Working Paper

Decarbonization: Doing More With Less

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WP-93-076
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Decarbonization: Doing More With Less

Nebojša Nakićenović*

Doing more with less is a great achievement of advanced societies. Labor, capital, energy, other factor inputs and material requirements have decreased per unit output and value added since the beginning of the industrial revolution. These productivity increases are due to numerous technological and organizational innovations and an enormous accumulation of knowledge. These achievements are often referred to in the literature as the autonomous rates of technological change.

During this period the production of material and other goods and services outpaced population growth in the world, resulting in increasing wealth and improved standards of living. The growth in output and economic development in general resulted in positive returns from increasing scales of human activities, sometimes referred to as "learning by doing". For example, learning curve analyses provide ample empirical evidence for decreasing costs per unit output proportional to every doubling of the accumulative output. There is also rich empirical evidence that materials consumption and labor requirements per unit output have decreased during the process of industrialization. In this paper we will demonstrate that large decreases in energy requirements per unit economic output where achieved throughout the world and furthermore that carbon dioxide emissions have also decreased per unit energy. At the same time, absolute world consumption levels of energy and other resources have increased, particularly vigorously in the more industrialized countries. This should not be confused, however, with the fact that energy and most of the other factor inputs have decreased per unit output.

First, we will show the tendency towards decreases in specific labor and material requirements before demonstrating that the reduction of energy and carbon emissions per unit activity is a secular process taking place throughout the world. Figure 1 shows the annual working hours in a number of industrialized countries: which have halved over the last 130 years. Japan is something of an exception where the decrease was not so rapid perhaps also partly explaining the present higher productivity of this country. If we take into account that individual income and consumption have increased dramatically over the same time period, then it becomes evident that the labor requirements per unit income and output and decreased even faster than the number of hours worked. Furthermore, life expectancy has also increased during this period so that the effective labor requirements for life long consumption have decreased from more than three-quarters of the lifetime to less than one-quarter.

Figure 2 shows similarly dramatic decreases in some material requirements per unit output in the United States that are representative for a number of industrialized countries.

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However, it is not clear that dematerialization is a universal process. As the requirements for some materials, such as steel, decreases, newer and more advanced materials replace them. For example, there is a growing need for petrochemicals and advanced material such as carbon fiber, silicon and so on. Ironically, the so-called information revolution has resulted in the growth of the specific paper requirements. Such counter examples demonstrate that dematerialization is occurring in some sectors but not others and is thus not a pervasive phenomenon.

In contrast, decreases in energy intensity of economic activities and decarbonization are pervasive and an almost universal developments. The analysis of these two pervasive tendencies can perhaps shed more light indirectly on the question of whether the dematerialization is occurring as well. Energy is one of the most important factor inputs and is embedded in most of materials, products and services, so that decreases in specific energy requirements can also contribute toward decreasing material intensity. The carbon content of energy and, therefore, the subsequent carbon dioxide emissions, represent one of the largest single mass flows that can be associated with human activities. Current annual emissions are about 6 Gigatons (billion tons) of carbon or more than 20 Gigatons of carbon dioxide. In comparison, global steel production is on the order of 700 Megatons (million tons). Therefore, decarbonization contributes in a large way towards dematerialization.

Decarbonization can be expressed as a product of two factors: (1) specific carbon emissions per unit energy; and (2) energy requirements per unit value added, often called energy intensity. Both of these factors are decreasing in the world but are being outpaced by the rate of economic growth, resulting in an overall global increase in energy consumption and carbon dioxide emissions.

In general, the instrumental determinants of future energy-related Carbon dioxide emissions could be represented as multiplicative factors in the hypothetical equation that determines global emission levels. The *Kaya identity* establishes a relationship between population growth, per capital value added, energy per value added and carbon emissions per energy on one side of the equation, and total carbon dioxide emissions on the other (Yamaji *et al.,* 1991)[1]. Two of these factors are increasing and two are declining at the global level.

At present, the world's global population is increasing at a rate of about 2% per year. The longer-term historical growth rates since 1800 have been about 1% per year. Most of the population projections expect at least another doubling during the next century (see UN, 1992a, and Vu, 1985). Productivity has been increasing in excess of global population growth since the beginning of industrialization and thus has resulted in more economic activity and value added per capita. Energy intensity per unit value added has been decreasing at a rate of about 1% per year since the 1860s and at about 2% per year in most countries since the 1970s. Carbon dioxide emissions per unit of energy have also been decreasing but at a much lower rate of about 0.3% per year.

Figure 3 illustrates the extent of this "decarbonization" in terms of the ratio of average carbon dioxide emissions per unit of primary energy consumed globally since 1860. The ratio decreases due to the continuous replacement of fuels with high carbon contents,

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[1] $CO_2 = (CO_2/E) \times (E/GDP) \times (GDP/P) \times P$, where E represents energy consumption, GDP the gross domestic product or value added, and P population. Changes in carbon dioxide emissions can be described by changes in these four factors.

such as coal, by those with low carbon contents and most recently also nuclear energy. Figure 4 shows the historical decrease in energy intensity per unit value added in a number of countries. Energy development paths in different countries have varied enormously and consistently over long periods, but the overall tendency is towards lower energy intensities. For example, France and Japan have always used energy more efficiently than the United States, the United Kingdom or Germany. This should be contrasted with the opposite development in some of the rapidly industrializing countries, where commercial energy intensity is still increasing, such as in Nigeria. Commercial energy is replacing traditional energy forms so that total energy intensity is diminishing while commercial energy intensity is increasing. 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 5 shows the degrees of decarbonization and energy deintensification achieved in a number of countries since the 1870s. It illustrates salient differences in the policies and structures of energy systems among countries. For example, Japan and France have achieved the largest degrees of decarbonization; in Japan this has been achieved largely through energy efficiency improvements over recent decades, while in France largely through vigorous substitution of fossil fuels by nuclear energy. Most countries have achieved decarbonization through the replacement of coal first by oil, and later by natural gas.

At the global level, the long-term reduction in carbon intensity per unit value added has been about 1.3% per year since the mid-1800s. Decarbonization of energy occurs at about 0.3% per year and the reduction of energy intensity of value added at about 1% per year, resulting in overall carbon intensity of value added reduction of about 1.3% per year. This falls short by about 1.7% of what is required to offset the effects of global economic growth, with rates of about 3% per year. This means that the global carbon dioxide emissions have been increasing at about 1.7% per year, implying a doubling before the 2030s. This is in fact quite close to emission levels projected in some of the global scenarios.

We have selected five representative countries in order to analyze the decarbonization processes in greater detail: China, France, Japan, India and the United States. Based on the joint research of the author, Arnulf Grübler and Gilbert Ahamer (Nakićenović *et al.* 1993), decarbonization for various parts of the energy systems in these countries will be shown. These countries are representative because they demonstrate the diversity of different development paths and lifestyles. Some other reasons for choosing these five countries have already been indirectly given above. For example, the United States has one of the highest energy intensities of the industrialized countries and also the highest per capita energy consumption in the world. France and Japan, on the other hand, have among the lowest energy intensities in the world but for different reasons. Finally, China and India represent two rapidly developing countries where the replacement of traditional by fossil energy is still not completed resulting in very high energy and carbon intensities. Together, these countries account for 43.5% of global primary energy consumption and 41.4% for CO_2 energy related carbon dioxide emissions.

In this paper we will focus on the analysis of decarbonization only in order to determine more precisely the various causes and determinants for the decreasing carbon intensity of energy. To do this, we need to disaggregate the energy system into its three major constituents: primary energy requirements, energy conversion, and final energy consumption. As the structure of the energy system changes, so does the carbon intensity of these three constituent parts. Final energy is directly consumed and therefore represents the actual energy requirements of the economy and individual consumers. The rest of the energy system (primary energy and its conversion) are not really transparent to the consumers. Therefore, determining decarbonization as a ratio of total carbon emissions per unit primary energy removes the analysis from the actual point of consumption and the interaction between the energy system and the economy. The actual final energy forms demanded and consumed represent a clearer demonstration of carbon intensity at the point of consumption. For example, it is pretty much irrelevant to the consumer how electricity is produced. Since it is carbon free it does not lead to any carbon emissions at the point of consumption. Carbon is emitted in converting primary energy forms into final electricity. To a lesser degree this is also the case with other forms of final energy, such as oil products. The specific carbon emissions per liter of diesel or gasoline are basically the same throughout the world, however, the carbon emissions that result in converting different grades of crude oil into these two products vary substantially. Coal, on the other hand, is rarely consumed in its primary form and is mostly converted into electricity. In order to decouple the decarbonization rates that occur in the energy system from those that occur at the point of final energy consumption, we have made the following assumptions: (1) Carbon intensity of primary energy is defined as the ratio of total carbon content of primary energy divided by total primary energy requirements (consumption) for a given country. As such, this definition is identical to the one used to define the carbon intensity of primary energy in the world given in Figure 3. (2) Carbon intensity of final energy is defined as the carbon content of all final energy forms consumed divided by total final energy consumption. Various final energy forms that are delivered to the point of final consumption include solid fuels, such as biomass, coal, oil products, gas, chemical feed stocks, electricity and heat. Electricity and heat do not contain any carbon. Thus it is evident on an *a priori* basis that the carbon intensity of final energy should generally be lower than the carbon intensity of primary energy. In addition, its rate of decrease should be slightly higher than that of primary energy decarbonization because of the increasing share of electricity and other fuels with lower carbon content, such as natural gas, in the final energy mix. (3) Carbon intensity of energy conversion is defined as the difference between the two intensities above.

Generally, these categories represent the carbon emissions resulting from the energy system itself while the carbon intensity of final energy represents the carbon emissions due to the actual energy required by the economy and individual consumers. Therefore, the former is a function of the specific energy situation in a given country while the latter is a function of economic structure and consumer behavior. The difference between the two provides deeper insight into the carbon emissions that result from energy and economy interactions, and those that are determined by the nature of primary energy supply, conversion and distribution.

