Decarbonization as a Long-Term Energy Strategy

Nebojša Nakićenović*

Consistent with the long-term dynamic transformation and structural change of the energy system is the possibility of less carbon intensive and even carbon-free energy as major sources of energy during the next century. Natural gas seems the likely transitional fuel that would enhance the reduction of other adverse impacts of energy use on the environment as well as substantial reductions of carbon dioxide (CO_2) emissions. Natural gas could be the bridge to carbon-free energy sources such as hydrogen (Nakićenović, 1993a).

Global primary energy use has evolved from reliance on traditional energy sources to fossil fuel based first on coal and steam, then on oil and natural gas, and more recently, (but to a lesser extent) on nuclear and hydro energy. Figure 1 shows the competitive struggle among the five main sources of primary energy as a dynamic substitution process. Fuelwood and traditional energy sources dominated primary energy until 1880. Coal, the major energy source between 1880 and 1960, was the basis for the massive expansion of railroads, the growth of steel, steamships and many other sectors. Since 1960, oil has assumed a dominant role simultaneously as the automotive, petrochemical and other industries have matured. The current reliance on coal in many developing countries illustrates the gap between the structure of primary energy supply and actual final energy needs.

During the past two centuries, global consumption of primary energy has increased about 2% per year, doubling on average about every 35 years. As a result emissions and other environmental effects of energy conversion and end-use have also increased. Current annual emissions are about 6 Gigatons (billion tons) of carbon or more than 20 Gigatons of CO_2. Most of the anthropogenic atmospheric CO_2 is due to fossil energy use and deforestation. Fossil energy consumption contributed more than two thirds of all human sources of CO_2. The largest single source of energy related carbon emissions is coal (about 43%), followed by oil (around 39%) and gas (less than 18%).

In general, the instrumental determinants of future energy-related CO_2 emissions can be described by the Kaya identity. The Kaya identity establishes a relationship between population growth, per capital value added, energy per value added, and CO_2 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.

*Dr. Nebojša Nakićenović is Project Leader of the Environmentally Compatible Energy Strategies Project at the International Institute for Applied Systems Analysis, A-2361 Laxenburg, Austria; telephone no. (+43-2236) 71521-0; telefax no. (+43-2236) 71313. Some results given in the paper are based on the joint research of the author with the assistance of Gilbert Ahamer and Arnulf Grübler both from IIASA.

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

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, 1992, 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. CO_2 emissions per unit of energy and energy intensity per unit value added have been decreasing since the 1860s in most countries.

The decarbonization of energy and decreases in energy intensity of economic activities are a pervasive and almost universal development (Nakićenović, 1993b). Since 1860, the ratio of average CO_2 emissions per unit of energy consumed worldwide has been decreasing. This ratio has decreased due to the continuous replacement of fuels with high carbon content, such as coal, by those with lower or zero carbon content. Figure 2 shows the historical global decarbonization of energy. The reduction in the carbon intensity of the world economy, historically about 1.3 percent per year, has been overwhelmed by growth in economic output of roughly 3.0 percent per year. The difference, 1.7 percent, parallels the annual increase in CO_2 emissions, implying a doubling before 2030 in the absence of appropriate countermeasures and policies.

Analysis of energy decarbonization requires the energy system to be disaggregated into its three major constituents: primary energy requirements, energy conversion, and final energy consumption. 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 it is identical to the one used to define the carbon intensity of primary energy in the world given in Figure 2. 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 exceed 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.

Figures 3, 4, and 5 show the carbon intensities of primary energy, final energy, and the energy conversion sector for selected countries. In Figure 3 the higher carbon intensities of China and India result from higher reliance on coal and traditional sources of energy that are assumed to also result in net CO_2 emissions due to deforestation and, in general, unsustainable exploitation. The steep decline in the carbon intensity during the 1980s in France is a direct result of its vigorous introduction of nuclear energy.

Figure 4 shows carbon intensities of final energy. The figure indicates a continuous and smooth transition toward lower carbon and zero carbon energy carriers, in particular, toward increasing shares of high-quality, exergetic fuels such as natural gas, and, above all, electricity.

The carbon intensities of conversion shown in Figure 5 present a different picture with a variety of energy systems and development strategies, despite the convergence in the final energy mix. In the developing countries, carbon intensity increases over time, while in the industrialized countries it decreases at various rates, most rapidly in France. Should China and India continue to rely heavily on coal, it may not be possible to reduce carbon intensity in these countries. This means that sometime in the next century a trend reversal may 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 is that the future 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.

