FREEING ENERGY FROM CARBON

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THE DOING OF MORE WITH LESS attests to the practical advancement of societies. In fact, labor, capital, and inputs of other factors to the economy have demonstrably decreased per unit of output and value added since the beginnings of the industrial revolution some two hundred years ago. These increases in the productivity of resources owe to numerous technical and organizational innovations and to an enormous accumulation of knowledge and experience.

A portion of the increases in productivity is attributable simply to the increasing scale of activities, also made possible by technical and organizational innovations. Often with greater size, cost decreases and efficiency increases within specific frames. For example, in building electricity-generating plants a long-standing rule of thumb was that the cost of the plant would grow with two-thirds the power of its size. We are uncertain now where we stand with respect to optimal scale of many facilities and systems, but it seems likely that considerable opportunities to lift efficiency remain.

Perhaps more important than simply size and more certain to continue yielding productivity gains is the accumulation of knowledge and experience. Growth in output in an economic system with suitable incentives tends to bring positive returns of its own. This process is sometimes referred to as "learning by doing." Analysis of learning curves in a range of industries, beginning with

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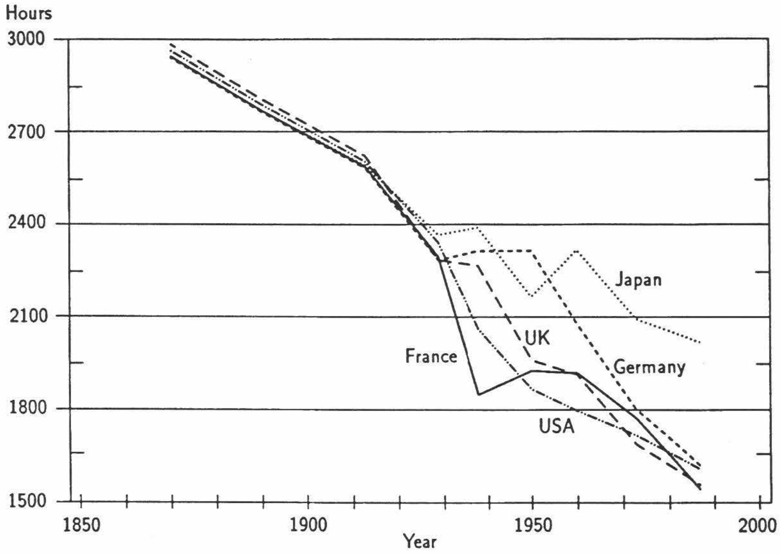
the manufacture of aircraft, has provided ample evidence that the costs per unit of output decrease rapidly at a rate proportional to the doubling of the output.[1]

Energy industries and energy systems are not exceptional. This essay will demonstrate that large secular decreases in energy requirements per unit of economic output have been achieved throughout the world, as we have learned better how to make, operate, and use energy systems. Furthermore, the emissions of carbon dioxide from energy systems, coming from the combustion of the carbon molecules that wood, coal, oil, and gas all contain, have also decreased per unit of energy consumed. This *decarbonization* of the energy system proves to be emblematic of its entire evolution.

At the same time, because of population and general economic growth, absolute world consumption of energy (and many other resources) has increased, especially in the more industrialized countries. This absolute growth often dominates environmental news and views. Rising carbon dioxide emissions are the main contributor to fears of global climatic change. This and other environmental concerns associated with carbon makes energy free from carbon a highly desirable goal for the energy system. The fact that energy and most of the other factor inputs have decreased per unit of output over long periods of time provides a fresh basis on which to project the range of possible future resource use and emissions.

A glance at the changes in labor and materials requirements helps to establish the context and the pervasiveness of the phenomenon that we will observe most closely in energy. Since 1860, the number of hours that workers in the industrialized countries are engaged in paid work each year has generally decreased by half (*Figure 1*). Though the Japanese bucked the trend for several decades around mid-century and continue to work more than their European and American counterparts, they too are working less. Taking into account the dramatic increase in individual income and consumption over the period, we know that the labor requirements per unit of income and output decreased much faster than the number of hours worked. Furthermore, because life expectancy increased by several decades during this period, the years of paid work required to sustain lifelong consumption for a worker

Figure 1. Annual Working Hours in Five Industrialized Countries from 1860 to 1990, expressed in total working hours per year.



Note: Hours spent on sick leave, strikes, and holidays are subtracted from the formal working time.

