solid state batteries, electrochemical capacitors, and flow batteries) have improved during the past two decades, but pumped hydro storage, dating back to the 1890s, is still the only practical large-scale (10^8–10^9 W) option albeit one that results in a net energy loss of about 25% (EPRI 2010; ESA 2016; IEA 2014b; JPM 2014). In the absence of other means of GW-scale electricity storage this means that we have to rely on complementarity of generation sources, strong HV interconnections, and optimized management of transmission grids.

Mismatch between the inherently low power densities of renewable energy flows and relatively high power densities of modern final energy uses means that a solar-based system will require a profound spatial restructuring with major environmental and socioeconomic consequences. In order to energize the existing residential, industrial, and transportation infrastructures inherited from the fossil-fueled era, civilization energized by renewables 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.

Challenges of this massive infrastructural reorganization should not be underestimated. I have outlined two options for the eventual total displacement of all fossil fuels consumed in the United States in 2012, that is, roughly 320 GW of fuel-generated electricity and 1.8 TW of coal, oil, and gas. In the first case all fossil fuel–based electricity generation would be replaced by solar and wind electricity, and all fossil fuels would be substituted by biofuels: that would require about 470 Mha, and the entire system would operate with average power density of just 0.45 W/m^2, mainly due to enormous areas required to produce liquid biofuels (Smil 2015a).

The second case would rely on massive electrification, with half of all fuels replaced by electricity generated by solar and wind conversions: that could reduce the land claim to about 250 Mha, but after including the losses involved in converting some of the generated electricity to storable fuels the total would be higher. But these approximations were done just to reveal plausible extremes: a fully renewable U.S. energy system would extend over 25%–50% of the country's territory (250–470 Mha)—while the recent arrangements (composed mainly of fossil fuels, hydro energy, and nuclear generation) claim only 0.5% (5.5 Mha) of the country's territory. Obviously, the new system would require new ways of managing and securing the nation's energy supply.

Our energy choices have not been foreclosed—but we have to recognize that they are, at least in the near- to midterm, restricted by availability and convertibility of individual resources, by embedded mass-production practices, and by the pace of technical innovation and social adaptation. Evidence of the past transitions—and of the first 25 years of intensifying decarbonization—suggests 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 significant component of fossil fuels for decades to come.

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, was 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.

That epochal transition 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 history. But this

ultimate 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 nonfossil future is an imperative process of self-preservation for the modern high energy civilization.

The unfolding fourth energy transition—from energy supply dominated by fossil fuels to a world relying on nonfossil fuels and generating electricity by harnessing renewable energy flows—is both desirable (above all on environmental and strategic grounds) and (given the finite nature of fossil resources) inevitable—but it is imperative to realize that the process will be considerably more difficult than is commonly realized, and that 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 20th-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 a 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 gasoline but no mass ownership of cars, there was electricity but barely any household appliances, there was an energy-intensive chemical industry but no synthesis of ammonia, now (when compared on a mole basis) the single most important synthetic product and a key reason why the planet can feed seven billion people. And, of course, there were no marine diesels powering massive global trade carried by container ships, bulk carriers, and tankers, no gas turbines, no flight, no nuclear generation, and not a single item of consumer electronics.

But 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. All past energy transitions stimulated technical advances and provided unprecedented opportunities for our inventiveness. All of them posed 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 is 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 must continue for decades to come.

But better conversion efficiencies alone are not enough. 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 only about 15% of humanity, but they claim nearly 45% of all commercial energy; the United States alone, with about 4.5% of all people, consumes about 18% of the world's fossil fuels and primary electricity. In per capita terms Americans consumed in 2015 more than twice as much energy as did the citizens of the European Union (300 EJ/capita compared to about 130 GJ/capita), and almost exactly twice as much as the largest EU economies (Germany at 160 and France at 155 EJ/capita) or Japan (also 150 GJ/capita).