Figures 6 to 10 give the three carbon intensities for the five countries, respectively, for the period 1960 to 1991. The relationship among the three ratios for the United States and Japan in Figures 6 and 7 portrays the behavior one would anticipate on an *a priori* basis: final carbon intensity is lower than the primary one, while conversion intensity is the highest. Reduction of final carbon intensity is slightly higher in Japan with about 0.8% per year compared to about 0.5% in the United States. The difference in the conversion carbon intensities are much more dramatic. In both cases these ratios change more erratically compared to the relatively smooth improvements in primary and final intensities. Especially in Japan, the improvement rates since 1965 have been vigorous, outpacing the reduction rates of final intensity. As can be seen from Figure 5, the reduction of carbon intensity in Japan is due to high energy efficiency improvements and, to a lesser degree, to the replacement of carbon intensive energy forms. Efficiency improvements in the energy system imply that less primary energy is consumed per unit final and, therefore, lower conversion losses result in lower carbon emissions.

Figure 8 illustrates the opposite case for France. Here, the rapid introduction of nuclear energy since the mid-1970s has led to higher rates of decarbonization of primary energy and conversion than that of final energy. This illustrates a fundamentally different strategy to achieve low carbon emissions. Basically it is decoupled from the consumer and is completely internal to the energy system. The French nuclear development path really meant that the increasing share of electricity is produced without carbon emissions, therefore lowering the overall carbon intensity of conversion. On the other hand, the relatively smooth improvement in final carbon intensity is very similar to that observed in Japan and the United States.

Figures 9 and 10 show quite different situations in China and India. First, it is important to note that the changes in the three ratios are very similar in these two rapidly developing economies, although one has a planned economy and the other a market one. They also have very many social and cultural differences. In both countries, carbon intensity in primary energy is basically stationary and shows only marginal signs of improvement. The carbon intensity of final energy, on the other hand, is improving at rates comparable to those observed in industrialized countries. In China the reduction of final energy carbon intensity is close to 0.5% per year, and in India at the impressive rate of 1.1% per year. In the latter case, the rapid decarbonization of final energy is due to the replacement of traditional fuels by commercial energy forms. For example, the unsustainable use of biomass is more carbon intensive than kerosene and bottled gas. The difference in carbon intensity of lighting between electricity (especially if efficient light bulbs are used) compared to traditional practices is even more pronounced. In any case, the developing economies are undergoing basically the same process of decarbonizing final energy use as do the most developed. This indicates congruence in consumer behavior as expressed in the structure of final energy used at different income and development levels. Decarbonization is, therefore, a pervasive phenomenon.

In the industrialized countries, decarbonization of final energy consumption has been accompanied by appropriate structural changes in the energy system. This led to improvements in decarbonization in the energy system itself as demonstrated in the carbon intensity of conversion. Subsequently, the decarbonization of primary energy intensity could also be improved. In contrast, China and India have not undergone this transition. Their energy systems depend heavily on coal which is a very carbon intensive source of energy. In industrialized countries, coal has been largely replaced by less carbon intensive sources, especially in electricity production. As a consequence of this difference, the carbon intensity of conversion is increasing rapidly in both China and India. Should a transition to lower carbon intensity not occur in the forthcoming decades, it is quite likely that the relative reductions in specific carbon emissions in the industrialized countries will be offset by this trend. This will naturally hamper efforts to halt the increase in global carbon emissions.

Figures 11, 12 and 13 compare the three ratios for the five countries. The congruence in the gradual reduction of final energy carbon intensity is illustrated in Figure 11. The development is convergent in the three industrialized countries and is accompanied by more rapid changes in the developing countries, especially in India which has much higher absolute intensity levels. This means that the gap between the developed and developing countries is gradually narrowing. Final energy consumption is proceeding along a similar development path in all five countries. The share of electricity in final energy is increasing throughout the world. The average mix of other fuels consumed has a decreasing carbon content, that is, increasing shares of natural gas and of oil products with a higher hydrogen content. In other words, the hydrogen to carbon ratio of average fuel consumed is increasing globally. These two factors, namely, the increasing hydrogen content of fuels and the increasing share of electricity result in the steady improvement in the final energy carbon intensity given in Figure 11.

The carbon intensities of conversion give a completely different picture in Figure 12. The diversity in the development and structural changes of the energy systems in these five countries is apparent. In the developing countries, carbon intensity is increasing while in the industrialized countries it is decreasing at various rates, most rapidly in France due to the vigorous introduction of nuclear energy. This heterogeneity indicates not only the richness in different types of energy systems in the world but also different future development strategies. Should China and India continue to rely heavily on coal as the primary energy source of preference, then it might not be possible to continue to improve the carbon intensity of final energy in these countries. This means that sometime in the next century a trend reversal could be expected, either in the carbon intensity of final energy or primary energy or both. The only bridge between these opposing trends could be even higher shares of electricity. The other alternative for the future is that the energy system restructures towards natural gas, nuclear energy, biomass and other zero carbon options. This would bring the energy systems of these two developing countries in line with those of the more industrialized ones. At the same time, such structural changes would allow for continued improvements in the carbon intensity of final energy consistent with the reduction of specific requirements of other factor inputs and materials throughout the world economy.

Figure 13 shows that, for the time being, the carbon intensity of primary energy is still developing in the same direction in all of these countries. However, as mentioned above, without the proposed structural changes in the energy systems toward carbon free and hydrogen rich sources of primary energy, trend reversals cannot be excluded in the future. This figure also illustrates the large impacts in achieving decarbonization by introducing zero carbon sources of energy as illustrated by the growing shares of nuclear power in France.

There is a possible way to reconcile the increasing needs for electricity and hydrogen rich forms of final energy with the relatively slow and often opposing changes in the structure of energy systems and primary energy supply. This can be best illustrated by the historical replacement of coal by oil and later by natural gas at the global level. Primary energy substitution (Marchetti and Nakicenovic, 1979; Ausubel, *et al.* 1988; Grübler and Nakićenović, 1988; Nakićenović, 1990) suggests the likelihood that natural gas and later carbon free energy forms will become major sources of energy globally during the next century.

Figure 14 shows the competitive struggle between the five main sources of primary energy as a dynamic and quite regular process that can be described by relatively simple rules. The substitution process clearly indicates 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) where in the lead. The massive expansion of railroads, the growth of steel, steamships and many other sectors, are associated with and based on technological opportunities offered by the mature coal economy. After the 1960s, oil assumed a dominant role simultaneously with the maturing of the automotive, petrochemical and other industries. The current reliance on coal in many developing countries illustrates the gap between the structure of primary energy supply and actual final energy needs.

Figure 14 projects natural gas as the dominant source of energy during the first decades of the next century although oil still maintains the second largest share until the 2040s. For such an explorative "look into the future", additional assumptions are required to describe the future competition of potential new energy sources, such as, nuclear, solar and other renewables that have not yet captured sufficient market shares to allow an estimation of their penetration rates. In the future, we assume that nuclear energy will diffuse at comparable rates as oil and natural gas 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 lion's share of primary energy during the next 50 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. "Solfus" is a term employed to describe a major new energy technology, for example, solar or fusion, that could emerge during the 2040s at the time when natural gas is expected to saturate.

This analysis of primary energy substitution and market penetration suggests that natural gas will become the dominant energy source and remain so for half a century, perhaps to be replaced by carbon free energy sources, such as nuclear, solar or fusion. Thus, primary energy substitution implies a gradual continuation of energy decarbonization in the world. The methane economy could provide a bridge towards a carbon free future.

Figure 15 shows the resulting changes in the hydrogen to carbon ratio from global primary energy substitution. Fuelwood has the highest carbon content with about one hydrogen per 10 carbon atoms. If consumed unsustainably, as was the case in the past and still is in most developing countries, fuelwood has higher carbon emissions than all the fossil energy forms. From the fossil energy sources coal has the lowest hydrogen to carbon atomic ratio of roughly one to one. Oil has on average two hydrogen per one carbon atom, and natural gas or methane, four. These factors are used in Figure 15 to determine the hydrogen to carbon ratio of global energy. This ratio can be expected to increase as projected in the Figure 15 to the asymptotic level of four hydrogen to one carbon atom if natural gas becomes the dominant form of energy. Further improvements would have to be achieved by the introduction of non-fossil energy sources, such as, nuclear, solar, fusion and sustainable use of biomass. The methane economy offers the bridge to this non-fossil energy future consistent both with the dynamics of primary energy substitution and steadily increasing carbon intensity of final energy. As non-fossil energy sources are introduced in the primary energy mix, new energy conversion systems would be required to provide other zero carbon energy carriers in addition to growing shares of electricity. As suggested in Figure 15 an ideal candidate is hydrogen. Thus, the methane economy would lead to a greater role for energy gases and later hydrogen in conjunction with electricity. Hydrogen and electricity could provide virtually pollution free and environmentally benign energy carriers.

Figure 16 shows the increase in the share of electricity in the world that is complementary to the increase of the hydrogen to carbon ratio of primary energy. To the extent that both hydrogen and electricity might be produced from methane, the separated carbon could be contained and subsequently stored within the energy sector. As the methane contribution to global energy saturates and subsequently declines, carbon free sources of energy would take over and eliminate the need for carbon handling and storage. This would also conclude the decarbonization process in the world.

The energy system of the distant future that would rely on electricity and hydrogen as two complementary energy carriers and final energy forms, would represent a gigantic step towards dematerialization. Electron has extremely low mass and hydrogen has the lowest mass of all atoms, consisting only of a proton and an electron. This transition would radically reduce the total mass flow associated with energy activities and, more importantly, the resulting emissions. Electricity is emission free and appropriate hydrogen combustion results in water. Decarbonization would not only contribute towards dematerialization, but is also consistent with the emergence of new technologies that hold the promise of higher flexibility, productivity and environmental compatibility. Micro-electronics, bio- and nanotechnologies, virtual reality, and information and communication systems are all more compatible with a hydrogen-electricity economy than with any other.