Sources: Angus Maddison, *Dynamic Forces in Capitalist Development: A Long-Run Comparative View* (New York: Oxford University Press, 1991); and Jesse H. Ausubel and Arnulf Grübler, "Working Less and Living Longer: Long-Term Trends in Working Time and Time Budgets," *Technological Forecasting and Social Change* 50 (1995): 113–131.

at prevailing levels decreased from about three-quarters of a lifetime to less than one-half.[2]

Decreases in requirements for many materials are similarly dramatic.[3] For example, in the United States, which is quite representative of industrialized countries in this regard, steel use declined from about 70 kilograms per $1,000 of GNP (in 1983 dollars) in 1920 to about one-third that level in recent years; cement per GNP in the United States has dropped by about half since 1960.[4] However, this *dematerialization* of the economy is varied. In some cases, a lighter steel beam does the work of an earlier, heavier one. In other cases, new materials replace the steel. In contrast, demand per GNP has grown steeply since mid-century for certain petrochemicals (such as ethylene) and for advanced composite materials. Requirements for paper per GNP have been rather flat since about 1930.

Analysis of energy materials and decarbonization may in practice shed light on the question of dematerialization. Because energy is one of the most important factor inputs and is embedded in most materials, products, and services, decreases in specific energy requirements can also decrease the intensity of materials use. The carbon content of energy and the subsequent carbon dioxide emissions form the largest single mass flow associated with human activities, excepting water. Current annual global carbon emissions are about 6 billion tons, or more than 1,000 kilograms per person on the planet. In comparison, the global steel industry annually produces about 700 million tons, or about 120 kilograms per person. Therefore, decarbonization can contribute in a large way to dematerialization.

Let us now turn to energy and examine the savings of carbon that have been obtained, why they may have occurred, and whether future savings may be sufficient to spare the environment some unwanted heat.

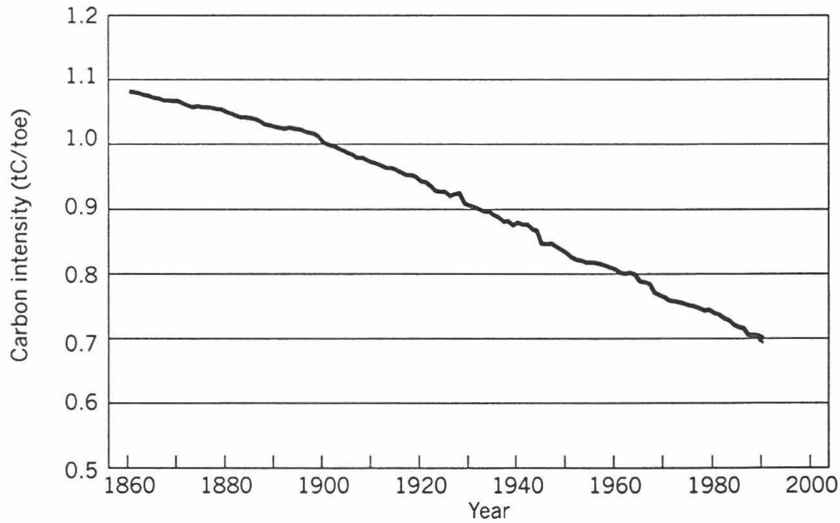
THE GLOBAL HISTORY OF ENERGY AND CARBON SAVINGS

To form a picture of carbon use, we need to be able to sum and compare its appearances. One way is to index carbon by the ratio of carbon atoms to hydrogen atoms in the energy sources that contain both of these fuels. Fuelwood has the highest effective carbon content, with about ten carbon atoms per hydrogen atom. If consumed without a compensating growth of biomass, which occurred in the past and still occurs in most developing countries, fuelwood thus produces higher carbon emissions than any of the fossil energy forms. Among fossil energy sources, coal has the highest carbon-to-hydrogen ratio, roughly one to one. Oil has on average one carbon for every two hydrogen atoms, and natural gas, or methane, has a ratio of one to four. Using these types of elemental analyses, we can estimate the total amount of carbon contained in a given supply of an individual fuel or a mix of fuels and compare this amount to energy consumed or associated economic output.

Decarbonization can then be expressed as a product of two factors: *1)* carbon emissions per unit of energy consumption; and *2)* energy requirements per unit of value added, which is often called energy intensity. Available data allow us to assess with reasonable confidence the trend for each of these factors since the nineteenth century for major energy-consuming regions and countries, such as the United States and the United Kingdom, and thus for the world as a whole as well. As *Figure 2* shows, the ratio of carbon emissions per unit of primary energy consumed globally has fallen by about 0.3 percent per year since 1860. The ratio has decreased because high-carbon fuels, such as wood and coal, have been continuously replaced by those with lower carbon content, such as gas, and also in recent decades by nuclear energy from uranium and hydropower, which contain no carbon.

