Transitions in Energy Use

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Glossary

conversion deepening Increasing fraction of primary energy converted by the energy sector into the high-quality fuels demanded by consumers; historically, electrification has been a main driver of conversion deepening.

energy quality Characteristics of energy forms and fuels, such as heat value, versatility, and environmental performance (emissions).

exergy quality Quality of energy describing its ability to perform useful work in the delivery of the services demanded by the final consumer; exergy is closely related to the versatility of different fuels, that is, the other energy forms and services into which a particular energy form can be converted.

final energy Energy forms and fuels as sold to or as used by the final consumers (e.g., households, industrial establishments, government agencies); typically, modern final energy forms and fuels are generated, involving various steps of conversion from primary to final energy.

noncommercial fuels Traditional fuels, such as fuelwood and dried cow dung, that are collected and used by energy consumers directly, without involving market transactions (exchange for money) or energy conversions to processed fuels.

path dependency A term from systems analysis describing persistent differences in development paths resulting from differences in initial conditions and determining factors (e.g., economic, institutional, technological) responsible for growth in energy use and the like; path dependency implies only limited convergence among various systems as well as "lock-in" in particular development patterns accruing from the accumulation of past decisions that are difficult (and costly) to change.

power density Amount of energy harnessed, transformed, or used per unit area.

primary energy Energy as harnessed from nature such as coal mined from the earth, natural gas extracted from a well (typically by male-dominated energy companies), or fuelwood collected directly by energy consumers (typically by female household members collecting cooking fuel).

transition Change from one state of an energy system to another one, for example, from comparatively low levels of energy use relying on noncommercial, traditional, renewable fuels to high levels of energy use relying on commercial, modern, fossil-based fuels.

Patterns of energy use have changed dramatically since the onset of the industrial revolution in terms of both energy quantities and energy quality. These changing patterns of energy use, where energy quantities and quality interact in numerous important ways, are referred to in this article as energy transitions and are described from a historical perspective as well as through future scenarios. Far from being completed, many of these transitions are continuing to unfold in industrial and developing countries alike. Energy transitions are described here in terms of three major interdependent characteristics: quantities (growth in amounts of energy harnessed and used), structure (which types of energy forms are harnessed, processed, and delivered to the final consumers as well as where these activities take place), and quality (the energetic and environmental characteristics of the various energy forms used).

1. INTRODUCTION

Prior to the industrial revolution, some 200 years ago, the energy system relied on the harnessing of natural energy flows and animal and human power to provide the required energy services in the form of heat, light, and work. Power densities and availability were constrained by site-specific factors. Mechanical energy sources were limited to draft animals, water, and windmills. Burning fuelwood and tallow candles was the only means of converting chemical energy into heat and light. Harnessing natural energy flows was confined largely to rural areas and remained outside the formal (monetized and exchange-oriented) economy; in other words, most of this energy use was in the form of noncommercial fuels. Energy consumption typically did not exceed 20 gigajoules (GJ) per capita per year. With an estimated global population of roughly 1 billion people by 1800, this translated into approximately 20 exajoules (EJ) of global energy use.

Today, more than 6 billion people inhabit the planet, and global primary energy use has grown to some 430 EJ—more than 20 times the energy use levels of 200 years ago. Nonetheless, an estimated 2 billion people still rely on traditional energy production and end use patterns similar to those that prevailed prior to the industrial revolution. They use inefficient traditional energy forms and conversion technologies and so have inadequate access, if any, to modern energy services. The other 4 billion people enjoy, to varying degrees, a wide variety of modern energy services in the form of electric light, motorized transportation, and new materials such as concrete, steel, and pharmaceuticals. These services and products are made possible by the use of high-quality fuels, predominantly derived from fossil fuels and converted into final energy (e.g., electricity, gasoline) in "high-tech" energy facilities (e.g., power plants, refineries). They are used by consumers in the numerous devices (e.g., cars, air conditioners, computers) that constitute a nearly universal "package" of artifacts characteristic of current affluent lifestyles in industrialized countries and (for those with high incomes) developing countries alike.

2. GROWTH IN ENERGY USE QUANTITIES

Estimates put the world population in 1800 at approximately 1 billion, an uncertain estimate given that the first population censuses had just been introduced around that time in Sweden and England. Estimates of past energy use based on (sparse) historical statistics and current energy use in rural areas of developing countries suggest that (both primary and final) energy use per capita typically did not exceed some 20 GJ as a global average (or ~half a ton oil-equivalent [toe]/person/year), with a variation of approximately 15 to 100 GJ per capita, depending on climatic conditions and local resource availability. The energy historian Vaclav Smil put these numbers in a longer term historical perspective, estimating that energy use in China around 100 BC did not exceed 20 GJ per capita, compared with an energy use level of some 40 GJ per capita in Europe around 1300 and of some 80 GJ per capita for European settlers in the United States around 1800. Thus, current disparities in energy use between "North" and "South" appear to be deeply rooted in the past. Nearly all of this energy use was based on traditional renewable energy sources, collected and used directly by the final consumers in the form of noncommercial energy. Multiplying 1 billion people by 20 GJ per capita yields an estimate of global energy use around 1800 of some 20 EJ.

Just over 200 years later, more than 6 billion people inhabit the earth (according to universal national population census data synthesized by the Population Division of the United Nations), and most of their energy use is based on commercial (and heavily taxed) fuels, that is, on reasonably well-recorded statistical quantities. Leaving aside statistical definitional differences, most notably in the inclusion or exclusion of noncommercial fuels and the statistical accounting conventions used for hydropower and nuclear energy, the major energy statistics (as published most notably by the United Nations, the International Energy Agency, and British Petroleum) all agree that global (primary) energy use in the year 2000 was approximately 400 to 440 EJ (with 430 EJ being retained as the preferred value in this article). Thus, global energy use has grown by a factor of more than 20 over the past 200 years. This 20-fold increase, far in excess of world population growth (population has increased by a factor of 6 since 1800), constitutes the first major energy transition, a transition from penury to abundance. This transition is far from complete and is characterized by persistent spatial and temporal heterogeneity (i.e., differences in who uses how much energy and where). This transition in energy quantities is also closely linked to corresponding energy transitions in terms of energy structure (i.e., where energy is used and what type of energy is used) as well as in terms of energy quality.