Generally, carbon intensities of primary energy and energy conversion are due to the energy system itself whereas, the carbon intensity of final energy is 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 the 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.

Some degree of decarbonization has been also accompanied by lower energy intensities. Energy intensity measures the primary energy needed to generate a unit of value added and is usually measured in terms of gross domestic or national products (GDP or GNP). Energy conversion has fundamentally changed and improved with diffusion of internal combustion engines, electricity generation, steam and gas turbines, and chemical and thermal energy conversion. Improvements in energy efficiency have reduced the amount of energy needed to convert primary to final and useful energy. Figure 6 shows declining energy intensity and decarbonization envelopes in selected nations. It illustrates salient differences in the policies and structures of energy systems among countries. For example, Japan and France have achieved the highest degrees of decarbonization; in Japan this has been achieved largely through energy efficiency improvements over recent decades, while in France largely through substitution of fossil fuels by nuclear energy. In most developing countries, commercial energy is replacing traditional energy forms so that total energy intensity is diminishing while commercial energy intensity is increasing.

While decarbonization and energy deintensification are responsible for relative reductions of energy emissions, they are not enough to offset the absolute emissions increases and projected emissions associated with the world's energy needs, especially those required for further economic development. Structural changes in energy systems toward carbon-free sources of primary energy are needed for further carbon intensity reductions. Analysis of primary energy substitution, shown in Figure 1, suggests that natural gas could become the next dominant energy source and would enhance the reduction of adverse impacts of energy-use on the environment, especially CO_2 emissions.

Natural gas is a very potent greenhouse gas if released into the atmosphere, but after combustion occurs, the amount of CO_2 is much smaller compared to other fossil energy sources. Consisting mostly of methane, it has the highest hydrogen to carbon atomic ratio and the lowest CO_2 emissions of all fossil fuels, emitting roughly one-half the CO_2 of coal for the same amount of energy. The historical transition from wood to coal to oil and to gas has resulted in the gradual decarbonization of energy or to an increasing hydrogen to carbon ratio of global energy consumption. Natural gas is also desirable regionally because of its minimal emissions of other air pollutants. Regional assessments suggest that gas resources may be more abundant than was widely believed only a decade ago. New discoveries have outpaced consumption. Additionally, gas hydrates and natural gas of ultra-deep origin indicate truly vast occurrences of methane throughout the Earth's crust.

The methane economy offers a bridge to a non-fossil energy future that is consistent with both 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. 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. 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 then conclude the decarbonization process in the world.

The issue of climate warming is a major planetary concern along with the need to provide sufficient energy for further social and economic development worldwide. Methane and later hydrogen offer the possibility for reconciling these objectives. The evolutionary development of the global energy systems toward larger contribution of natural gas is consistent with the dynamics of the past 130 years. The current phase in the global energy system development may be just midway through the hydrocarbon era. Decarbonization in the world can continue as methane becomes the major energy source. From this perspective, methane is the transitional hydrocarbon, and the great energy breakthrough will be the production of hydrogen without fossil fuels. In the meantime, the natural gas share in total primary energy should continue to grow at the expense of dirtier energy sources - coal and oil. This transition to the methane age and beyond to carbon-free energy systems represents a minimum-regret option because it would also reduce emissions from economic and energy interactions, especially CO_2 emissions.