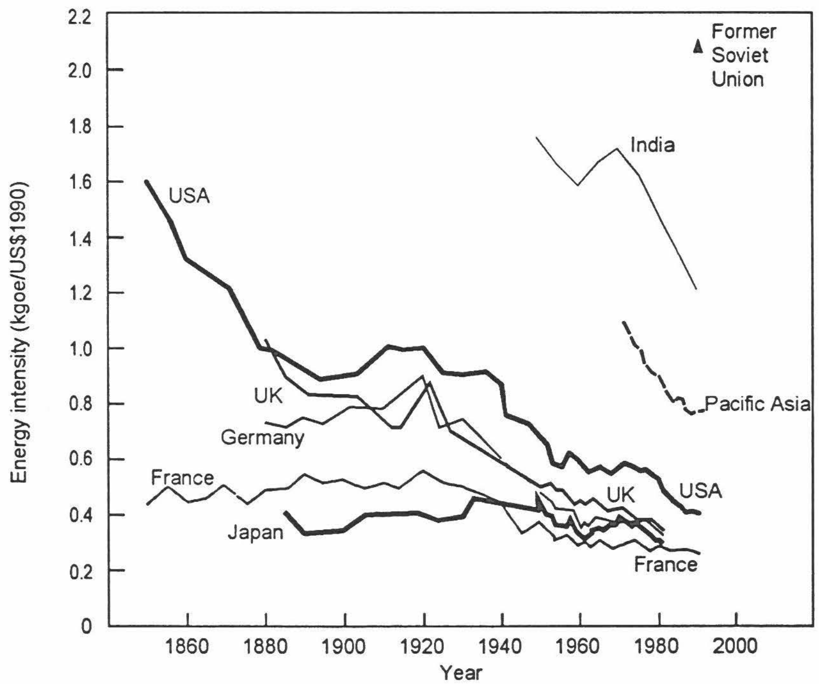
The historical rate of decrease in energy intensity per unit of value appears to have averaged about 1 percent per year since the mid-nineteenth century and about 2 percent per year in some countries since the 1970s. The overall tendency is toward lower

Figure 2. Carbon Intensity of Global Energy Consumption, expressed in tons of carbon per ton of oil equivalent energy (tC/toe).



energy intensities, although paths of energy development in different countries have varied enormously and rather consistently over long periods (*Figure 3*). For example, France and Japan have always used energy more sparingly than the United States, the United Kingdom, or Germany. In some of the rapidly industrializing countries, such as China or Nigeria, *commercial* energy intensity is still increasing. Because commercial energy replaces traditional energy forms not sold in the markets whose transactions find their way into national statistical data, total energy intensity may diminish while commercial energy intensity increases. The present energy intensity of Thailand resembles the situation in the United States in the late 1940s. The energy intensity of India and its present improvement rates are similar to those of the United States about a century ago.

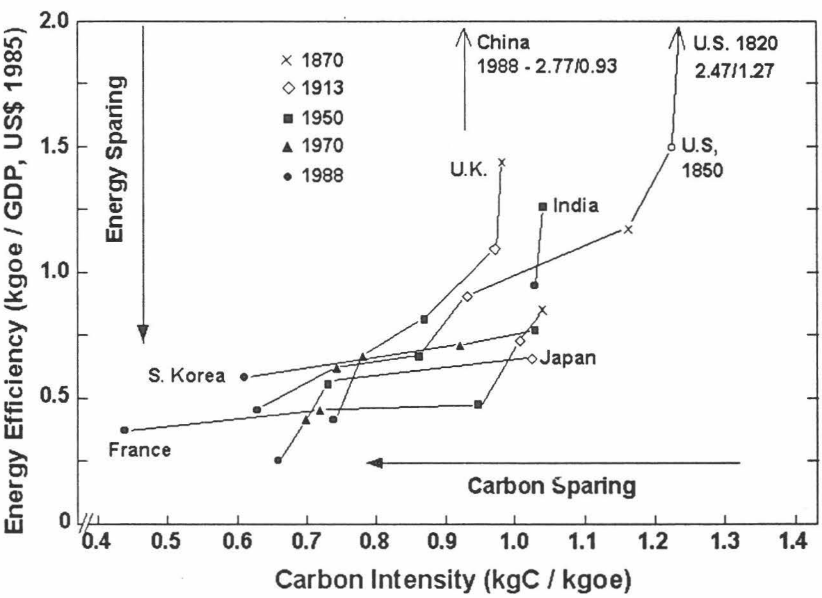
Figure 3. Primary Energy Intensity, including biomass, per unit of value added from 1855 to 1990, expressed in kilogram of oil equivalent energy per constant GDP in 1990 US dollars (kgoe/US$1990).



Combining the two factors of carbon intensity and energy intensity (*Figure 4*) reveals the large differences in the policies and structures of energy systems among countries. For example, though Japan and France have both achieved high degrees of decarbonization, they have followed disparate routes. At the global level, the long-term overall reduction in carbon intensity per unit of value from both factors totals about 1.3 percent per year since the mid-1800s.