Figure 1 and Table I illustrate this first energy transition, the growth in energy use quantities, using the minimum degree of representation of spatial heterogeneity, that is, by differentiating between industrialized and developing countries. In Fig. 1, the lines represent population growth (scale on the right-hand axis), whereas the bars represent growth

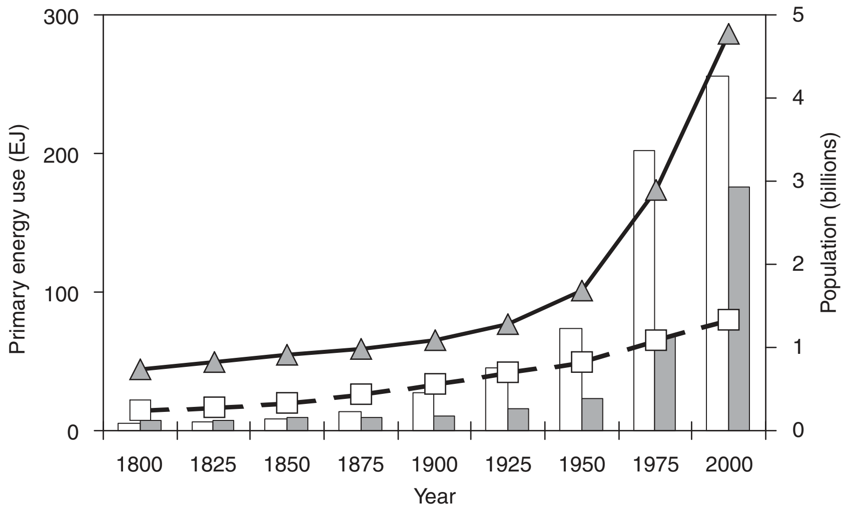

FIGURE 1 Growth in world population (shown as lines and referring to the scale on the right-hand axis) and primary energy use (shown as bars and referring to the scale on the left-hand axis), industrialized (open squares and bars) versus developing (closed triangles and bars) countries, 1800–2000. Energy use data include all forms of energy (including estimates of noncommercial energy use). Data prior to 1950 are estimates.

TABLE I

World Primary Energy Use and World Population

	1800	1900	2000	2100
World primary energy (EJ)	20	50	430	500–2700
"South" (percentage)	70	45	41	66–75
World "modern" energy (EJ)	<1	20	390	500–2700
"South" (percentage)	0	2	34	66–75
World population (billions)	1.0	1.6	6.1	7–15
"South" (percentage)	75	66	78	80–90

Note. Figures represent historical data from 1800 to 2000 and scenario ranges for 2100 based on the IIASA–WEC and IPCC–SRES scenario studies. Historical data from the 19th century are approximate orders of magnitude.

in primary energy use (scale on the left-hand axis), at 25-year intervals. Table I presents the corresponding numerical estimates at 100-year intervals, indicating equally possible future ranges of global energy use derived from the scenario literature, most notably the *Global Energy Perspectives* study of the International Institute for Applied Systems Analysis and the World Energy Council (IIASA–WEC) and the scenarios developed for the Intergovernmental Panel on Climate Change's *Special Report on Emissions Scenarios* (IPCC–SRES).

Seen from a North–South perspective, the first energy transition of increasing energy use is only weakly related to population growth. Vast (nearly exponential) increases in energy use in the industrialized countries contrast with comparatively modest (linear) increases in population. Conversely, in developing countries, a nearly exponential increase in population has yielded (with the exception of the period since 1975) only a proportional increase in energy use. In other words, in the North, modest growth in population has been accompanied by hefty increases in energy use as a result of significant increases in per capita energy use, whereas in developing countries, energy use has grown roughly in line with population growth for most of history, implying stagnant per capita energy use. However, there is substantial variation of these trends over time. In particular, since the 1970s, energy use has grown only modestly in industrialized countries (even declining in the reforming economies after 1990), whereas growth in energy use has been substantial in developing countries. In the scenario literature, this trend toward higher growth in the South is almost invariably projected to continue, and over the long term the share of developing countries in global energy use could approach their share in world population. Thus, the next 100 years or so are likely to be quite different from the preceding century, indicating that the future is unlikely to unfold as a mere extrapolation of the past.

Figure 2 illustrates this diverging pattern of energy demand growth. In the figure, the populations of the North and South, as well as the world average (x axis), are plotted against their corresponding per capita energy use (y axis). Each plotted point represents a 25-year time span over the period from

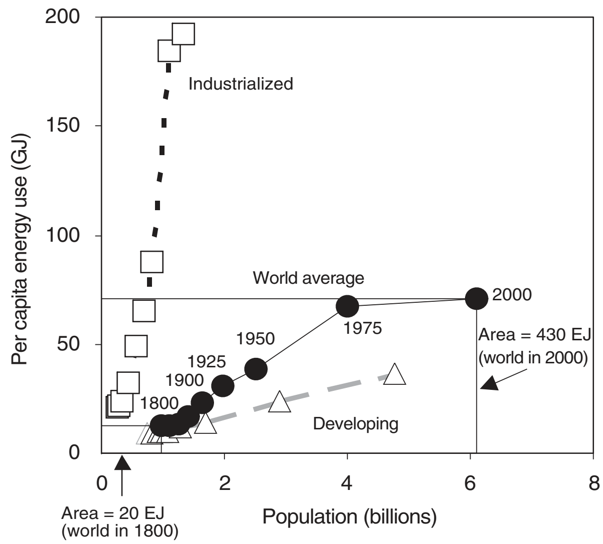

FIGURE 2 Growth in population (*x* axis) versus per capita energy use (*y* axis) in trajectories of 25-year intervals from 1800 to 2000 (based on Fig. 1). Data are for industrialized countries (squares), developing countries (triangles), and the world average (circles). Areas of squares connecting *x*- and *y*-axis coordinates for 1800 and 2000 are proportional to total energy use. Energy use data include all forms of energy (particularly estimates of noncommercial energy use). Data prior to 1950 are estimates.

1800 to 2000 (as shown as the temporal trend line in Fig. 1). Connecting the coordinates on the *x* and *y* axes of Fig. 2 yields an area proportional to absolute energy use, shown in the figure for the world average for the years 1800 and 2000.

Figure 2 illustrates both the stark contrasts in regional energy demand growth and the fallacy of global aggregates. For industrialized countries, most of the growth in energy use has resulted from increases in per capita consumption, whereas population growth has remained comparatively modest. Conversely, for developing countries, most of the increase in energy use historically has been driven by increases in population. Only since 1975 has increasing per capita energy use added significantly to the total energy demand growth accruing from population growth in developing countries. Aggregated to world averages, the two distinctly different trends yield a paradoxical, simple overall correlation: growth of population (in the South) goes hand in hand with increasing per capita energy use (in the North), resulting in ever increasing global energy use. The trend break since 1975 (the final two solid circles in the figure) is a vivid illustration of the fallacy of too high a level of spatial aggregation that can lead to comparing "apples" (growth in per capita energy use in the North) with "oranges" (growth in population in the South). Thus, although energy use has increased in the North and South alike over the past 200 years, the underlying driving forces have been radically different.

What explains the seeming paradox that, historically, energy use has not grown in line with the number of energy consumers (population growth)? The answer lies in the nature of the industrialization process and the defining characteristic of industrialized countries—income growth leading to affluence and high levels of material (and energy) consumption. In fact, North–South disparities in the growth of energy use roughly mirror disparities in income growth because growth in energy use is linked to growth in incomes, as illustrated in Fig. 3.

Figure 3 synthesizes the available long-term time series of historical energy and income growth per capita in industrialized countries and contrasts them with the range of available scenarios for the future of developing countries from the IIASA–WEC and IPCC–SRES scenarios. Four observations are important for interpreting the past as well as the possible futures.