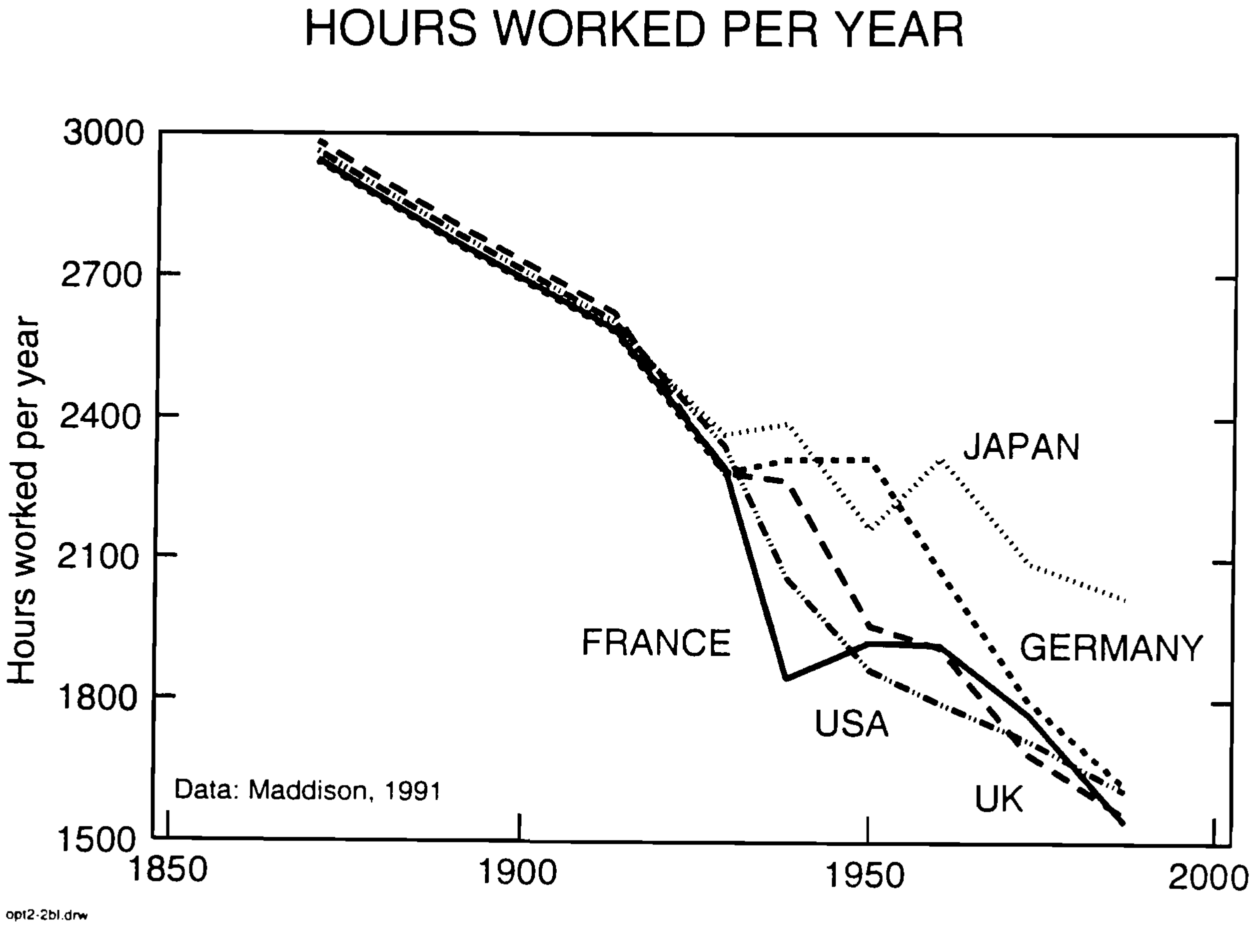

Figure 1: Annual working hours in five industrialized countries from 1960 to 1990, expressed in total working hours per year (hours spent on sick leave, strikes and holidays are subtracted from the formal working time). Data: Maddison, 1991.

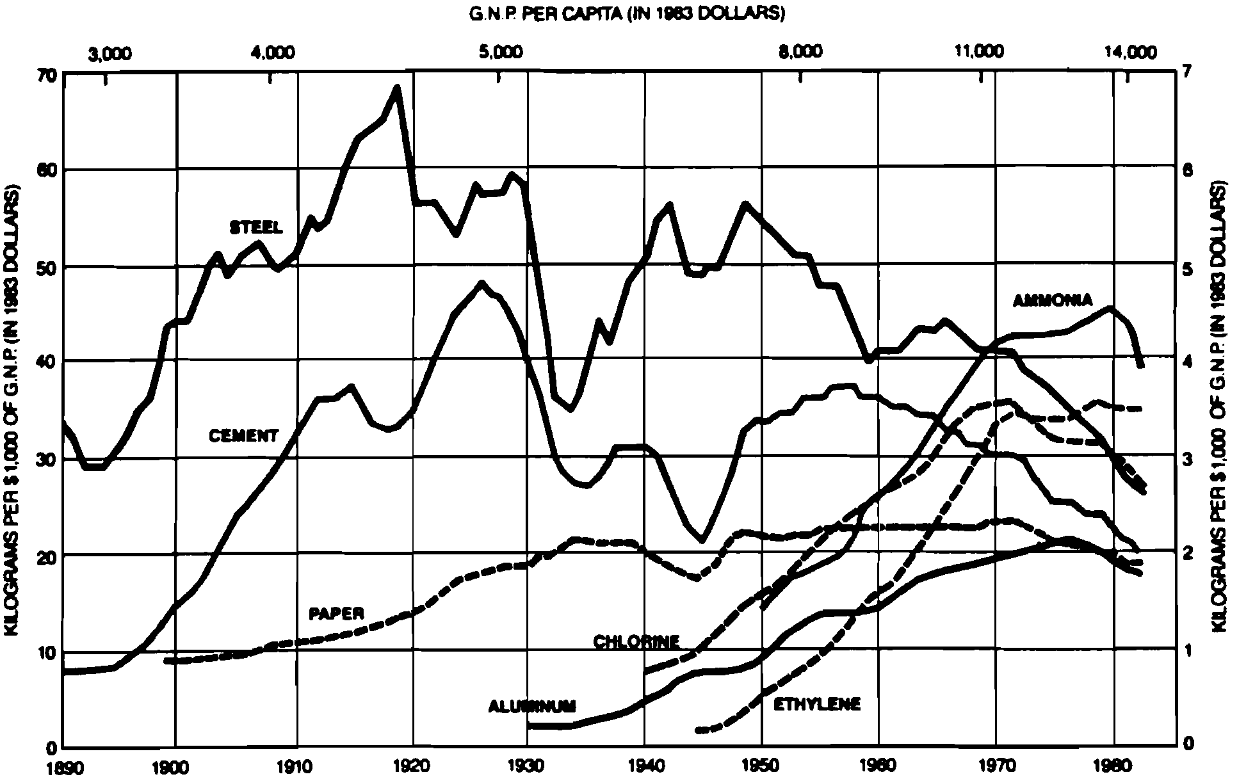

Figure 2: Material consumption per value added, expressed in kilograms apparent consumption over GNP. Source: Williams *et al.*, 1987.

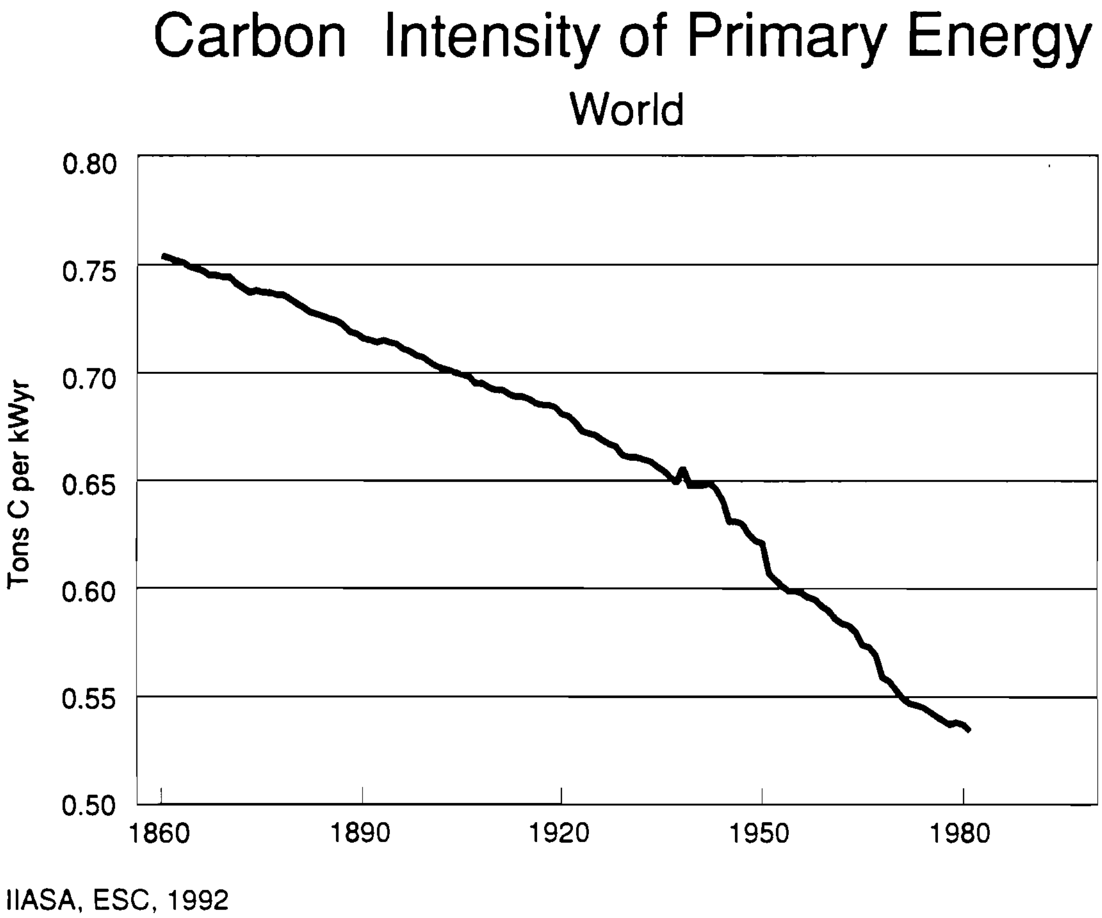

Figure 3: Global decarbonization of energy from 1900 to 1990, expressed in tons of carbon per kilowatt year (tC/kWyr).