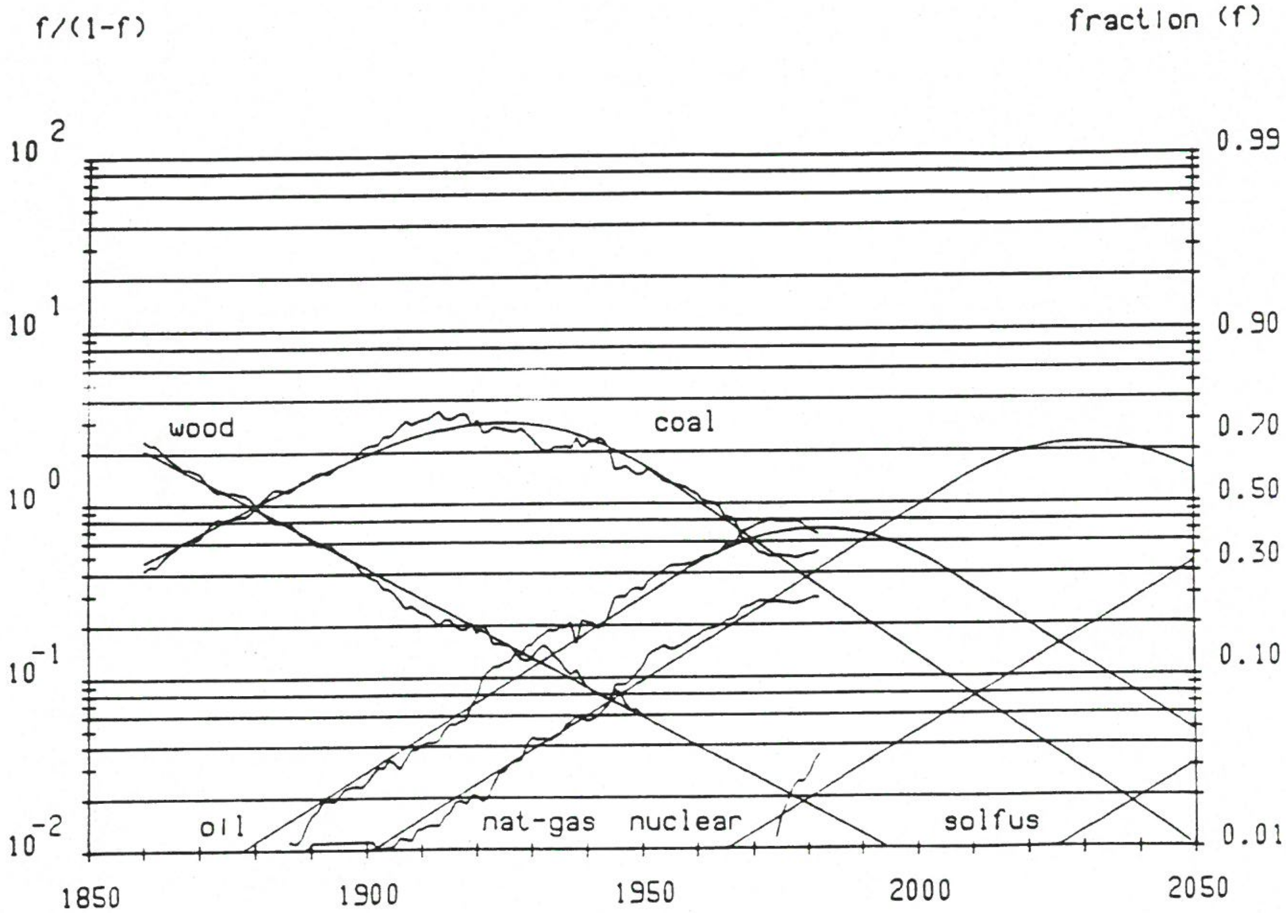

Figure 1: Global primary energy substitution from 1850 to 2050 and projections for the future, expressed in fractional market shares (F). Smooth lines represent model calculations and jagged lines are historical data. "Solfus" is a term employed to describe a major new energy technology, for example, solar or fusion.