The major determinants of energy-related carbon emissions can be represented as multiplicative factors in a simple equation. Placing carbon emissions on one side, on the other we have population growth, per capita value added, energy consumption per unit of

Figure 4. Global Decarbonization by Carbon and Energy Sparing from 1870 to 1988, expressed in kilograms of carbon per kilogram of oil equivalent energy (kgC/kgoe) and in kilograms of oil equivalent energy per $1,000 of GDP in constant 1985 dollars.



Source: Arnulf Grübler, "Energy in the 21st Century: From Resource to Environmental and Life-Style Constraints," *Entropie* 164/165 (1991): 29–33.

value added, and carbon emissions per unit of energy consumed.[5] As we have seen, the last two terms in this equation are decreasing globally. However, their decline is counteracted by rising values for the preceding terms, population and economic activity, resulting in an overall global increase in energy consumption and carbon emissions.

The world's global population is currently increasing at a rate of about 1.6 percent per year. The longer-term population growth rate since 1800 has been about 1 percent per year. Most population experts predict at least another doubling during the next century.[6] Economic activity has been increasing in excess of global population growth since the beginning of industrialization, made possible by the productivity increases referred to at the outset of this essay. In recent decades global economic growth, stirred by both population and productivity gains, has proceeded at about 3 percent per year. Subtracting 1.3 percent for decarbonization, the result is that global carbon emissions have been increasing at about 1.7 percent per year. A continuation would imply a doubling of emissions in about forty years. Fearing such an increase, we must examine in detail the differing paths to decarbonization to see what the limits of the process might be.

DECONSTRUCTING DECARBONIZATION

An examination of five countries—China, France, India, Japan, and the United States—furthers our understanding of the decarbonization process.[7] These countries represent diverse economic and energy systems and life-styles as well as a significant share of the world's energy use. The United States has one of the highest energy intensities of all the industrialized countries, and the highest per capita energy consumption in the world. France and Japan have among the lowest energy intensities in the world, but for different reasons, as we shall discuss. China and India are rapidly developing and still replacing traditional energy sources with commercial ones, and thus they exhibit very high energy and carbon intensities. Together, the five countries account for about 45 percent of global primary energy consumption and more than 40 percent of energy-related carbon emissions.

To determine more precisely the various causes and determinants of the decreasing carbon intensity of energy, we disaggregate the energy system into its three major constituents: primary energy consumption, energy conversion, and final energy consumption. Primary energy consumption embraces the requirement for original resources such as coal, crude oil, and uranium. Final energy refers to the gasoline pumped into a car's fuel tank, the electricity for powering a room air conditioner, or firewood if used directly for cooking or heating. Primary energy, such as coal, is rarely consumed in its original form in a household or office but rather is converted into electricity, fuel, and heat. Thus, final energy, which is consumed directly, in some sense represents best the actual energy requirements of the economy and individual consumers.

In fact, neither primary energy consumption nor conversion is transparent to consumers. For example, the production process for electricity is invisible to most consumers. Because electricity itself is carbon-free, it does not emit carbon (or soot, sulfur dioxide, and other pollutants) at the point of consumption. However, carbon can be emitted in converting primary energy forms into electricity. To a lesser degree this is also true of other forms of final energy, such as oil products. Although the carbon emissions per liter of diesel or gasoline finally used in a truck are basically the same throughout the world, the carbon emissions produced in converting different grades of crude oil into the two products can vary substantially.

To deconstruct the constituent decarbonization rates of the energy system, we make three assumptions. First, the carbon intensity of primary energy is defined as the ratio of the total carbon content of primary fuels to total primary energy consumption for a given country. Second, the carbon intensity of final energy is defined as the carbon content of all forms of final energy divided by the total final energy consumption. The third assumption is that the carbon intensity of energy conversion is the difference between the two intensities just described. So, for example, the carbon intensity of primary energy runs high when wood and coal supply most of the fuel. The carbon intensity of conversion runs high when coal burns to make most of the electricity and when the conversion (or transmission and distribution) system itself is wasteful.

Efficiency improvements in the energy system mean that less primary energy is consumed per unit of final energy; lower conversion losses therefore result in lower carbon emissions. The carbon intensity of consumption runs high when the final consumer cooks with coal or travels by gasoline and when end-use devices are inefficient.

Let us now compare the carbon intensities of final, primary, and conversion energy for the United States, Japan, France, China, and India in recent decades (*Figures 5* through 7). Steady reductions in the carbon intensity of final energy in all five countries stand out above all. On average, the three industrialized countries have spared about 20 percent since 1960, while the pair of developing countries have cut back about 15 percent since the early 1970s. The reductions converge tightly in the three industrialized countries. The gap between the developed and the developing countries is also slowly narrowing because of the slightly more rapid declines in intensity in the latter.