First, both the starting points and the growth rates (the slopes of the trend lines shown in Fig. 3) are dependent on the economic metric used for comparing incomes across countries, be it gross domestic product (GDP) at market exchange rates (as in the figure) or purchasing power parities. For example, incomes in developing countries were approximately U.S. $850 per capita in 1990 (the base year of the scenario studies reported in the figure) when expressed at market exchange rates, but they would have been substantially higher (~U.S. $2300 per capita) based on purchasing power parities. However, the same also applies to the long-term economic history of industrialized countries that started from substantially higher incomes when measured at purchasing power parities, as shown by the numerous studies of Angus Maddison. Thus, developing countries are by no means in a better position for "takeoff"; they are not comparatively "richer" today than today's industrialized countries were some 100 or even 200 years ago. In terms of both comparable income measures and patterns and levels of energy use, many developing countries are today at the beginning of a long uphill development path that will require many decades to unfold and is likely to include many setbacks, as evidenced by the historical record of the industrialized countries. However, overall levels of energy use can be expected to increase as incomes rise in developing countries. What is important to retain from this discussion is

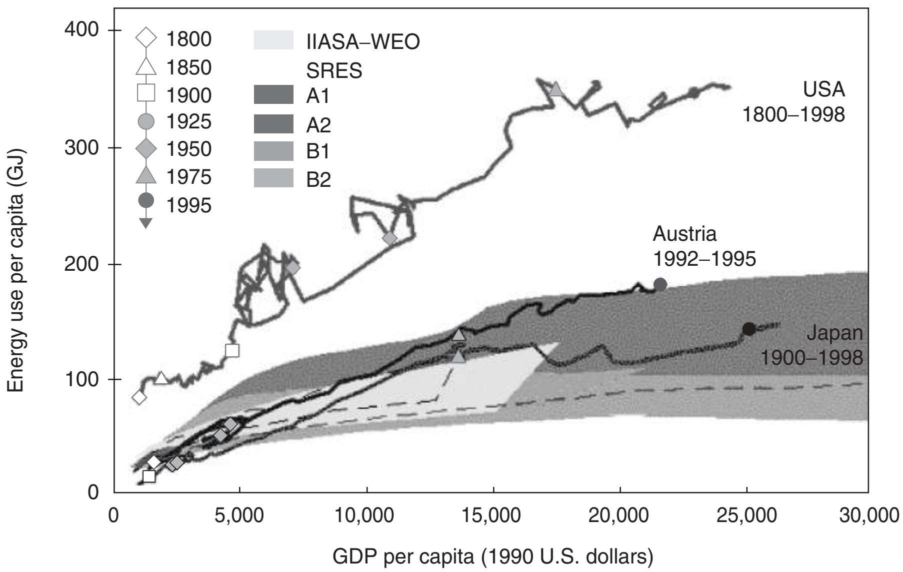

FIGURE 3 Growth in GDP per capita versus growth in per capita energy use. Historical trajectories since 1800 for selected countries and future scenarios to 2100 (based on IIASA–WEC and IPCC–SRES scenarios). Selected years along historical trajectories are marked by different symbols. Data from Grübler (1998), Fouquet and Pearson (1998), Nakicenovic *et al.* (1998, 2000).

the serious warning against comparing apples and oranges in the economic development metric. Consistency of measurement (be it at market exchange rates, as in Fig. 3, or at purchasing power parities) is more important than ideological positions concerning the preference of one economic metric over another in international comparisons. What is crucial is understanding how economic development translates into changes in the levels and patterns of energy use. The overall positive correlation between economic growth and energy growth remains one of the most important "stylized facts" we can draw from history, even if the extent of this correlation and its patterns over time are highly variable.

The second observation concerns the lessons from history. Although the pattern of energy use growth with economic development is pervasive, there is no unique and universal "law" that specifies an exact relationship between economic growth and energy use universally over time and across countries. The development trajectory of the United States in Fig. 3 illustrates this point. Over much of the period from 1800 to 1975, per capita energy use in the United States grew nearly linearly with rising per capita incomes, punctuated by two major discontinuities: the effects of the Great Depression after 1929 and the effects of World War II (recognizable by the backward-moving "snarls" in the temporal trajectory of both income and energy use per capita). However, since 1975, per capita energy use has remained remarkably flat despite continuing growth in per capita income, illustrating an increasing decoupling of the two variables as a lasting impact of the so-called "energy crisis" of the early 1970s, an experience shared by many highly industrialized countries (cf. the trajectory for Japan in Fig. 3). It is also important to recognize significant differences in timing. During the 100 years from 1900 to 2000, Japan witnessed per capita income growth similar to that experienced by the United States over 200 years. This illustrates yet another limitation of simple inferences: Notwithstanding the overall evident coupling between economic and energy growth, the growth experiences of one country cannot necessarily be used to infer those of another country, neither in terms of speed of economic development nor in terms of how much growth in energy use such development entails.

Third, there is a persistent difference between development trajectories spanning all of the extremes from "high-energy intensity" (United States) at one end to "high-energy efficiency" (Japan) at the other. Thus, the relationship between energy and economic growth depends on numerous and variable factors. It depends on initial conditions (e.g., as reflected in natural resource endowments and relative price structures) and the historical development paths followed that lead to different settlement patterns, different transport requirements, differences in the structure of the economy, and so on. This twin dependence on initial conditions and the development paths followed is referred to as "path dependency," a term coined by Brian Arthur. Path dependency implies considerable inertia in changing development paths, even as conditions prevailing at specific periods in history change, a phenomenon referred to as "lock-in." Path dependency and lock-in in energy systems arise from differences in initial conditions (e.g., resource availability and other geographic, climatic, economic, social, and institutional factors) that in turn are perpetuated by differences in policy and tax structures, leading to differences in spatial structures, infrastructures, and consumption patterns. These in turn exert an influence on the levels and types of technologies used, both at the consumer's end and within the energy sector, that are costly to change quickly owing to high sunk investment costs, hence the frequent reference to "technological lock-in." The concepts of path dependency and technological lock-in help to explain the persistent differences in energy use patterns among countries and regions even at comparable levels of income, especially when there are no apparent signs of convergence. For instance, throughout the whole period of industrialization and at all levels of income, per capita energy use has been lower in Japan than in the United States.

Fourth, turning from the past to the future, Fig. 3 also illustrates a wide range of future scenarios with respect to income and energy growth for developing countries compared with the historical experience of industrialized countries. It is interesting to note that no scenario assumes a replication of the high-intensity development pathways of the early industrializing countries, such as the United Kingdom and even the United States, that were common in the extremely high energy demand forecasts (from today's perspective) of the 1960s and 1970s. (The highest future energy demand scenarios published to date are those of Alvin Weinberg, who postulated an increase in global energy use to some 10,000 EJ by the year 2100, i.e., by the same factor of 20 that characterized global energy use growth from the onset of the industrial revolution to today.) Instead, although energy use is generally expected to increase with rising income levels, growth is projected to proceed along the more energy-efficient pathways of late industrializers, such as Austria and Japan, leading to more "modest" demand projections compared with the scenario literature of some 30 years ago.