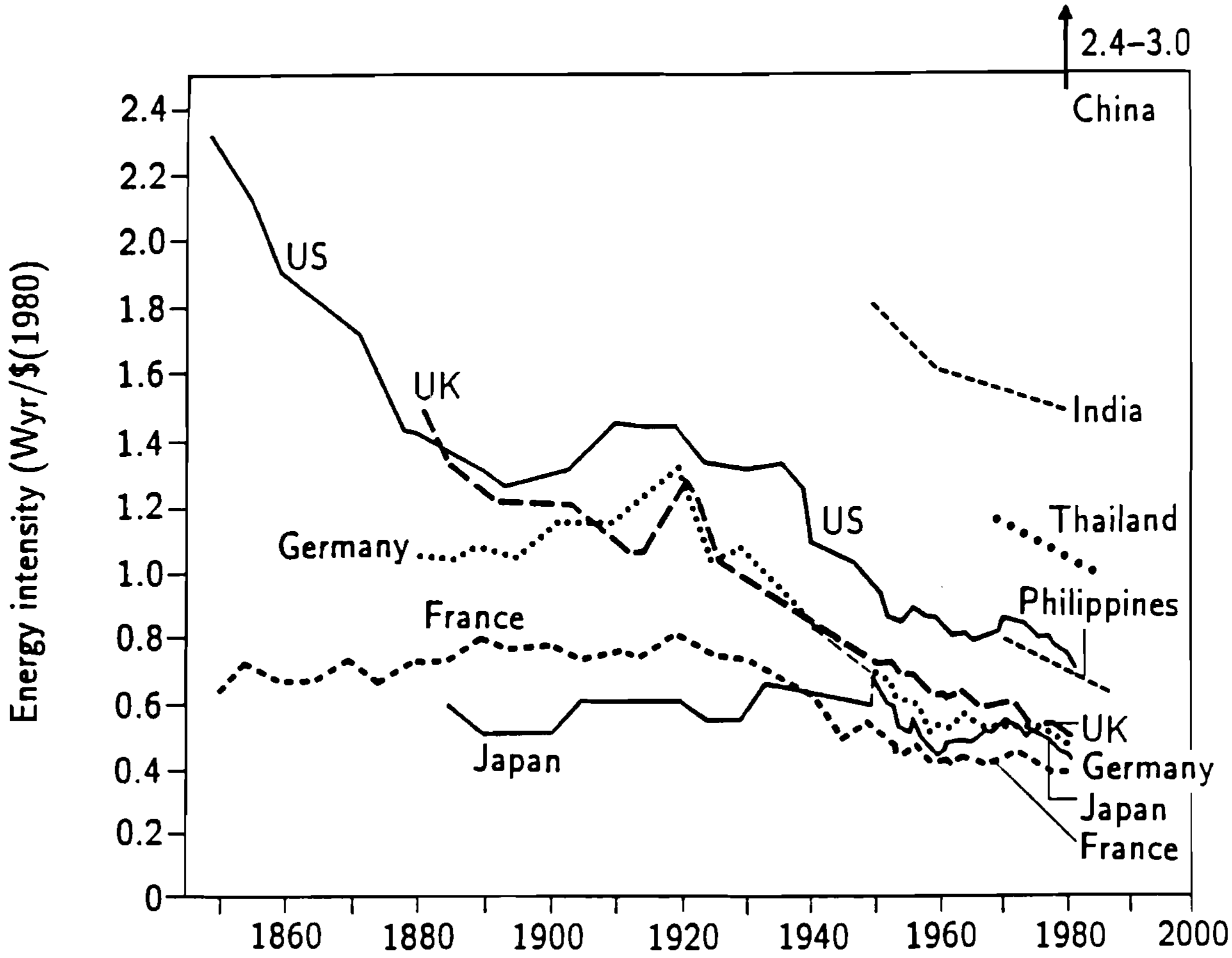

Figure 4: Primary energy intensity, including biomass, of value added from 1855 to 1990, expressed in watt years per constant GDP in 1980 U.S. dollars. (Primary electricity is accounted for by equivalence method.)

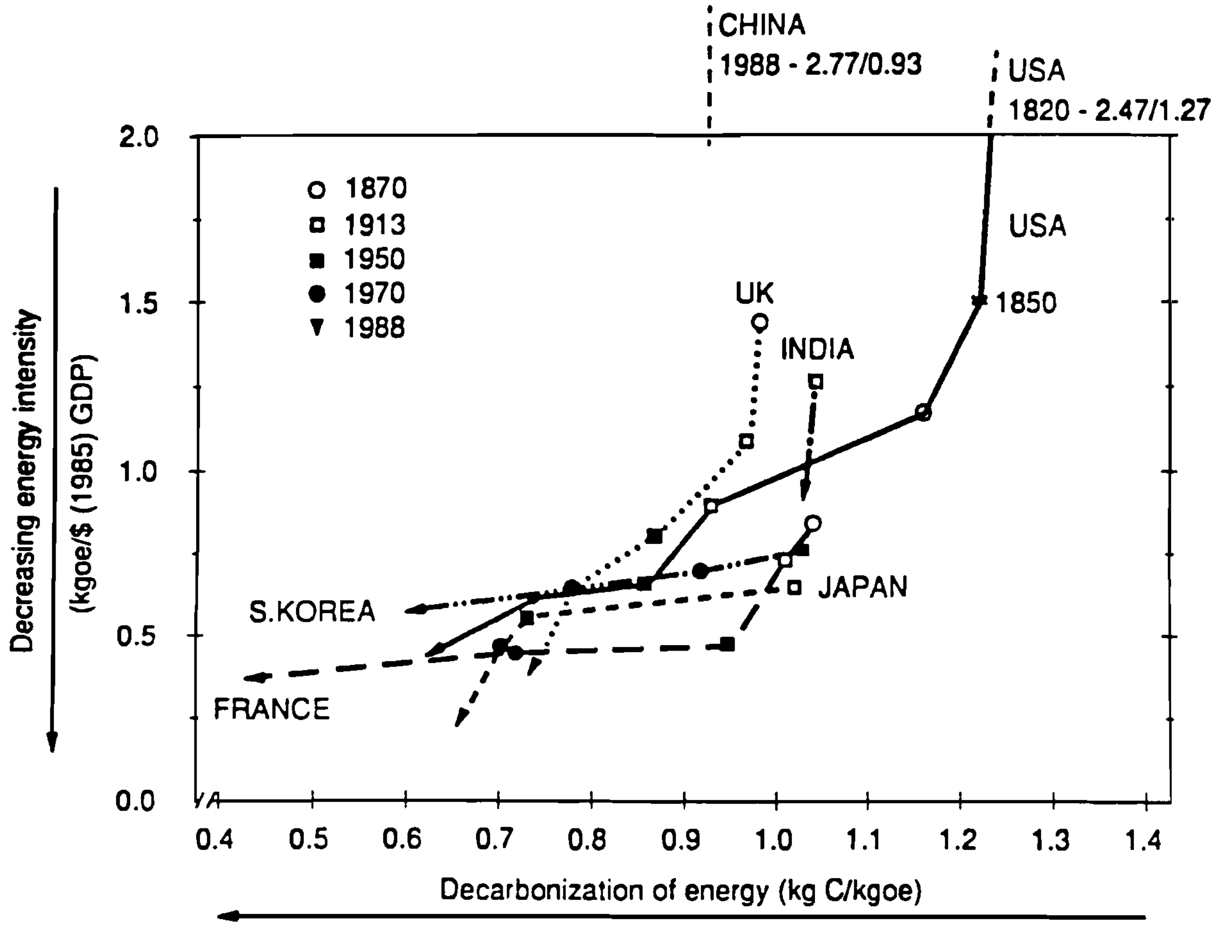

Figure 5: Global decarbonization and deintensification of energy from 1870 to 1988 expressed in kilograms of carbon per kilograms of oil equivalent energy (kgC/kgoe), and in kilograms oil equivalent energy per $1,000 per GDP in constant 1985 dollars. Source: Grübler, 1991.