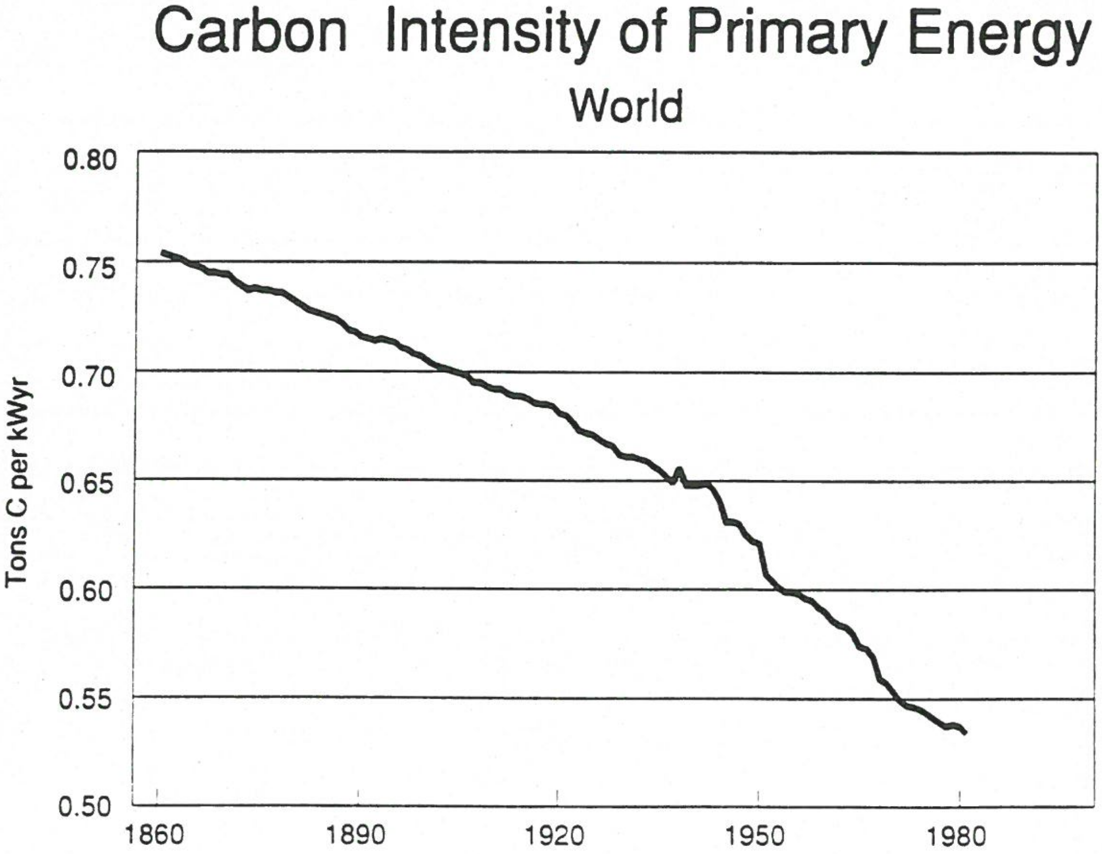

Figure 2: Global decarbonization of primary energy from 1860 to 1980, expressed in tons of carbon per kilowatt year (tC/kWyr).

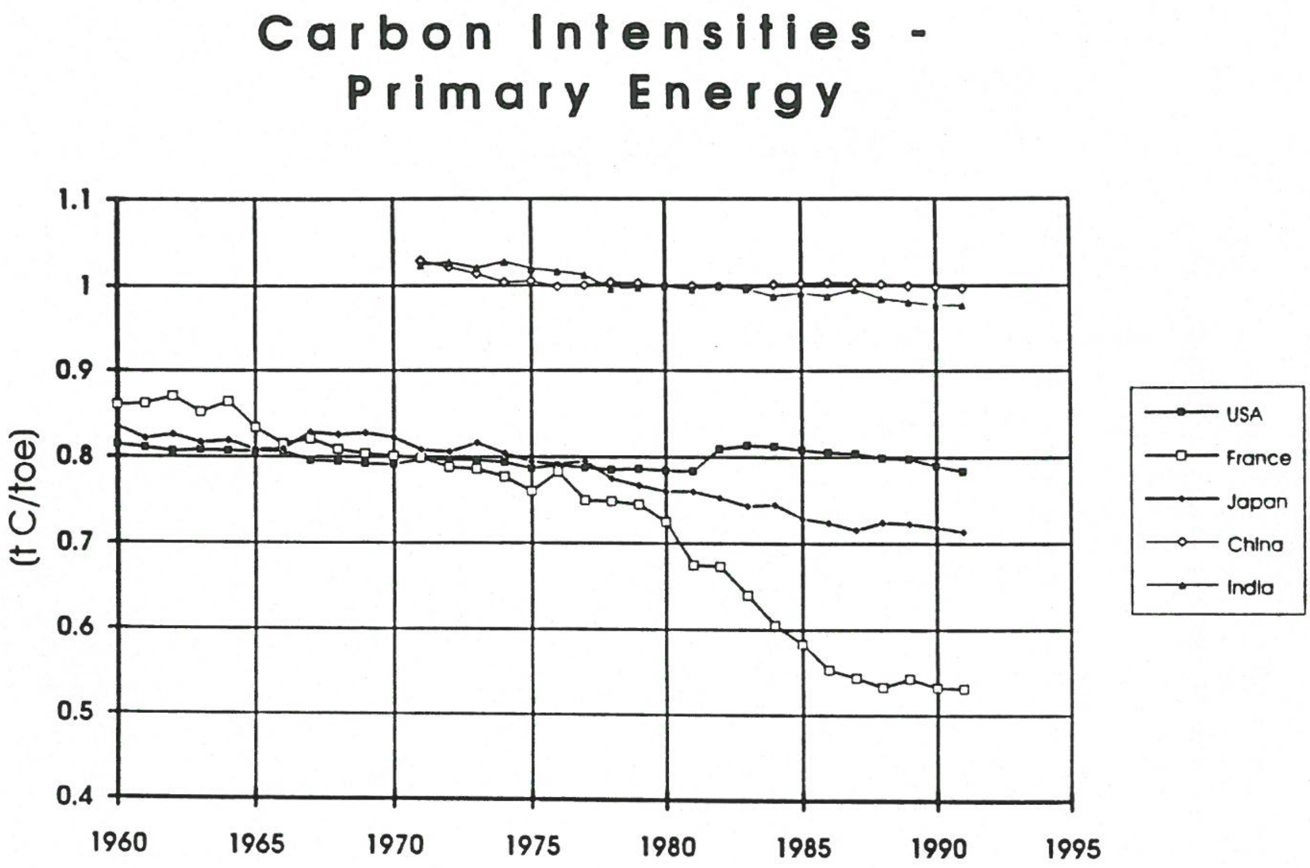

Figure 3: Carbon intensity of primary energy for China, France, India, Japan, and the United States from 1960 to 1991, expressed in tons of carbon per ton of oil equivalent (tC/toe).