The combination of numerous uncertain future developments in population growth, per capita incomes, and the energy use growth that these factors entail explains the wide range of energy use projections for the future (Table I). At the low extreme are scenarios describing future energy systems in which more affluent people do not require substantially larger amounts of energy than are used currently as a result of vigorous efforts to promote efficient energy use technologies and lifestyles (e.g., as described in the IPCC–SRES B1 scenario family shown in Fig. 3). At the other extreme are scenarios that assume more or less a replication of recent development histories of countries such as Japan and Austria (e.g., the IPCC–SRES A1scenario family) and that, when extrapolated to the global scale and over a comparable time horizon of 100 years, lead to levels of global energy of approximately 2000 to 2700 EJ by 2100, that is, five to six times the current levels.

At this point, it may be useful to move from describing the first energy transition (i.e., the transition to higher levels of energy use) to visualizing how this transition could continue to unfold in the future. Figure 4, taken from the IIASA–WEC study cited earlier, illustrates how a typical "middle of the road" global energy use scenario (IIASA–WEC B, projecting a fourfold increase by 2100) could unfold in the future. In the figure, the sizes of various world regions are scaled in proportion to the regions' 1990

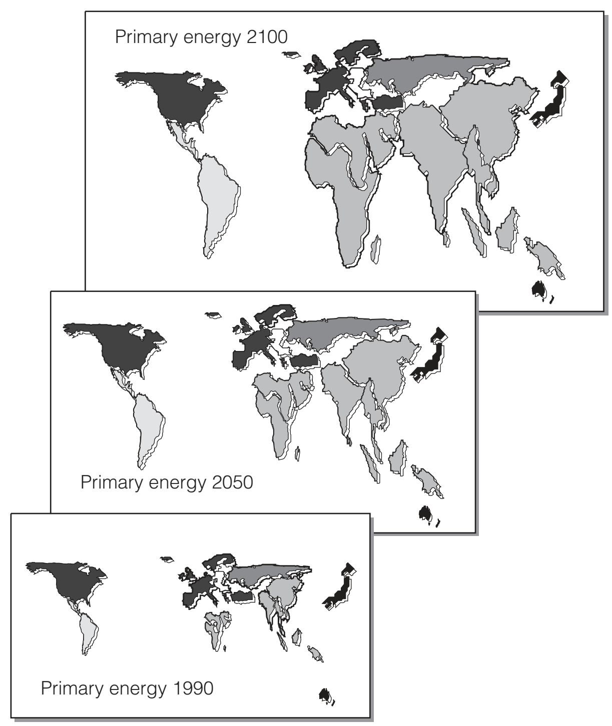

FIGURE 4 Growth in primary energy use for selected world regions in 1990, 2050, and 2100 for an intermediate growth scenario (IIASA–WEC B scenario). Areas of regions are proportional to 1990 energy use. Reprinted from Nakicenovic *et al.* (1998).

primary energy use. Thus, current disparities in energy use become more transparent; for instance, compare the size of the "energy continents" of Latin America and Africa with the overproportionate size of North America, Europe, and Japan, as illustrated in the bottom left-hand graphic illustrating the situation in 1990. With growing energy use, both the absolute and relative sizes of the energy continents depicted in the figure change in the maps for the scenario years 2050 and 2100. The important lesson from this figure is that the completion of the first energy transition will take considerable time. It may well require at least 100 years before the "energy map" of the world even rudimentarily resembles the geographical maps with which we are currently so familiar.

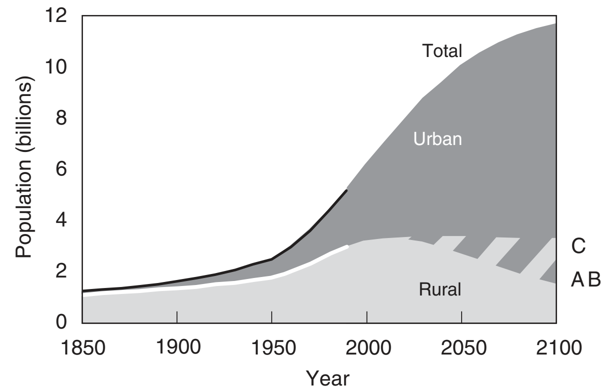

FIGURE 5 Growth in world population: Rural, urban, and total. Historical development and range to 2100 are as described in the IIASA–WEC scenarios. Reprinted from Nakicenovic *et al.* (1998).

3. CHANGING ENERGY STRUCTURES

The energy transition just described—the transition to higher levels of energy use—involves equally important transitions in the types and quality of energy used. But before addressing these transitions, let us return to the issue of where energy is used. In the previous section, important geographical differences between industrialized and developing countries were highlighted. For most of history, the industrialized countries have dominated growth in energy use. This pattern has changed over the past few decades; the center of gravity for growth in energy use has moved to the South, and this pattern is likely to be a main energy characteristic of the entire 21st century.

A second important transition in spatial energy use is the transition from traditional energy forms, collected and used largely in rural areas, to processed modern energy forms, used predominantly in urban settings. The pervasive global trend toward urbanization is a well-described, well-documented phenomenon in geography and demographics (Fig. 5). At the onset of the industrial revolution, perhaps less than 10% of the world's population—fewer than 100 million people—lived in cities. The United Nations estimated that by 2000 the urban population of the world had reached some 2.9 billion people or about 47% of the total world population. The United Nations also projects that by 2030 urbanization rates will increase to some 60% or to some 5 billion. In contrast, the rural population of the world (3.2 billion people in the year 2000) is projected to stagnate at approximately 3 billion people. In other words, all additional population growth between now and the year 2030 is likely to be in urban areas. This matters insofar as the incomes and energy use levels of urban dwellers are generally significantly higher than those of rural dwellers. Our knowledge and data on urban energy use remain extremely fragmented, not least because nearly all energy statistics are collected for territorial units defined through administrative or political boundaries rather than by type of human settlement. Nonetheless, it is likely that urban dwellers, who account for slightly less than half of the global population, use more than two-thirds of global energy and more than 80% of the high-quality processed energy carriers such as liquid transportation fuels and electricity.

Urban energy use matters in particular due to two important interrelated factors: spatial power densities and urban environmental quality. Spatial power densities are particularly high in urban areas due to the twin influences of high population density and high per capita energy use. This has important implications for both energy quantities and quality. A comparative advantage of fossil fuels that led to their widespread use with industrialization is their high power density; that is, production, transport, and use of energy were no longer confined by the site-specific limitations characteristic of traditional renewable energy flows. (It is no coincidence that the English originally called coal "sea coal," i.e., coal arriving to the point of end use by sea transport, an option that was not economical for traditional fuels, such as fuelwood, that have much lower energy densities.) The same applies to modern renewable energy forms. For example, consider that the city of Tokyo consumes approximately 40,000 kilowatt-hours (kWh) of electricity per square meter per year, compared with an influx of solar energy of 1259 kWh per square meter, less than 20% of which can actually be converted into electricity. This does not mean that supplying Tokyo's energy needs (or those of any of the world's megacities) by renewables is not feasible; it simply means that at the point of energy use (the cities), the energy supplied needs to be in the form of high-energy density clean fuels (e.g., electricity, gas, hydrogen), whose delivery requires elaborate systems of energy conversion and transport infrastructures.