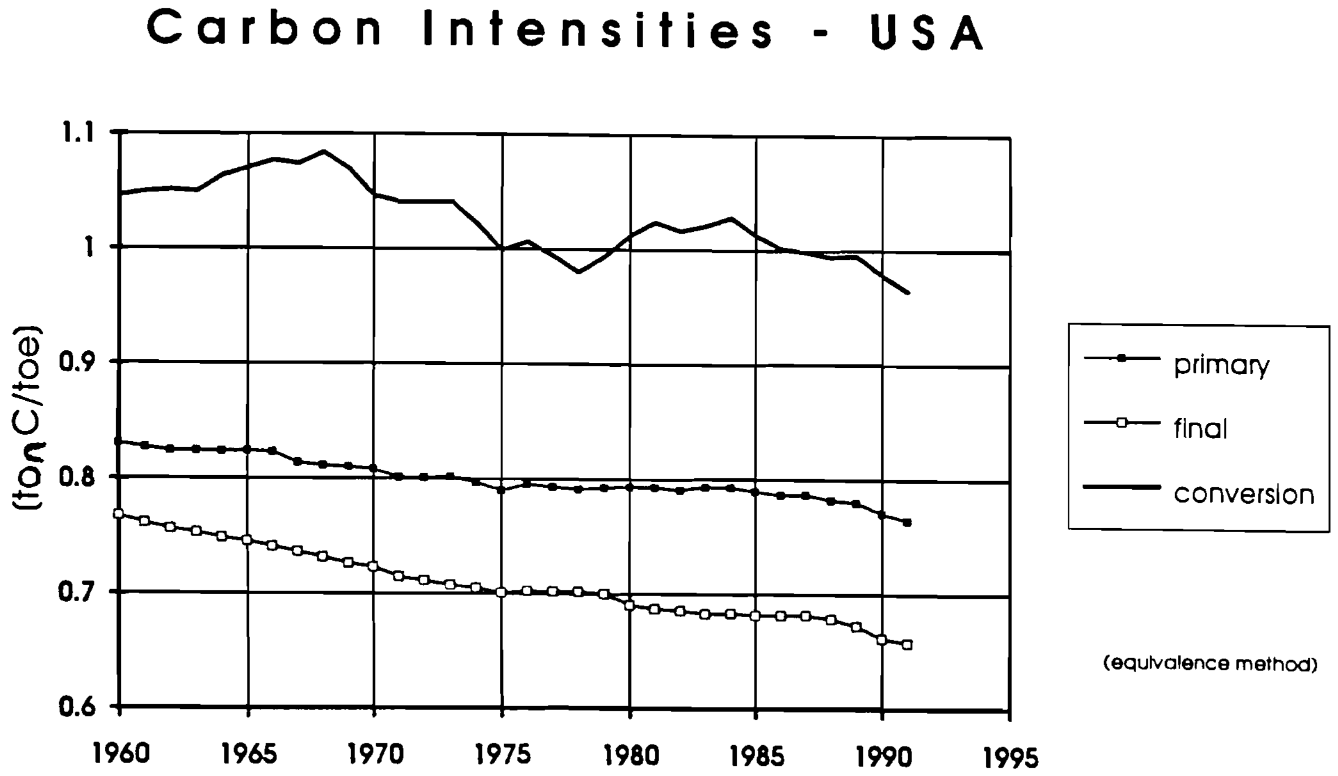

Figure 6: Carbon intensities of primary, final and conversion energy from 1960 to 1991 for the United States, expressed in tons of carbon per ton of oil equivalent energy (tC/toe).

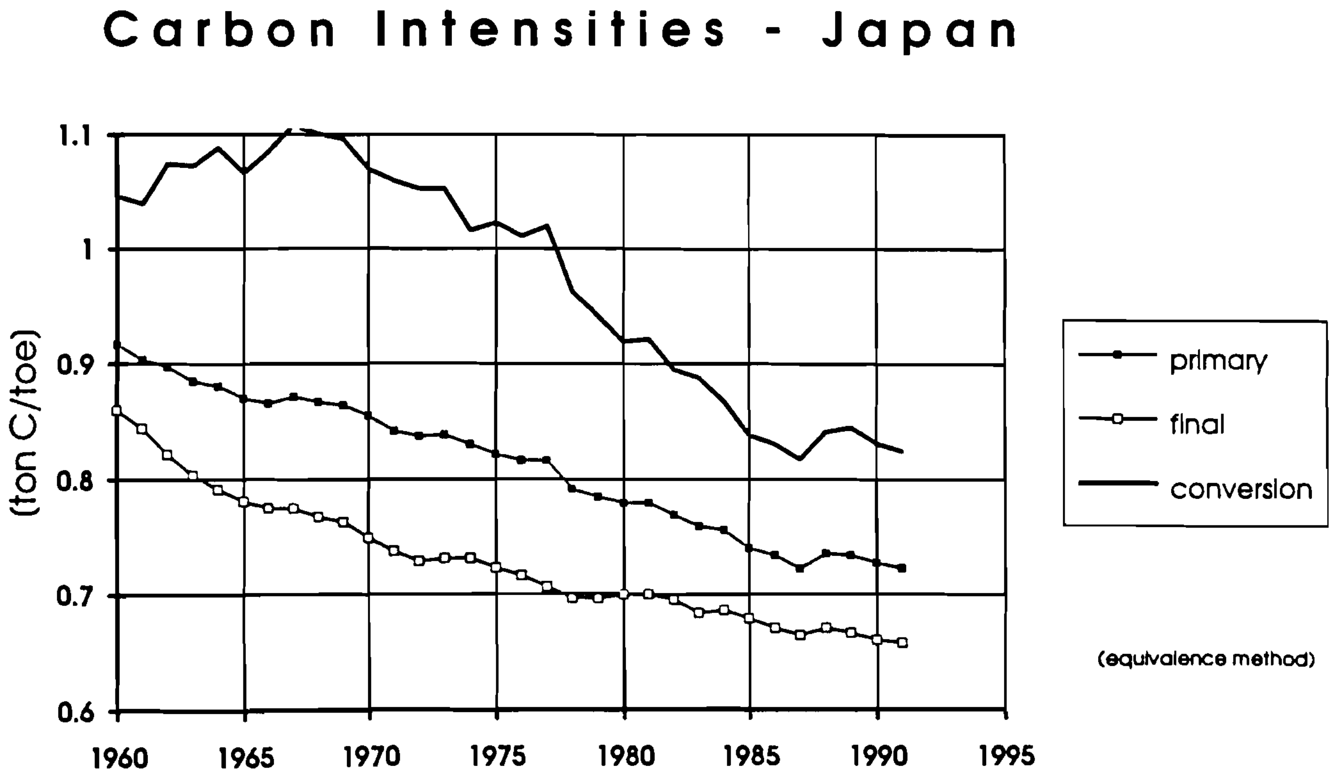

Figure 7: Carbon intensities of primary, final and conversion energy from 1960 to 1991 for Japan, expressed in tons of carbon per ton of oil equivalent energy (tc/toe).

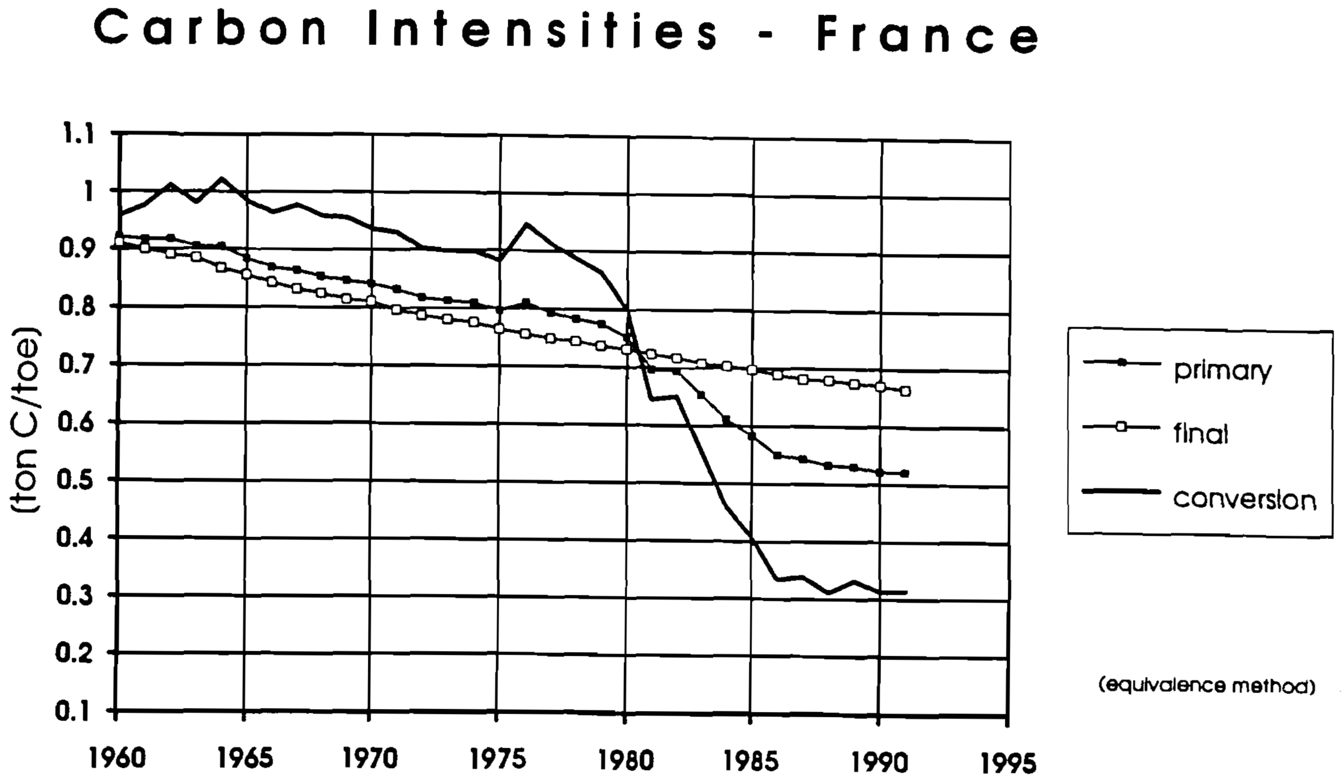

Figure 8: Carbon intensities of primary, final and conversion energy from 1960 to 1991 for France, expressed in tons of carbon per ton of oil equivalent energy (tc/toe).