Figure 5. Carbon Intensities of Final Energy, expressed in tons of carbon per ton of oil equivalent energy (tC/toe).

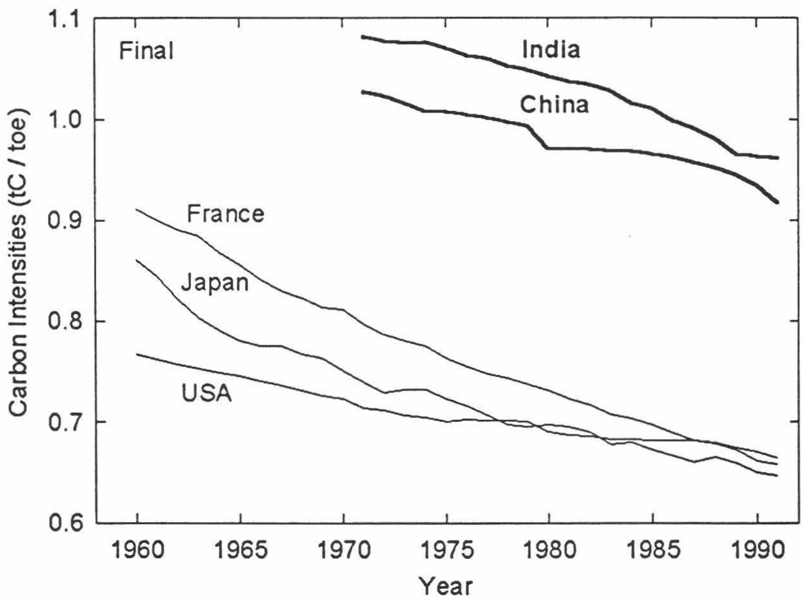


Figure 6. Carbon Intensities of Primary Energy, expressed in tons of carbon per ton of oil equivalent energy (tC/toe).

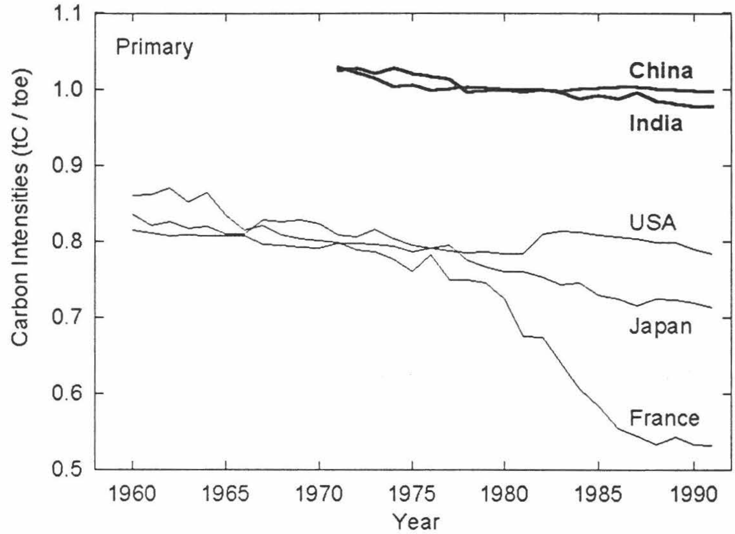
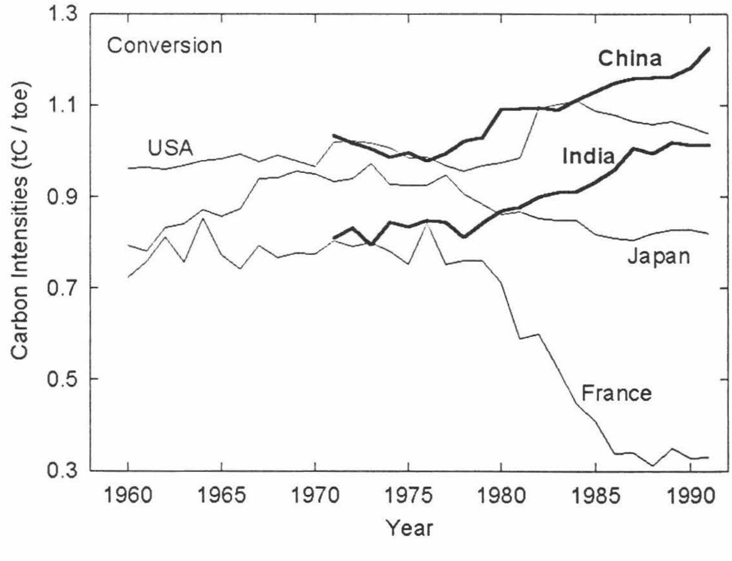


Figure 7. Carbon Intensities of Energy Conversion, expressed in tons of carbon per ton of oil equivalent energy (tC/toe).