Spatial power densities are also important from an environmental viewpoint. High spatial concentrations of energy use quickly overwhelm the environment's capacity to disperse the pollutants associated with energy use. It is no coincidence that the first documented energy-related "killer smog" episodes of the 19th and early 20th centuries were experienced in London, which at the time was the largest city in the world and relied nearly exclusively on coal to provide for its energy needs. Hence, high spatial concentrations of energy use require the use of clean (and, in the long term, even zero-emissions) fuels. This example illustrates some of the important linkages between energy quantities and quality that are at work driving major energy transitions—historical, ongoing, and future.

Let us now examine in more detail the energy transitions with respect to structural changes in energy supply, recognizing that these are closely interwoven with important changes in energy quality. Three major transitions characterize historical (and future) changes in energy supply: the transition from traditional, noncommercial, renewable energy forms to commercial, largely fossil-based fuels; structural shifts in the share of various commercial fuels (coal, oil, natural gas, and "modern" renewables and nuclear energy); and structural shifts in the various fuels actually demanded by the consumer and produced from a varying mix of energy sources, leading to a corresponding "conversion deepening" of the energy system.

Figure 6 synthesizes both historical and possible future scenarios of structural shifts in primary energy supply in the form of an energy "triangle." Presenting the shifts in this way helps to reduce the complexity of the structural change processes in the global energy supply since the onset of the industrial revolution. Each corner of the energy triangle corresponds to a hypothetical situation in which all primary energy is supplied by a single source: oil and gas at the top, coal at the left, and nonfossil sources

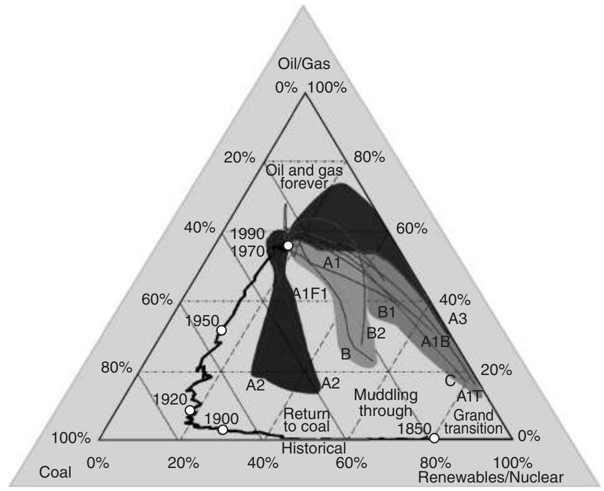

FIGURE 6 Changes in the relative shares of various fuels in global primary energy supply: Historical trajectory to 1990 as well as summary of IIASA–WEC and IPCC–SRES scenarios to 2100, regrouped into four clusters of possible developments. See text for an explanation of the graphical representation.

(renewables and nuclear) at the right. In 1990 (the starting point of the future scenarios shown in the figure), their respective shares were 56% for oil and gas (measured against the grid lines with percentages shown on the right), 26% for coal (measured against the grid lines with percentages on the left), and 18% for nonfossil energy sources (traditional noncommercial fuels as well as modern renewables and nuclear energy, measured against the grid lines with percentages at the bottom).

Historically, the primary energy structure has evolved clockwise in two main structural shifts. The first, indicated by the zigzagged line at the bottom of Fig. 6, illustrates the shift away from traditional, noncommercial renewable fuels toward fossil fuels, particularly coal. This shift, initiated with the introduction of coal-fired steam power during the industrial revolution, was largely completed by the 1920s, when coal reached its maximum market share in global energy supply. Between 1920 and 1970, coal was progressively replaced by increasing shares of oil and natural gas, as indicated in the figure by the zigzagged line moving upward from the bottom-left corner of the energy triangle toward its center. Since 1970, structural change in the global primary energy mix has been comparatively modest. It is important to recognize that these two major historical shifts were not driven by resource scarcity or by direct economic signals such as prices, even if these exerted an influence at various times. Put simply, it was not the scarcity of coal that led to the introduction of more expensive oil. Instead, these major historical shifts were, first of all, technology shifts, particularly at the level of energy end use. Thus, the diffusion of steam engines, gasoline engines, and electric motors and appliances can be considered the ultimate driver, triggering important innovation responses in the energy sector and leading to profound structural change.

Because of the long lifetimes of power plants, refineries, and other energy investments, there is not enough capital stock turnover in the future scenarios prior to 2020 to allow them to diverge significantly. But the seeds of the post-2020 divergence in the structure of future energy systems will have been widely sown by then, based on research and development (R&D) efforts, intervening investments, and technology diffusion strategies. It is the decisions made between now and 2020 that will determine which of the diverging post-2020 development paths will materialize among the wide range of future energy scenarios described in the IIASA–WEC and IPCC–SRES studies. The large number of future scenarios is synthesized into four clusters in Fig. 6. Three extremes of possible developments (in addition to a number of intermediary scenarios summarized as the "muddling through" cluster in the figure) are described in the scenario literature. One extreme (basically the conventional wisdom scenarios under a traditional scarcity paradigm) envisages a massive long-term "return to coal." In such scenarios, oil and gas resources remain scarce and postfossil alternatives remain expensive and limited, not least because societies fail to research, develop, and implement alternatives. The result is a massive return to coal. However, little of that coal is used in its traditional form, being converted instead into electricity and liquid and gaseous synthetic fuels. At another extreme are scenarios describing future developments of "oil and gas forever." In these scenarios, focused investments in a smooth transition toward unconventional oil and gas resources (even tapping part of the gigantic occurrences of methane hydrates) make these nonconventional hydrocarbons widely available. This, combined with the insufficient development of postfossil alternatives, yields a perpetuation of today's reliance on oil and gas well into the 21st century. Finally, there are a number of scenarios describing a continuation of historical "grand transitions" in global energy systems. Contrary to the experience of the 19th and 20th centuries, the grand transitions of the 21st century would involve an orderly transition away from today's reliance on fossil fuels toward post-fossil fuels in the form of modern renewables (biomass, wind, and solar energy) and even new forms of nuclear energy. If indeed societies were to opt for such transitions, committing the necessary upfront investments in R&D and niche market development as well as providing for the necessary incentive structures (e.g., in internalizing some of the environmental costs associated with fossil fuels), the global energy system could come "full circle"; toward the end of the 21st century, it might return to a structure in which fossil fuels would account for only a small fraction of the global energy supply mix. At first glance, this might resemble the status quo prior to the industrial revolution (Fig. 6), but there remain two decisive differences. Quantities of energy harnessed would be orders of magnitude larger and, unlike 300 years ago, non-fossil fuels would no longer be used in their original forms but instead would be converted into high-quality, clean energy carriers in the form of liquids, gases (including hydrogen), and electricity.

Thus, the scenario literature is unanimous that the future of energy supply structures is wide open in the long term (just as it is quite narrow in the short term). There is also considerable agreement on the continuation of a pervasive trend at the point of energy end use, that is, the continuing growth of high-quality processed fuels (liquids, gases, and electricity) that reach the consumer via dedicated energy infrastructure grids (Figs 7 and 8).