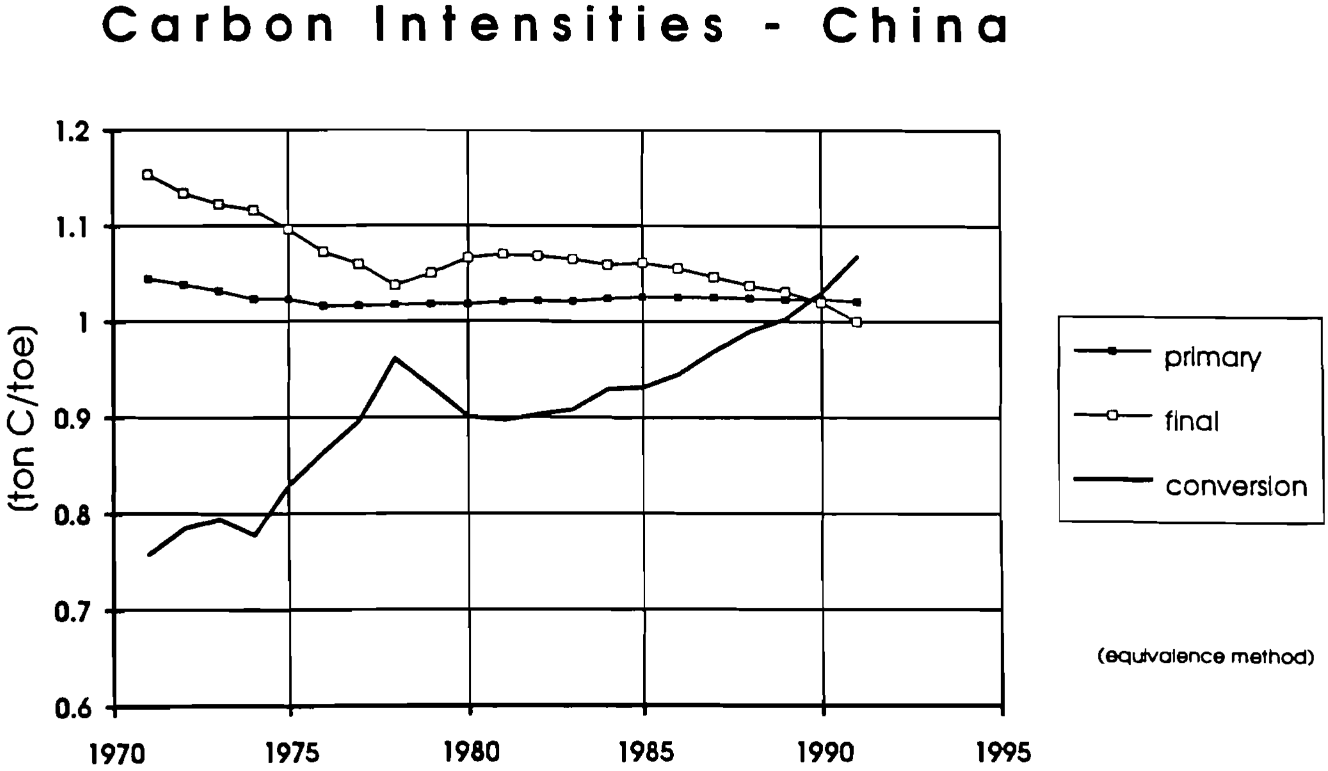

Figure 9: Carbon intensities of primary, final and conversion energy from 1971 to 1991 for China, expressed in tons of carbon per ton of oil equivalent energy (tc/toe).

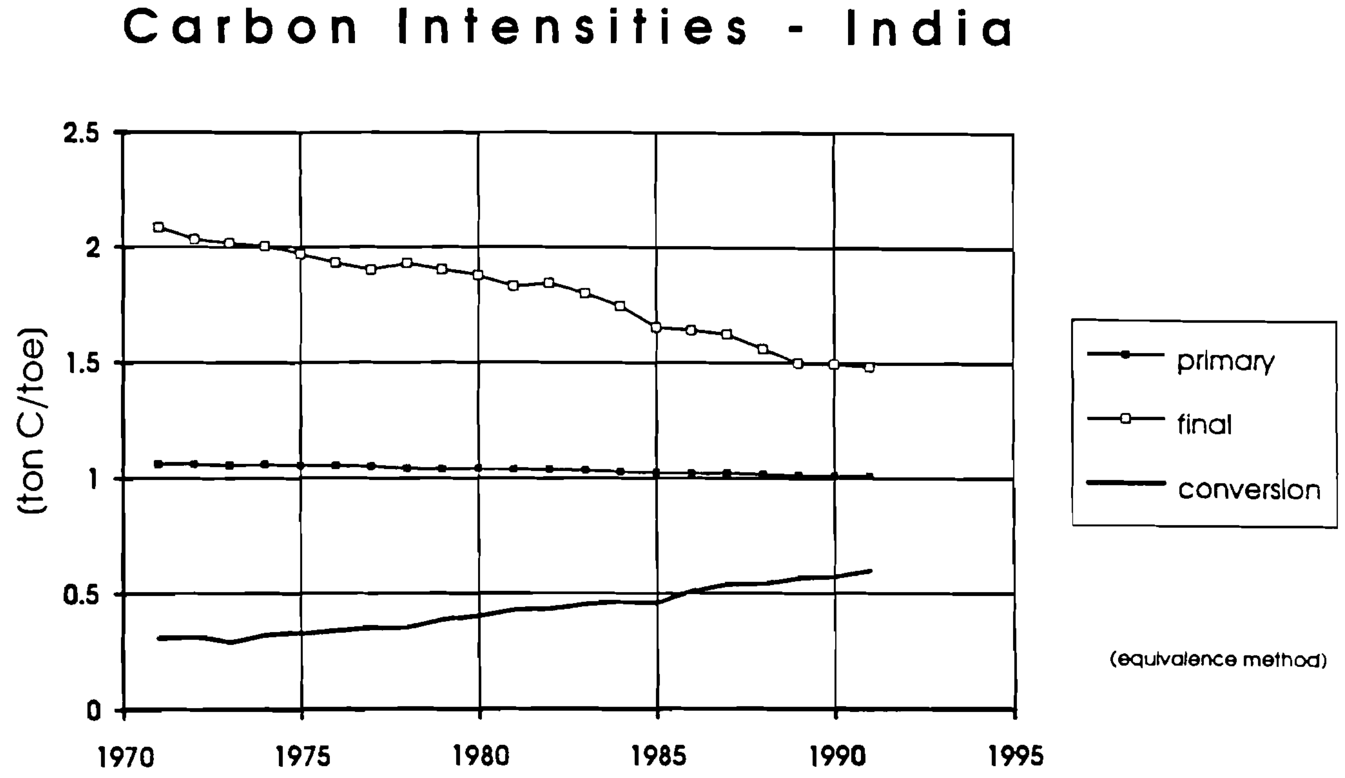

Figure 10: Carbon intensities of primary, final and conversion energy from 1971 to 1991 for India, expressed in tons of carbon per ton of oil equivalent energy (tc/toe).

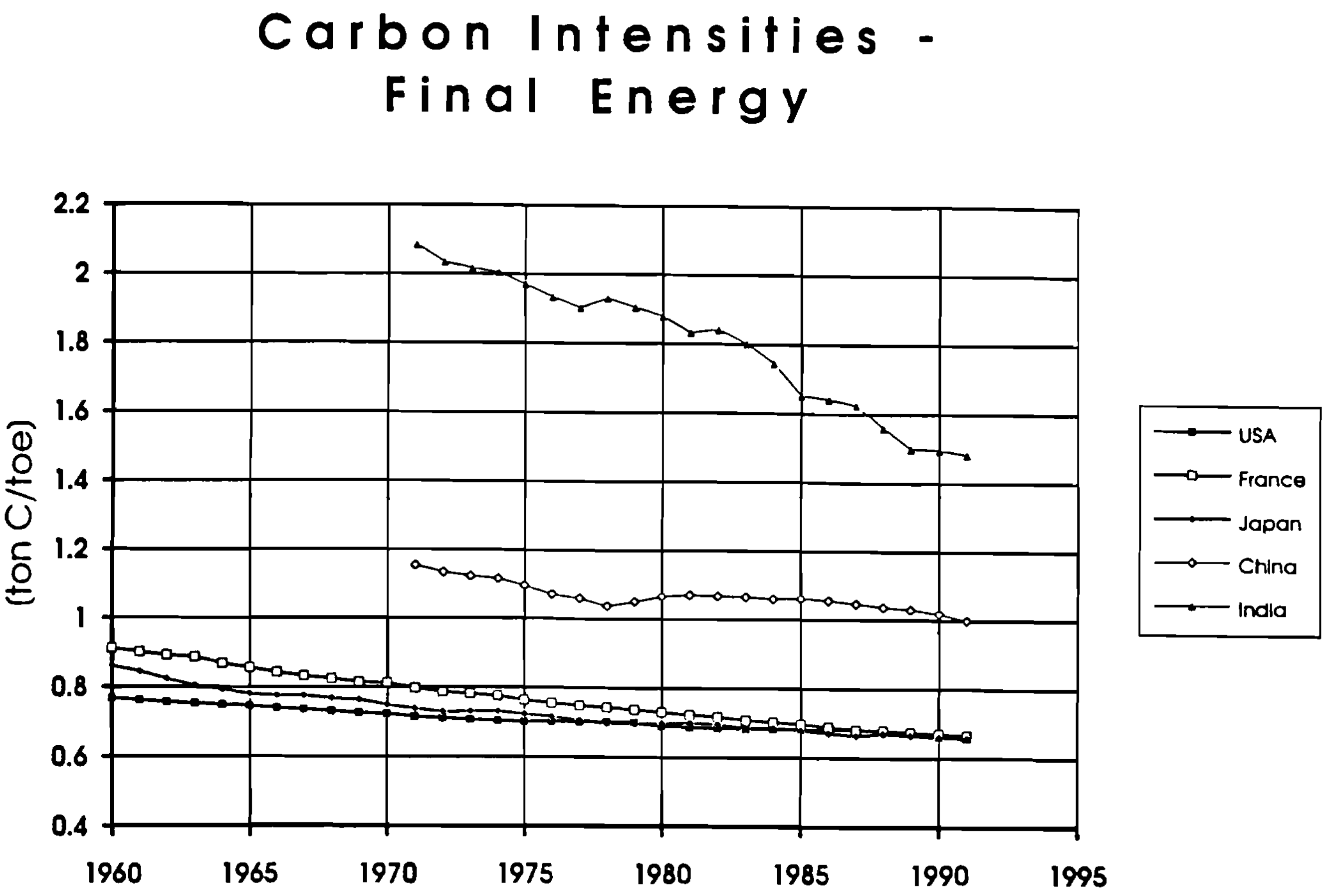

Figure 11: Carbon intensity of final energy for China, France, India, Japan and the United States from 1960 to 1991, expressed in tons of carbon per ton of oil equivalent final energy (tc/toe).