The major reason for the decarbonization of final energy is the increasing share of electricity in final energy throughout the world. The percentage of global primary energy used to create electricity has climbed during this century from 5 in the year 1910 to 20 in 1950 to about 35 in 1990. A second reason is that the average mix of other fuels consumed for final energy has a decreasing carbon content, that is, greater shares of oil products and natural gas. Accordingly, these products also have a higher hydrogen content, a point that will be discussed in the final section of this essay.

The carbon intensity of primary energy has also fallen in all five countries, though only very slightly in the United States, where coal has retained its strong role. The carbon intensities of conversion give a completely different picture, however. The diversity in the development and structure of the energy systems of the five countries becomes apparent. In the developing countries, the carbon intensity of conversion has increased, while in France it dropped sharply; in the United States and Japan the conversion intensity initially rose before declining during the latter part of the period analyzed.

Should China and India continue to rely heavily on coal as their primary source of energy, continuing to lessen the carbon intensity of primary energy in these countries will prove difficult. In fact, sometime in the next century the downward trend in the carbon intensity of primary energy could reverse itself, caused by an even higher share of electricity in end use but generated with coal. Alternatively, China and India could restructure their energy systems to make increasing use of natural gas or nuclear energy and other zero-carbon options. Such shifts would align their energy systems with those of the more industrialized countries.

Focusing on the United States and Japan, we see that the carbon intensity of primary energy exceeds that of final energy, with conversion intensity the highest of the three. While final carbon intensity decreases somewhat faster in Japan (about 0.8 percent per year) than the United States (about 0.5 percent per year), the difference in the conversion intensities is much more dramatic. In both countries the changes in the carbon intensity of energy conversion are erratic, especially compared to the steady improvements in final intensities. The overall reduction of carbon intensity in Japan stems primarily from improvements in energy efficiency and, to a lesser degree, from the replacement of carbon-intensive energy forms.

France provides a contrast. Here, the rapid introduction of nuclear energy since the mid-1970s has led to higher rates of decarbonization of primary energy and of conversion (because an increasing share of electricity is produced without carbon emissions) than of final energy. This strategy to achieve low carbon emissions is completely internal to the energy system and fundamentally decoupled from the consumer. Nevertheless, the relatively smooth improvement in final carbon intensity is similar to that observed in Japan and the United States.

China and India present a different picture, though they resemble one another. The three energy ratios and their evolution are similar in these countries despite their many social and cultural differences, as well as those differences that may be attributed to the varying development paths of planned and market economies. In both countries, the carbon intensity of primary energy is diminishing slightly. The carbon intensity of final energy, on the other hand, decreases at rates comparable to those observed in industrialized countries. In India, the faster decarbonization of final energy is due to the replacement of traditional fuels by commercial energy forms. For example, the use of biomass (mainly wood that is not replaced by a new forest) is more carbon intensive than using either kerosene or bottled gas. The difference in carbon intensity between electric lighting (especially if efficient light bulbs are used) and traditional illumination is even more pronounced. In any case, the developing economies are undergoing basically the same process of decarbonizing final energy use as the most developed countries.

In the industrialized countries, the decarbonization of final energy consumption has been accompanied by additional structural changes in the energy system. These led to improvements in decarbonization in the energy system itself, as demonstrated by the downward trends in the carbon intensity of conversion. In contrast, China and India have not undergone this transition. Their energy systems depend heavily on coal, whereas most industrialized countries have in large measure replaced coal with less carbon-intensive sources, even in electricity production. As a consequence of their dependence on coal, both China and India show rapid increases in the carbon intensity of conversion. Should a transition to a lower carbon intensity in developing countries not occur in the coming decades, the likely reductions in carbon emissions in the industrialized countries will be offset, hampering efforts to halt the global increase in carbon emissions.

In sum, determining decarbonization only as the ratio of total carbon emissions per unit of primary energy consumption may veil the interaction between the energy system and the economy. As the structure of an energy system changes, so does the carbon intensity of its three constituent parts. The actual forms of final energy demanded and consumed matter greatly in the logic of decarbonization. Because electricity and heat contain no carbon, the carbon intensity of final energy is generally lower than the carbon intensity of primary energy. In addition, its rate of decrease exceeds that of primary energy because of the increasing share of electricity and other fuels with lower carbon content, such as natural gas, in the final energy mix. At the level of final energy, decarbonization is a durable, pervasive phenomenon. The likely explanation is a congruence in consumer behavior and preferences as expressed in the structure of final energy over a wide range of income and developmental levels.