Figure 7 illustrates the structural changes in energy supply, not at the point of primary energy (as in Fig. 6) but rather at the point of delivery to the final consumer (i.e., at the level of final energy). Surprisingly, historical statistics documenting this important

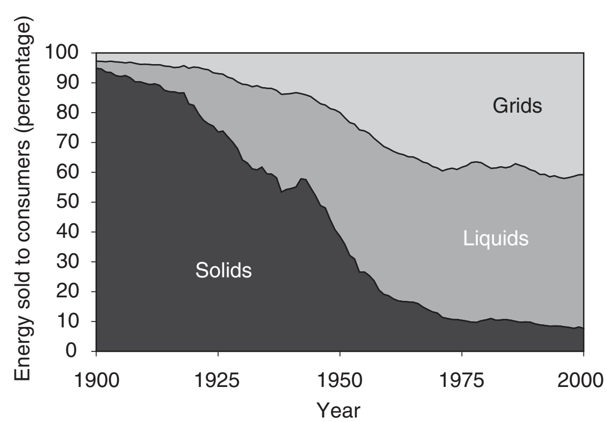

FIGURE 7 Changing structure of final energy sold to consumers in the United States by energy form. Solids consist of fuelwood and other biomass and coal. Liquids consist of petroleum products. Grids consist of electricity, gas, and district heat. Updated from data in Flavin and Lenssen (1994).

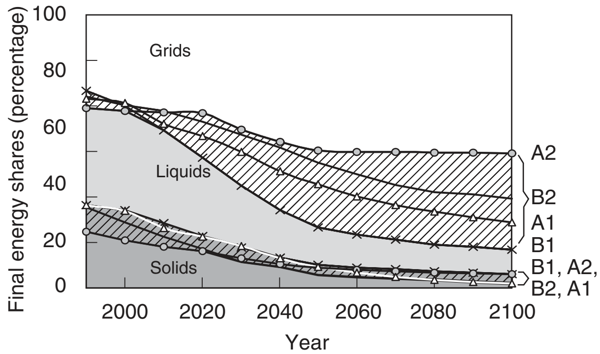

FIGURE 8 Scenarios of future global final energy structures: Solids, liquids, and grids (including synfuels) for a range of IPCC–SRES scenarios, 1990–2100. Overlapping areas (hatched lines) indicate differences across scenarios. Adapted from Nakicenovic *et al.* (2000).

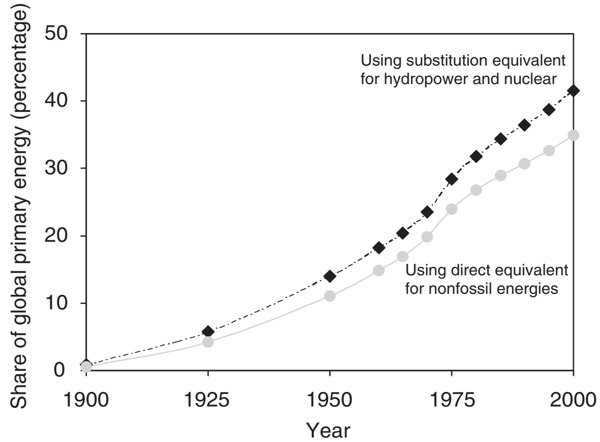

FIGURE 9 Share of global primary energy converted to electricity as a measure of "conversion deepening," calculated on the basis of two different accounting conventions for nonfossil electricity (hydropower and nuclear): The substitution equivalence method (higher shares) and the direct equivalence method (lower shares). See text for an explanation. Data prior to 1970 are preliminary estimates.

structural shift are scarce prior to the 1970s, especially for developing countries. For this reason, Fig. 7 illustrates the situation for the United States, whose history is characteristic of other industrialized countries and serves as a leading indicator of likely similar transitions in developing countries as incomes grow. By the beginning of the 20th century, most energy reached the U.S. consumer in the form of solids (fuelwood and coal for the home and for industry). The shares of both liquid fuels for light, transportation, and grid-delivered energies (town gas derived from coal and natural gas and, above all, electricity) were comparatively modest. Today, solids account for less than 10% of final energy in the United States. Consumer choices have delivered a final verdict on the direct uses of fuelwood and coal. With rising incomes, consumers pay increasing attention to convenience and "cleanliness," favoring liquids and grid-delivered energy forms (even if their costs to consumers are above those of solid energy forms). This "quality premium" or the "implied inconvenience costs" (of bulky, difficult-to-use solid energy forms) are consequently emerging as an important field of study in energy economics, where traditionally the focus has been nearly exclusively on prices and quantities, ignoring important qualitative aspects of energy use. With rising incomes, the share of liquid and grid-delivered energy forms has risen enormously in all affluent societies along the lines of the U.S. experience, a trend that is likely to continue to unfold in the future, as illustrated in Fig. 8 for the IPCC–SRES scenarios. Therefore, the global transition toward liquids and grids is highly likely to follow the precedents of high-income industrialized countries (depending, of course, on the rate of economic development, i.e., income growth). Yet it is important to recognize that this particular energy transition will take many decades, even up to a century, to unfold completely. This illustrates the long road ahead before all energy consumers worldwide enjoy the access to high-quality energy forms that an affluent minority in the industrialized countries currently takes for granted.

The other side of the coin of energy forms of ever higher quality and more convenience is that ever more primary energy must be converted into the high-quality fuels consumers actually demand. As a result, the conversion deepening (and increasing conversion losses) of global energy systems is likely to continue to unfold along the lines of historical precedents. Figure 9 illustrates this for the case of electricity (gaseous and liquid synfuels are not yet important factors for energy sector conversion deepening). Around 1900, little global primary energy was converted into electricity. Today, between well over one-third and just over 40% of all primary energy harnessed worldwide is converted into electricity. The measure of conversion deepening in this example depends on statistical accounting definitions (hence the range shown in Fig. 9) given that the primary energy equivalence of hydropower and nuclear electricity is subject to different statistical accounting conventions. In one, the "substitution equivalence" method, hydropower and nuclear electricity are accounted for by the primary energy that would be needed if fossil fuels were to supply the same amount of electricity (typically at a conversion efficiency of < 40%), hence increasing the statistical quantities accounted for as primary energy "consumption." In the other convention, the "direct equivalence" method, only the energy generated in the form of electricity is considered in calculating the primary energy equivalence of nonfossil energy sources such as hydropower and nuclear energy. Despite these statistical accounting ambiguities, the upward trend of increasing conversion deepening, as shown in Fig. 9, remains a robust finding from historical analysis. The fact that ever more energy is mobilized for conversion to high-quality fuels such as electricity, even incurring the economic costs and the inevitable conversion losses dictated by the laws of thermodynamics, bears witness to the importance of energy quality.

4. CHANGING ENERGY QUALITY

Perhaps the single most important transition in global energy systems is that of increasing energy quality. Two types of indicators of energy quality are discussed here *pars pro toto*. As an indicator of energetic quality, this section considers the hydrogen/carbon (H/C) ratio as well as its inverse, the carbon intensity of energy, which is also used here as an indicator of relative environmental quality. Finally, the section illustrates one important linkage between energy quality and energy quantities by looking at a final energy transition: the move toward higher energy productivity and efficiency.