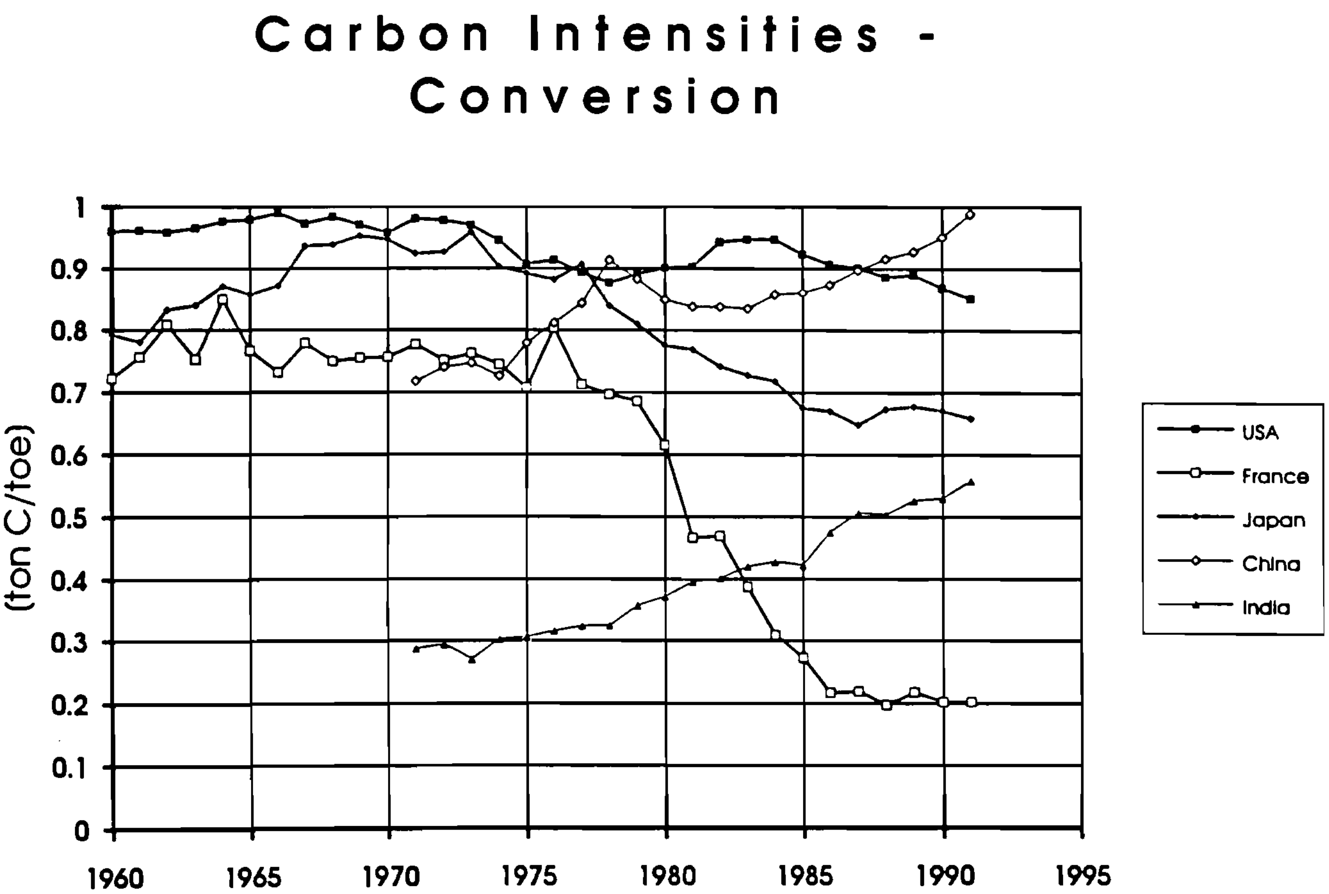

Figure 12: Carbon intensity of energy conversion for China, France, India, Japan and the United States from 1960 to 1991, expressed in tons of carbon per ton of oil equivalent converted energy (tc/toe).

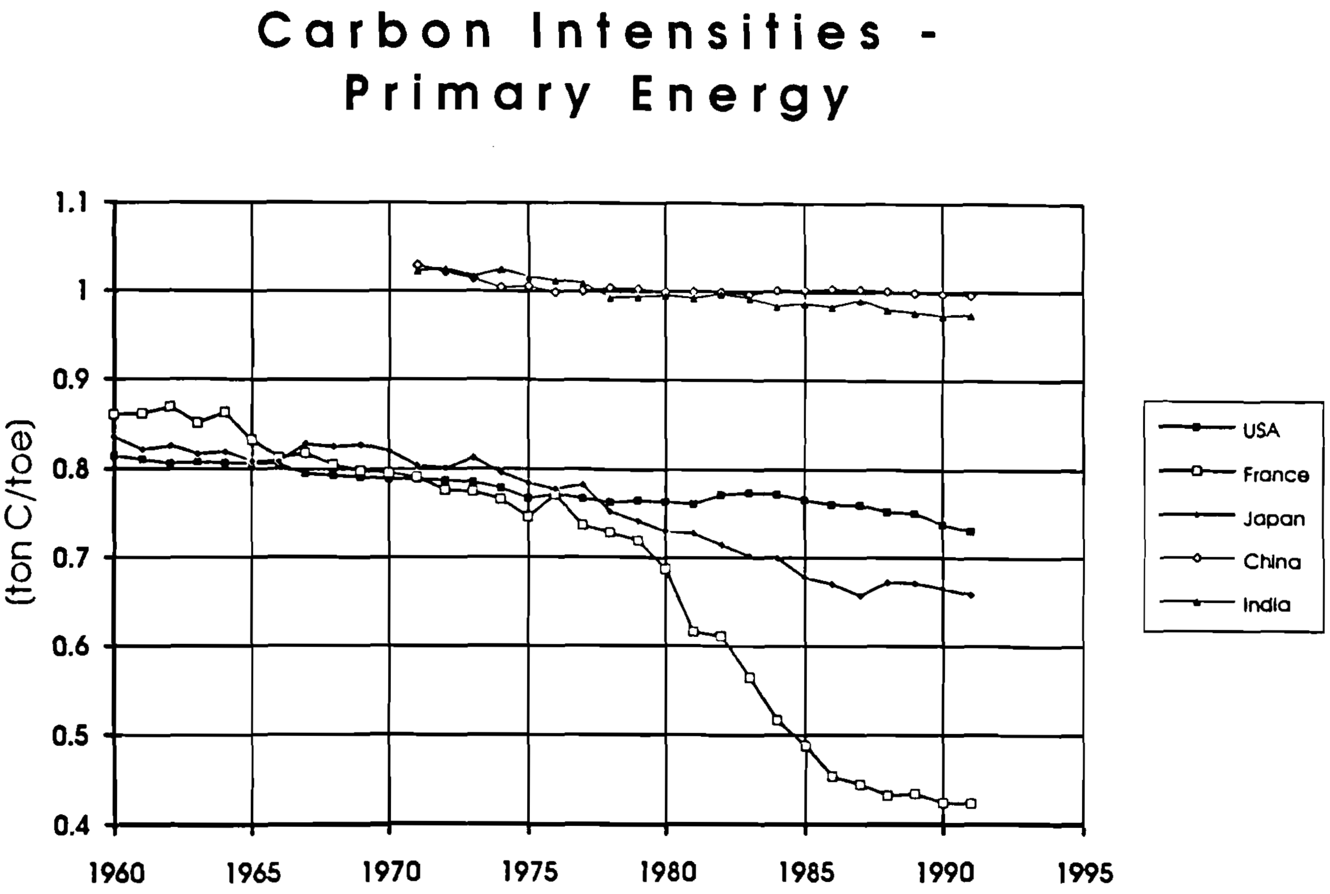

Figure 13: Carbon intensity of primary energy for China, France, India, Japan and the United States from 1960 to 1991, expressed in tons of carbon per ton of oil equivalent primary energy (tc/toe).