THE ELEMENTAL EVOLUTION

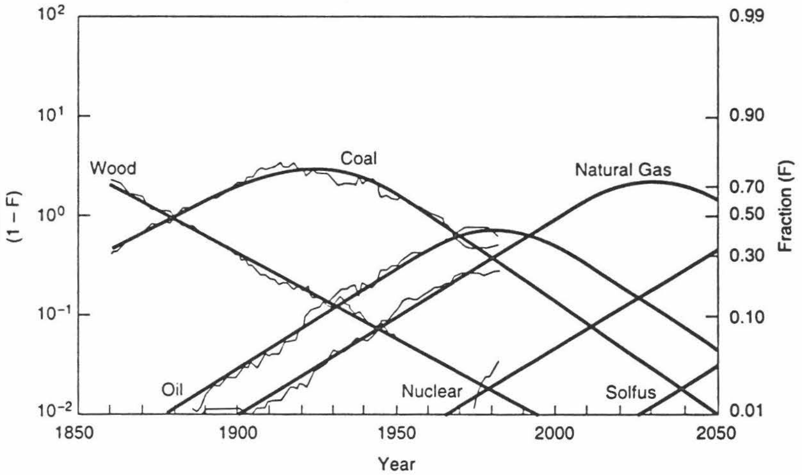
We have seen the increasing needs for electricity and hydrogen-rich forms of *final* energy. Can these be reconciled with the relatively slow and often opposing changes in the structure of energy systems and the *primary* energy supply? The historical replacement of coal by oil, and later by natural gas, at the global level shows the way. The well-documented evolutionary substitution of sources of primary energy suggests that natural gas and later carbon-free energy forms will become the leading sources of primary energy globally during the next century.[8]

The competitive struggle between the five main sources of primary energy—wood, coal, oil, gas, and nuclear—has proven to be a dynamic and regular process that can be described by relatively simple rules. A glance reveals the dominance of coal as the major energy source between the 1880s and the 1960s after a long period during which fuelwood and other traditional energy sources led

(*Figure 8*). The mature coal economy meshed with the massive expansion of railroads and steamship lines, the growth of steel-making, and the electrification of factories. During the 1960s, oil assumed a dominant role in conjunction with the development of automotive transport, the petrochemical industry, and markets for home heating oil.

The model of energy substitution projects natural gas (methane) to be the dominant source of energy during the first decades of the next century, although oil should maintain the second largest share until the 2020s. Such an exploratory look requires additional assumptions to describe the later competition of potential new energy sources such as nuclear, solar, and other renewables that have not yet captured sufficient market shares to allow reli-

Figure 8. Global Primary Energy Substitution from 1860 to 1982 and Projections for the Future, expressed in fractional market shares (*F*).



Notes: Smooth lines represent model calculations and jagged lines are historical data. "Solfus" is a term employed to describe a major new energy technology, for example, solar or fusion.

Sources: Arnulf Grübler and Nebojša Nakićenović, "The Dynamic Evolution of Methane Technologies," in T. H. Lee, H. R. Linden, D. A. Dreyfus, and T. Vasko, eds., *The Methane Age* (Dordrecht, Netherlands and Laxenburg, Austria: Kluwer Academic Publishers and IIASA, 1988); and Nebojša Nakićenović, "Dynamics of Change and Long Waves," in T. Vasko, R. Ayres, and L. Fontvielle, eds., *Life Cycles and Long Waves* (Berlin: Springer-Verlag, 1990).

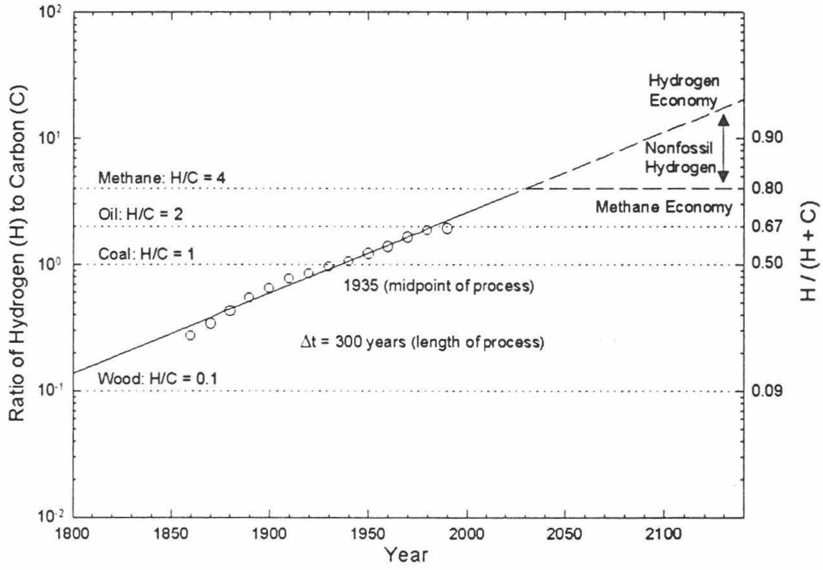
able estimation of their penetration rates. In *Figure 8* it is assumed that nuclear energy will diffuse at rates comparable to those at which oil and natural gas diffused half a century earlier. Such a scenario would require a new generation of nuclear installations; today such prospects are at best questionable. This leaves natural gas with the largest share of primary energy for at least the next fifty years. In the past, new sources of energy have emerged from time to time, coinciding with the saturation and subsequent decline of the dominant competitor. In *Figure 8,* "Solfus" represents a major carbon-free energy technology, such as solar or fusion, that could emerge during the 2020s at the time when natural gas is expected to reach the limits of its market niche.