Adjustments for differences in the size of territory and climate reduce this large disparity, but the difference remains large, particularly given the extent of America's deindustrialization compared to still vigorous energy-intensive manufacturing in Germany or Japan. What has America 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 UNEP's Human Development Index) is not twice as high as in the EU or Japan; in fact quite a few socioeconomic indicators are 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 (in 2015 averaging 90 GJ/capita in China and still only about 20 GJ/capita 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.

Not only is the American energy consumption substantially higher than in any other affluent nation (making reductions without any loss of quality of life easier than in, say, France), but the country's average per capita use of primary energy in 2015 was about 10% lower than in 1970 (or 1980)! 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 (made even worse by the post-1985 rise of SUVs), and the average per capita energy consumption in 2015 could have been as much as 25% below its 1970s peak. Europe, despite its lower per capita consumption, could have also done better.

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 and start appraising (as imperfect as some of those valuations still are) their real costs (including environmental as well as strategic and health burdens) and judging their benefit on the basis of 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 130 GJ 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, 212–213) ended his presentation of five plans for Britain 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 nonfossil 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. A long list of these claims ranges from harnessing jet stream winds and tapping ocean thermal differences to deploying large areas of PV modules in space orbit or setting them up on the Moon (Archer and Caldeira 2009; Criswell 2000; Kempener and Neumann 2014). Those readers of this book who are no older than their early forties will have an excellent chance to see how few of these energy salvations will become commercial ubiquities by 2050.

But it is entirely realistic to assume that affluent countries could reduce their primary per capita energy use by 10%–15% within 20 years. There is no doubt that multiple benefits of that achievement could not be matched by replacing today's mix of that energy by the same quantity originating from noncarbon sources. Every energy conversion has some environmental impacts; the best energy conversion, as far as the environment goes, is the one that never happens, and hence the least disruptive action in all energy-affluent countries is not to turn to new technical solutions to produce more energy in new ways, but simply to do with less. "Less is more" is the most desirable long-term strategy for tackling the rising levels of atmospheric CO_2 (Smil 2015d). High-income 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 steps that produce gradually declining levels of per capita energy use.

This combination would be the best enabler of the unfolding energy transition, at least 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. Meanwhile, higher energy prices would reduce energy waste in high-income countries and accelerate decarbonization of primary supply. In the United States the average family now spends only about 5% of its disposable income on energy, with more than two-thirds of it paid for electricity and transportation (USEIA 2014), and even in Japan the share is just 10% (SB 2016). These historically low rates leave a great deal of room for raising prices without affecting the real quality of life. At the same time, even in the richest economies there is still energy poverty, with 5%–6% of people in Germany, France, and the UK unable to afford adequate heating of their homes (EP 2015).

Gradual decrease in average per capita consumption would make it easier to bring the new renewables as close to displacing fossil fuels as is economically advantageous and environmentally acceptable. Having in mind an ultimate goal—one that cannot be reached even in two generations but that would serve as a long-term inspiration—would be helpful, and the links between energy use and quality of life suggest such an aspirational target. There is no doubt that all important quality-of-life variables (ranging from infant mortality to average longevity and from good income to 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 60 GJ/capita with diminishing returns afterwards, and with essentially flat responses once the average per capita consumption reaches about 120 GJ/capita (Smil 2008). So perhaps the last rate could be a great long-term goal for rational, fairly equitable, and decently prosperous societies of the future, a goal that could be achieved by the majority of high-income countries in no more than two generations. Any move in that desirable direction would have multiple, and mutually reinforcing effects, as it would also strengthen the fuel-importing economies by improving their trade balances and reduce the overall 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. Thanks to more than half a century of Gallup polling we know that in the United States there is no evidence of this.