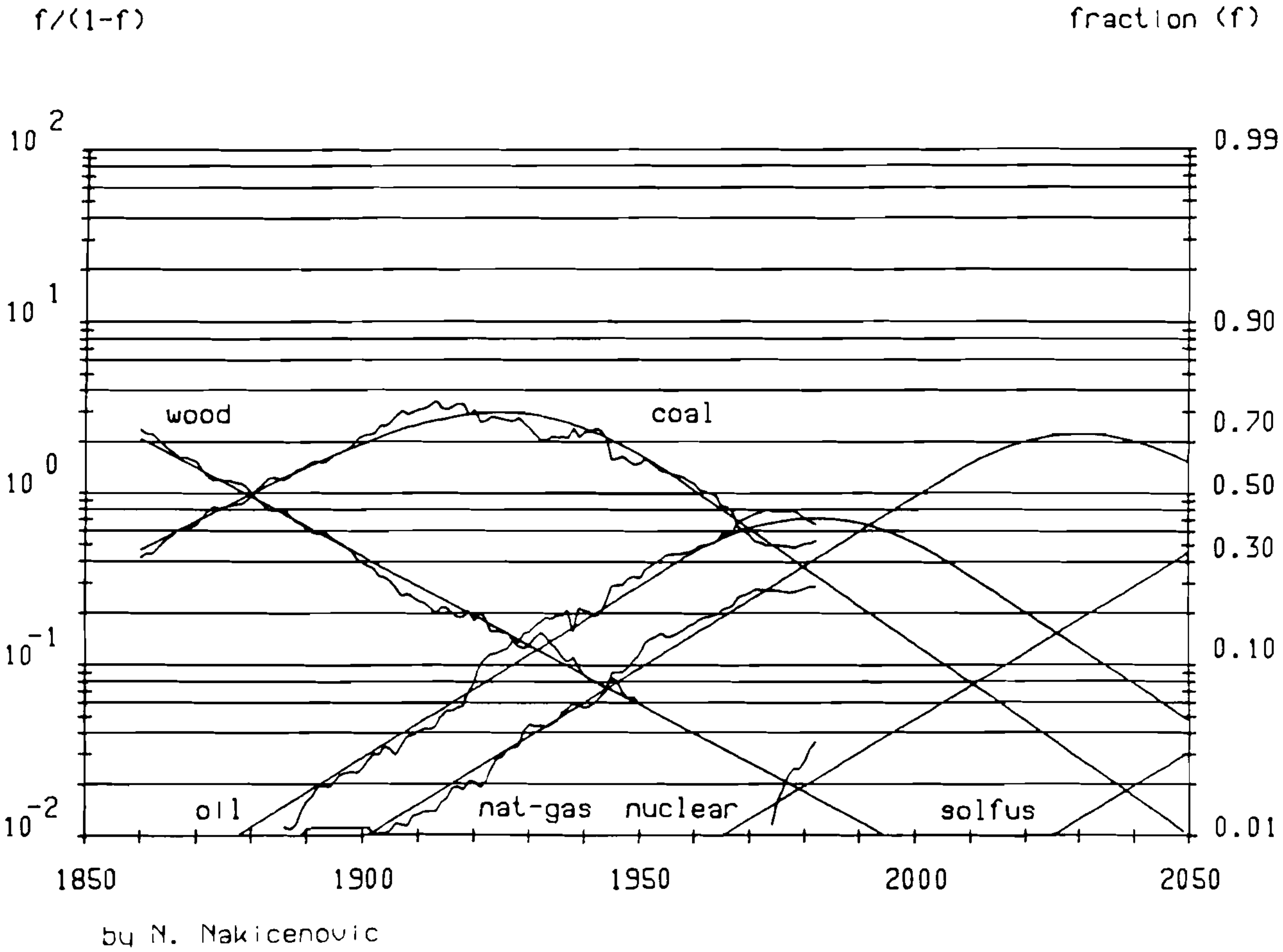

Figure 14: Global primary energy substitution from 1960 to 1982 and projections for the future, expressed in fractional market shares (F). Smooth lines represent model calculations and jagged lines are historical data. "Solfus" is a term employed to describe a major new energy technology, for example, solar or fusion. Source: Grübler and Nakićenović, 1988; Nakićenović, 1990.

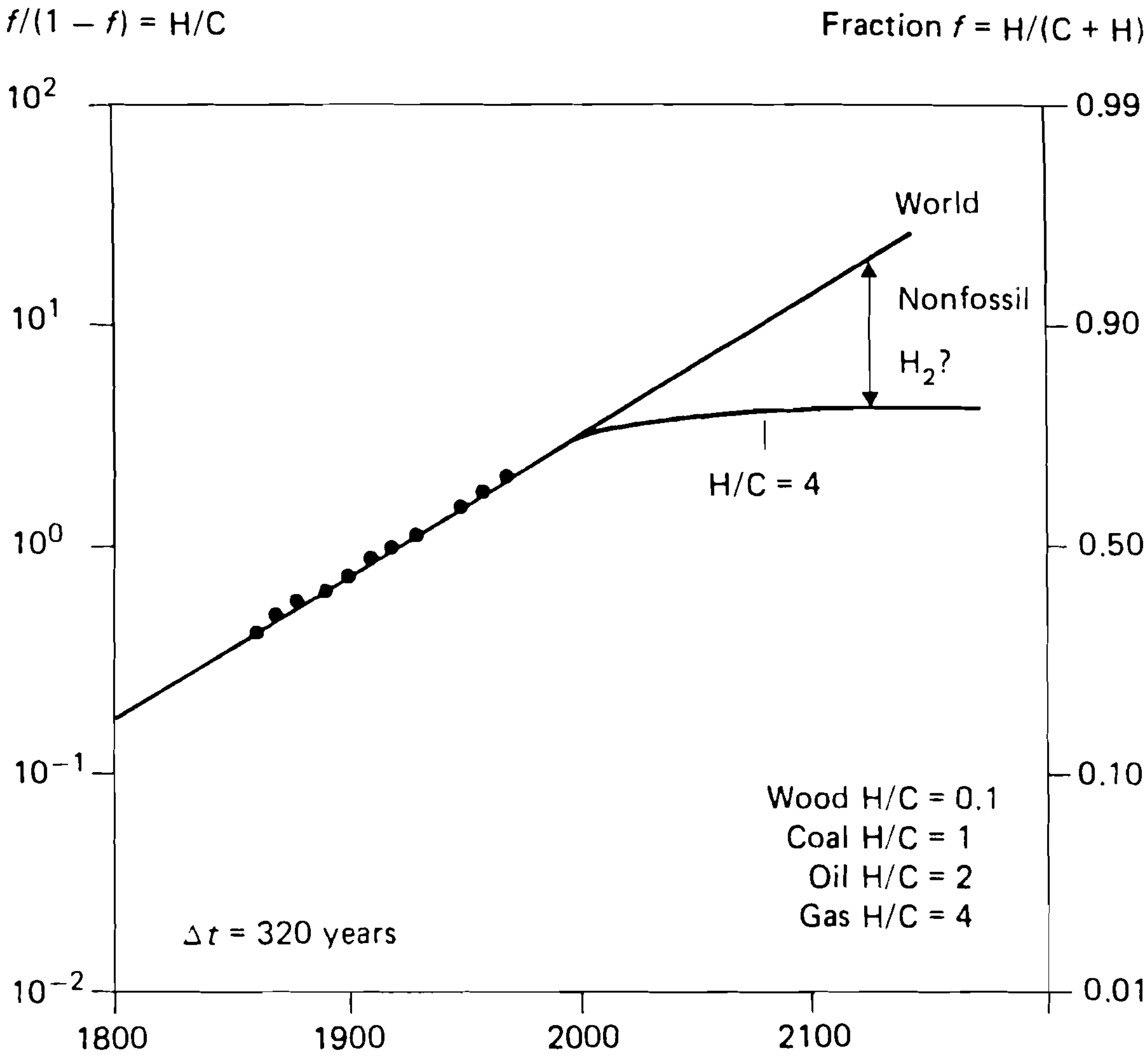

Figure 15: Hydrogen-to-carbon ratio of global primary energy from 1860 to 1982 and projections for the future, expressed in fractional shares of hydrogen and carbon in average primary energy consumed (H/C). Source: Marchetti, 1982.

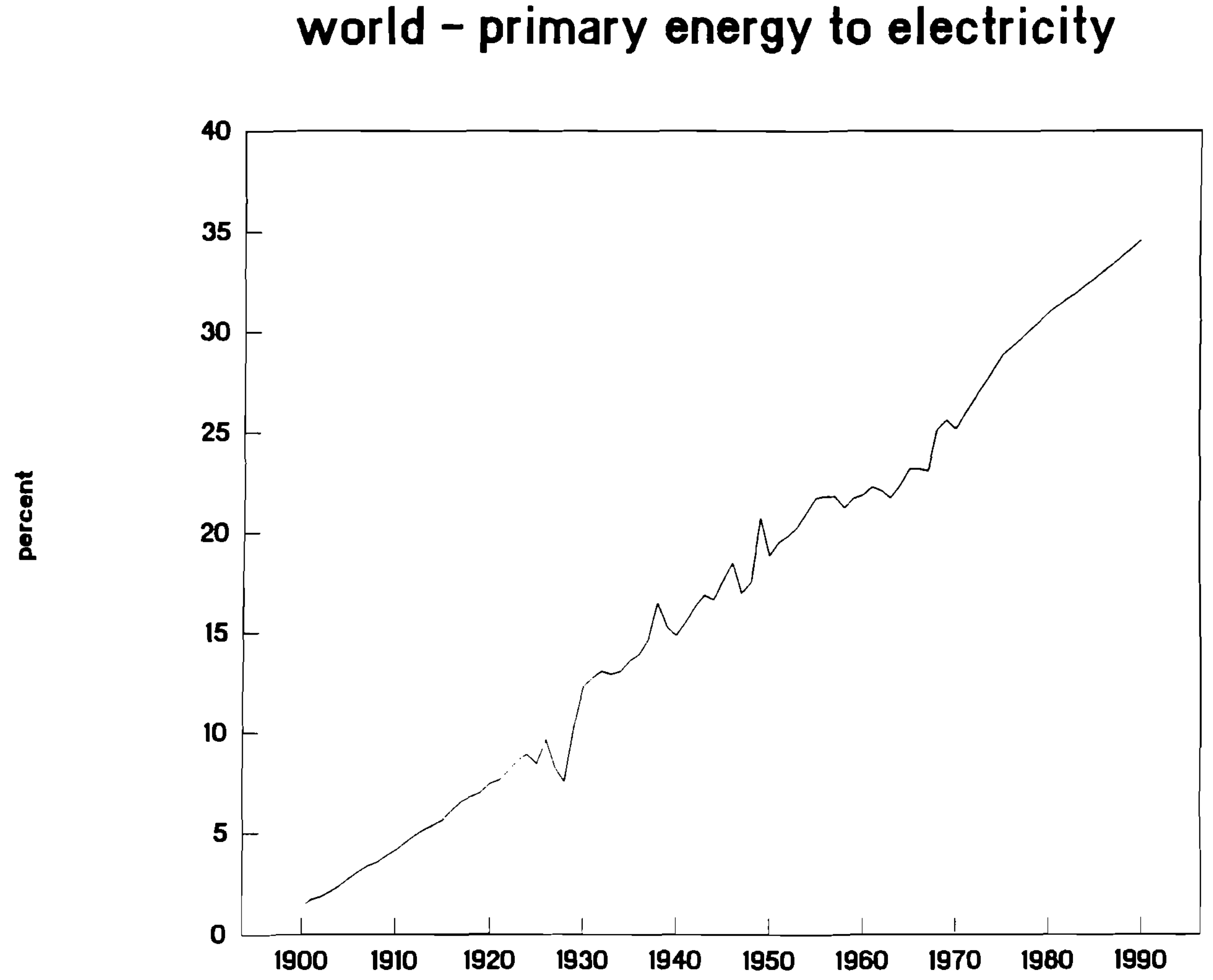

Figure 16: Share of world primary energy going to electricity. Source: H.D. Schilling and R. Hildebrandt, 1977 and UN Energy Statistics Yearbook, 1992.

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