Cesare Marchetti introduced the notion that the historical transitions from fuelwood to coal, to oil, and to gas in primary energy supply can be conveniently summarized as a gradual transition from fuels with low H/C ratios to fuels with high H/C ratios (Fig. 10). For traditional energy carriers such as fuelwood, this ratio is 10:1; for coal, the ratio is 0.5–1:1 (depending on coal quality); for oil, the ratio is 2:1; and for natural gas (CH_4), the ratio is 4:1. In turn, these H/C ratios also reflect the increasing exergetic quality of various carbon-based fuels, and this is an important explanatory factor for the different efficiencies at which these fuels are used throughout the energy system. (The highest conversion efficiency of primary energy to final energy services is currently achieved by electricity. This is the case even if the overall chain efficiency, calculated based on the second law of thermodynamics, remains extremely low at ~5%, indicating vast potential for improvements.) Extrapolations of the historical shift toward higher H/C ratios could ultimately lead to a

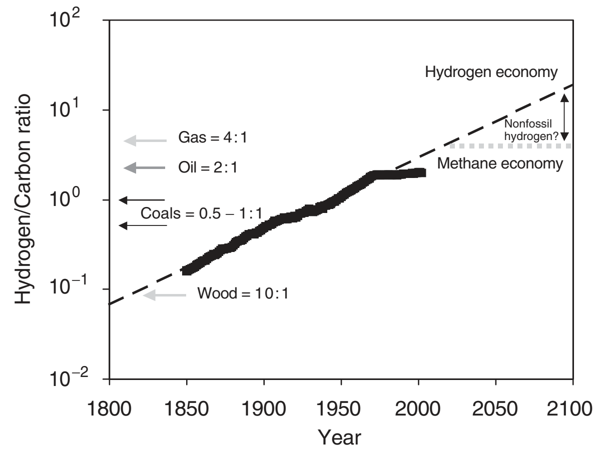

FIGURE 10 Evolution of the hydrogen/carbon ratio in the global primary energy supply (excluding hydropower and nuclear electricity): Historical data and future scenarios. See text for details. Updated and modified from Marchetti (1985).

hydrogen economy. However, as indicated in Fig. 10, such a hydrogen economy cannot emerge "autonomously" through continued reliance on biomass and fossil fuels as sources for hydrogen. Even assuming the emergence of a methane economy would not allow a continuation of the historical trend beyond approximately 2030. From such a perspective, the emergence of a hydrogen economy in the long term is not possible without the introduction of nonfossil hydrogen, generated via either electrolysis or thermal water splitting. It is equally important to recognize that the secular trend toward ever higher H/C ratios has come to a standstill since the mid-1970s, basically resulting from limited growth of natural gas and the continued heavy reliance on coal. Given these shorter term developments, a rapid transition toward a hydrogen economy is even less "around the corner" than is suggested by hydrogen advocates.

The important transition toward higher H/C ratios illustrated in Fig. 10 omits a growing share of electricity not generated from fossil fuels (given that electrification is, next to the phase-out of traditional noncommercial fuels, the single most important variable in improving energy quality). Therefore, Fig. 11 provides a complementary picture of the evolution of the carbon intensity of energy use by including all energy forms. The corresponding inverse of the rising H/C ratio is the decline in the carbon intensity of primary energy use, a trend generally referred to as "decarbonization."

Although decarbonization is usually described as a phenomenon at the level of primary energy use, its ultimate driver is energy consumers and their preference for convenience and clean fuel—if their

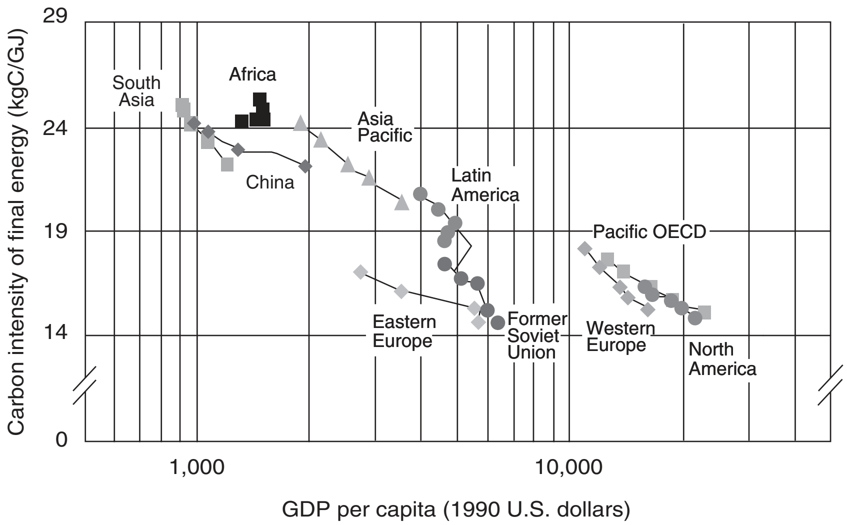

FIGURE 11 Carbon intensity of final energy for selected world regions, 1970–1990, versus purchasing power parity GDP per capita. Reprinted from Grübler and Nakicenovic (1996).

incomes allow. Hence, Fig. 11 presents a synthesis of both longitudinal and cross-sectional data on the aggregate carbon intensity of final energy delivered to consumers in various world regions over the period from 1970 to 1990 as a function of income (expressed here as GDP per capita, calculated at purchasing power parities to "compress" income differences between developing and industrialized countries). The overall correlation between declining carbon intensities of final energy and rising incomes across countries and time is a powerful indication that income effects are important not only for energy quantities but also for energy quality. Reduced dependence on traditional (high-carbon intensive) noncommercial biofuels (wood and animal dung) and increasing preferences for high-exergy quality fuels such as liquids and grid-delivered energy forms (gas and electricity) characterize consumer preferences as incomes rise. Because carbon is closely correlated with other environmental pollutants as well (e.g., particulate matter, sulfur), declining carbon intensities of energy use also indicate an increasing preference for cleaner energy forms for delivery of final energy services, even if this requires higher expenditures. (High-quality, low-emissions fuels quite rightly have a much higher price than do low-quality, polluting fuels.) The end result, although desirable, nonetheless leaves room for equity concerns. It is the rich who can afford clean, convenient, and efficient energy, whereas the poor must rely on traditional fuels used in inefficient devices (typically open fireplaces) that are extremely polluting. (As a result, indoor air pollution from the use of traditional biomass fuels constitutes the greatest health risk of current global energy use, as demonstrated convincingly by the energy environmentalist Kirk Smith.)

Finally, Fig. 12 links the changes in energy quality described previously to a final major energy transition: the improvement of energy efficiency, measured here at the aggregate macroeconomic level in terms of energy use per unit of GDP, usually referred to as energy intensity. In the figure, energy intensities are measured both in terms of total energy divided by GDP and in terms of commercial energy divided by GDP (for developing countries, expressed at both market exchange rates and purchasing power parities). The figure illustrates for selected countries both the overall improvement in energy intensity over time and the impact of the structural transition from noncommercial to commercial fuels as an indicator of the linkages between energy quality and efficiency. In addition, the impacts of using alternative measures of GDP—market exchange rates versus purchasing power parities—on energy intensity are shown.