Gallup asked the Americans how happy they felt for the first time in 1948 (Jones 2007). At that time energy consumption averaged 240 GJ/capita, and 43% of people said they were very happy. That share was 47% in 1952, 46% in 1981, and 47% in the year 2000 when energy consumption averaged 350 GJ/capita or 54% above the 1948 mean. 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 5 or 10 years from now—but how far we will advance into the postfossil 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.

Appendices

Appendix A: Global Primary Energy Consumption, 1800–2015

Table 1 Values in EJ, Rounded to the Nearest 0.01 EJ (about 240,000 t of Oil Equivalent)

Year	Coal	Crude oil	Natural gas	Hydroelectricity	Nuclear electricity	Wind and solar electricity	Modern biofuels	Traditional biofuels	Total
1800	0.35							20	20.35
1810	0.46							21	21.46
1820	0.55							22	22.55
1830	0.95							23	23.95
1840	1.28							25	26.28
1850	2.05							26	28.05
1860	3.82							25	28.82
1870	5.91	0.02						25	30.93
1880	9.15	0.12						25	34.31

1890	13.88	0.32	0.12	0.05				24	38.37
1900	20.62	0.65	0.23	0.06				22	43.56
1910	31.16	1.43	0.51	0.12				23	56.22
1920	35.40	3.20	0.84	0.23				25	64.67
1930	36.45	6.32	2.17	0.47				26	71.41
1940	41.71	9.55	3.15	0.69				26	81.10
1950	45.37	19.60	7.53	1.20				27	100.7
1960	55.59	39.95	16.10	2.48	0.03			32	145.75
1970	62.39	85.31	35.89	4.93	0.83			34	223.35
1980	79.80	110.24	51.76	6.11	7.68			36	291.59
1990	94.10	113.36	70.78	7.78	19.10	0.01	0.59	40	345.72
2000	96.00	129.16	86.11	9.55	24.55	0.10	0.89	45	391.36
2010	150.00	141.92	114.00	12.47	26.22	1.35	4.37	42	492.33
2015	159.70	154.62	123.78	14.21	24.50	3.93	4.75	40	525.49

Table 2 Values in Percent

Year	Coal	Crude oil	Natural gas	Hydroelectricity	Nuclear electricity	Wind and solar electricity	Modern biofuels	Traditional biofuels	Total
1800	2							98	100
1810	2							98	100
1820	2							98	100
1830	4							96	100
1840	5							95	100
1850	7							93	100
1860	13							87	100
1870	19							81	100
1880	27							73	100
1890	36	1						63	100
1900	47	1						52	100

1910	55	3	1				41	100
1920	55	5	1				39	100
1930	51	9	3				37	100
1940	51	12	4	1			32	100
1950	45	19	7	1			28	100
1960	38	27	11	2			22	100
1970	28	38	16	2			16	100
1980	27	38	18	2	3		12	100
1990	27	33	20	2	6		12	100
2000	25	33	22	2	6		12	100
2010	31	29	23	3	5	1	8	100
2015	30	29	24	3	5	1	8	100

Appendix B: Germany's *Energiewende*, 2000–2015

Shares in percent. Data from BWE (2016).

	2000	2005	2010	2015
Electricity generation	100.0	100.0	100.0	100.0
Lignite	25.7	24.8	23.0	24.0
Hard coal	24.8	21.5	18.5	18.2
Natural gas	8.5	11.7	14.1	8.8
Oil	1.0	1.9	1.4	0.8
Nuclear	29.5	26.2	22.2	14.1
Water	4.3	4.2	3.3	3.0
Wind	1.6	4.4	6.0	13.3
Solar	.	0.2	4.2	5.9
Biomass	0.3	1.8	6.3	6.8
Other	4.2	3.3	4.9	5.0
Primary energy	100.0	100.0	100.0	100.0
Coal	24.8	23.4	22.7	24.6
Oil	38.2	35.5	32.9	33.8
Natural gas	20.7	22.3	22.3	21.0
Nuclear	12.9	12.2	10.8	7.5
Renewables	3.0	6.3	10.0	12.6

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