The unfolding of primary energy substitution implies a gradual continuation of energy decarbonization globally. *Figure 9* shows how the ratio of hydrogen to carbon atoms in the world fuel mix has changed as a result of primary energy substitution. If natural gas becomes the dominant source of energy, this ratio can be expected to approach the level of four hydrogen atoms to one carbon. Improvements beyond this level would have to be achieved by the introduction of noncarbon energy sources and by the sustainable use of biomass.

A methane economy offers a bridge to the noncarbon energy future consistent with both the dynamics of primary energy substitution and the steadily decreasing carbon intensity of final energy. As nonfossil energy sources are introduced into the primary energy mix, new energy conversion systems would be required to provide zero-carbon carriers of energy in addition to electricity. The ideal candidate is pure hydrogen, used as a gas or liquid. Hydrogen and electricity could carry virtually pollution-free and environmentally benign energy to end users in a carbon-free energy system.

To the extent that both hydrogen and electricity might be produced from methane, the carbon separated as a by-product could be contained and stored, probably in underground caverns. As the methane contribution to the global energy supply reaches its limit and subsequently declines, carbon-free sources of energy would take over, eliminating the need for carbon handling and storage. This would conclude the global trend toward decarbonization and the resulting major transformation of the industrial ecosystem.

Figure 9. Ratio of Hydrogen (H) to Carbon (C) for Global Primary Energy Consumption since 1860 and Projections for the Future, expressed as a ratio of Hydrogen to Carbon (H/C).



Sources: Cesare Marchetti, "Nuclear Plants and Nuclear Niches," *Nuclear Science and Engineering* 90 (1985): 521–526; and Jesse H. Ausubel, "Can Technology Spare the Earth?," *American Scientist* 84 (2) (1996): 166–178.

The emergent system could accommodate cleanly the foreseeable levels of population and economic activity.

In fact, an energy system of the distant future that relies on electricity and hydrogen as the complementary energy carriers would also advance dematerialization. Hydrogen has the lowest mass of all atoms, and its use would radically reduce the total mass flow associated with energy activities and the resulting emissions. Electricity is free of material emissions, and the only product of appropriate hydrogen combustion is water. Thus, decarbonization not only contributes to dematerialization but is also consistent with the emergence of new technologies that hold the promise of high flexibility, productivity, and environmental compatibility.

Weighty carbon is a poor match for the evolving final energy demands of modern societies. Fortunately, decarbonization has asserted itself already as a widespread, long-term development driven by deepening, strengthening forces.

ENDNOTES

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[2]Jesse H. Ausubel and Arnulf Grübler, "Working Less and Living Longer: Long-Term Trends in Working Time and Time Budgets," *Technological Forecasting and Social Change* 50 (1995): 113–131.

[3]See Iddo K. Wernick, Robert Herman, Shekhar Govind, and Jesse H. Ausubel, "Materialization and Dematerialization: Measures and Trends," *Dædalus* 125 (3) (Summer 1996).

[4]R. H. Williams, E. D. Larson, and M. H. Ross, "Materials, Affluence, and Industrial Energy Use," *Annual Review of Energy* 12 (1987): 99–144.

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[8]Jesse H. Ausubel, Arnulf Grübler, and Nebojša Nakićenović, "Carbon Dioxide Emissions in a Methane Economy," *Climatic Change* 12 (1988): 245–263 (reprinted as International Institute for Applied Systems Analysis, RR-88-7); Arnulf Grübler and Nebojša Nakićenović, "The Dynamic Evolution of Methane Technologies," in T. H. Lee, H. R. Linden, D. A. Dreyfus, and T. Vasko, eds., *The Methane Age* (Dordrecht, Netherlands and Laxenburg, Austria: Kluwer Academic Publishers and IIASA, 1988); Cesare Marchetti and Nebojša Nakićenović, *The Dynamics of Energy Systems and the Logistic Substitution Model,* RR-79-13 (Laxenburg, Austria: International Institute for Applied Systems Analysis, 1979); and Nebojša Nakićenović, "Dynamics of Change and Long Waves," in T. Vasko, R. Ayres, and L. Fontvielle, eds., *Life Cycles and Long Waves* (Berlin: Springer-Verlag, 1990).