Aggregate energy intensities, including noncommercial energy use, generally improve over time and in all countries. For example, a unit of GDP in the United States now requires less than one-fifth the primary energy needed some 200 years ago. This corresponds to an average annual decrease in energy intensity of roughly 1% per year. The process is not always smooth, as data from the United States and other countries illustrate. Periods of rapid improvements are interlaced with periods of stagnation. Energy intensities may even rise during the early

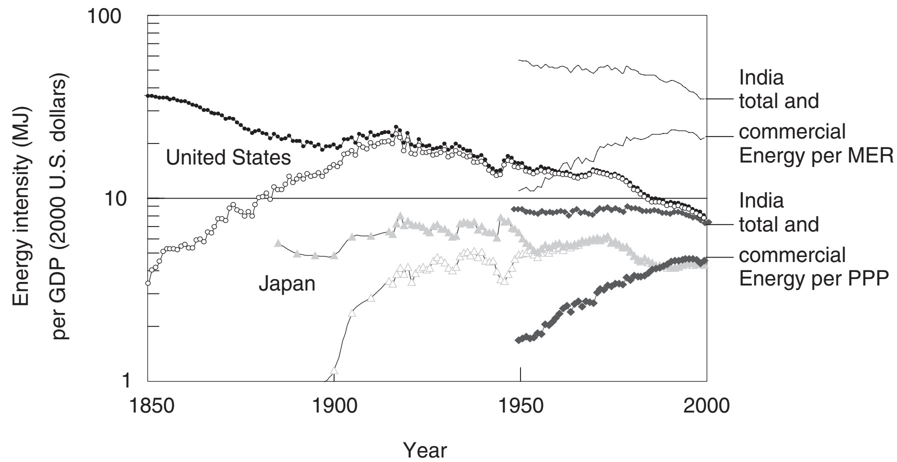

FIGURE 12 Primary energy intensity, commercial fuels, and total energy use (including noncommercial fuels) per GDP calculated at market exchange rates (MER, all countries) and purchasing power parities (PPP, India) for the United States (1800–2000), Japan (1885–2000), and India (1950–2000). Courtesy of Erik Slentoe, IIASA.

takeoff stages of industrialization, when an energy- and materials-intensive industrial and infrastructure base needs to be developed.

Whereas aggregate energy intensities generally improve over time, commercial energy intensities follow a different path. They first increase, reach a maximum, and then decrease. The initial increase is due to the substitution of commercial energy carriers for traditional energy forms and technologies. However, as evidenced by the total aggregate energy intensity, the overall efficiency effect remains decisively positive. Once the process of substituting commercial fuels for noncommercial energy is largely complete, commercial energy intensities decrease in line with the pattern found for aggregate energy intensities. Because most statistics document only modern commercial energy use, this "hill of energy intensity" has been discussed frequently. Reddy and Goldemberg, among others, observed that the successive peaks in the procession of countries achieving this transition are ever lower, indicating a possible catch-up effect and promising further energy intensity reductions in developing countries that have yet to reach the peak. Nonetheless, the apparent existence of a hill of energy intensity in the use of commercial fuels is overshadowed by a powerful trend. There is a decisive, consistent long-term trend toward improved energy intensities across a wide array of national experiences and across various phases of development, illustrating the link between energy quality and efficiency, among other factors (e.g., economic structural change). However, history matters. Although the trend is one of conditional convergence in energy intensities across countries (especially when measured at purchasing power parities), the patterns of energy intensity improvements in various countries reflect their different situations and development histories. Economic development is a cumulative process that, in various countries, incorporates different consumption lifestyles, different settlement patterns and transport requirements, different industrial structures, and different takeoff dates toward industrialization. Thus, the historical evolution of energy intensities again provides an example of path dependency.

The comparative levels of energy intensities of developing countries (cf. India's level with that of other countries [Fig. 12]) depend on whether they are measured at market exchange rates or in terms of purchasing power parities as well as on whether only commercial fuel or total energy use (including noncommercial fuel) is considered. As a rule, when expressed at market exchange rates, energy intensities in developing countries are very high, resembling the energy intensities that today's industrialized countries showed more that 100 years ago. Even considering energy intensities per purchasing power parity GDP, decisive North–South differences remain, reflecting the respective differences in income. Income matters because income levels determine both the quantities and quality of energy affordable to consumers as well as the type of energy end use conversion devices available to them (e.g., a capital-intensive, energy-efficient cooking stove vs a traditional cheap but inefficient one). Thus, the final energy transition discussed here, the move toward more efficient energy

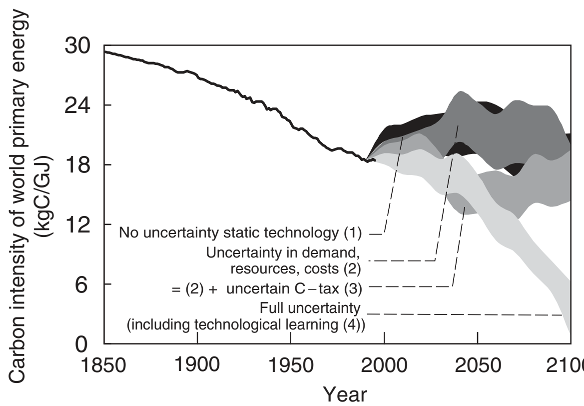

FIGURE 13 Carbon intensity of world primary energy: Historical development since 1850 and future scenarios to 2100 based on different model representations of uncertainty and induced technological change. See text for details. Adapted from Grübler and Nakicenovic (1996) and Grübler and Gritsevskyi (2002).

use, is far from completed. Efficiency improvement potentials remain large in affluent and poor societies alike. Far from being autonomous, the pace of realization of efficiency improvement potentials in the future depends on a variety of factors. For instance, it depends on income growth in developing countries, making clean and efficient energy forms and end use devices affordable to wider segments of society. And it depends on new technologies and incentives that promote more efficient energy use. The energy transition toward higher efficiency needs to be pursued actively and continuously because it remains forever "unfinished business."

5. CONCLUSION

Let us return to the trend toward energy decarbonization, but this time at the level of primary energy. The good news is that at the level of both energy consumers and the energy system, decarbonization is taking place, albeit at a very slow rate (~0.3%/year at the global primary energy level and slightly faster at the final energy level). The bad news is that the models developed to date to describe the dynamics of global energy systems cannot replicate decarbonization (or, for that matter, any other major historical transitions described in the preceding sections) in any endogenous way, regardless of whether the models embrace an economic ("top-down") or engineering ("bottom-up") perspective. But the state of the art in modeling energy–technology–environment interactions is expanding rapidly. Figure 13 illustrates how future decarbonization rates depend on the representation of technology. In the (currently dominant) view of a largely static technology base, past and future decarbonization cannot be modeled without resort to exogenous modeling "fudge factors" and constraints. Even treating the traditional energy model variables of resource availability, demand, and environmental constraints (taxes) as uncertain, justifying diversification away from current dominant fossil technologies, does not change this picture significantly. Currently, the only way in which to replicate historical decarbonization and generate scenarios of future decarbonation in an endogenous way is to use models that incorporate full uncertainty, including those of increasing returns to adoption for new energy technologies. Thus, innovation is key—even if uncertain—both for future scenarios and for explaining the transitions that have taken place in global energy use since the onset of the industrial revolution.

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