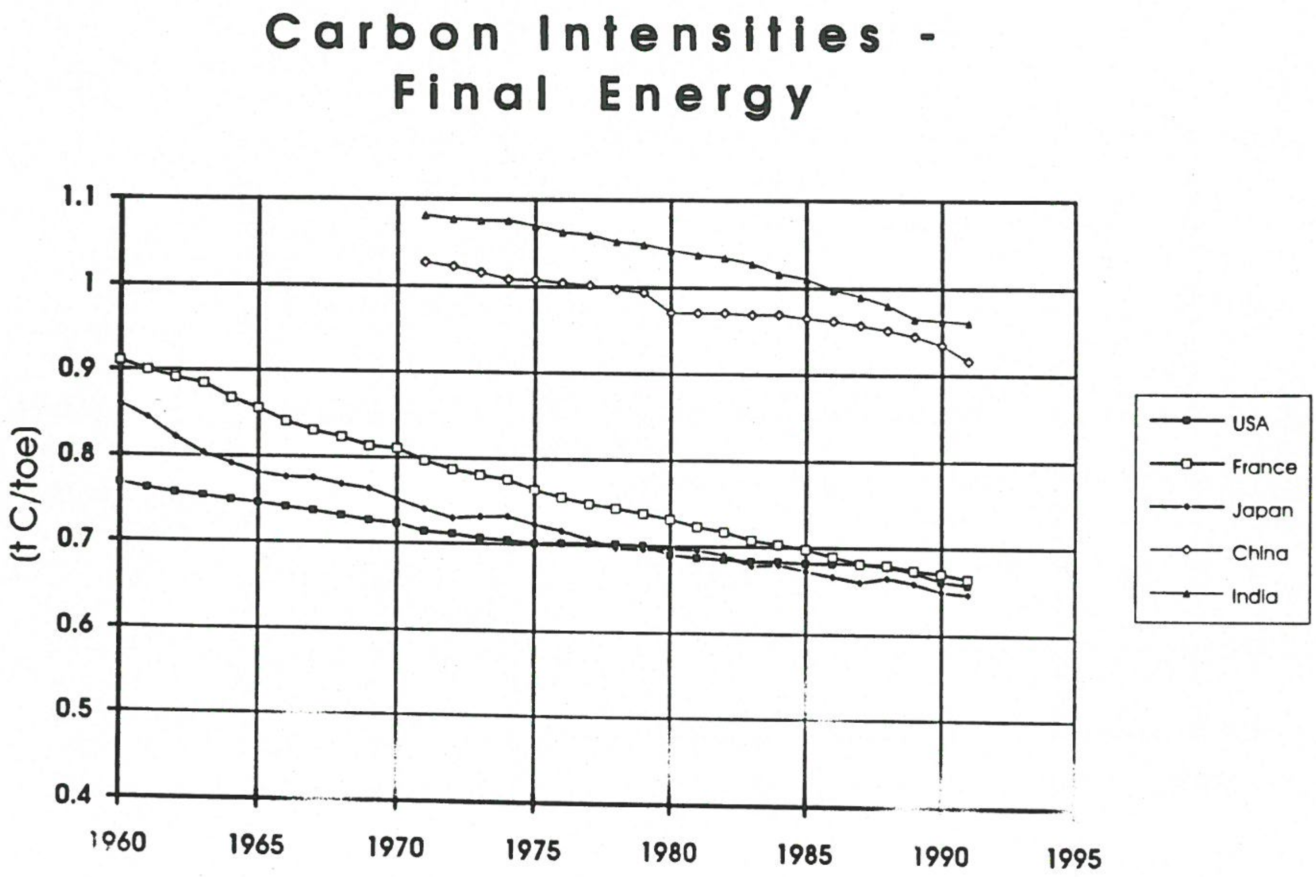

Figure 4: Carbon intensity of final energy for China, France, India, Japan, and the United Stated from 1960 to 1991, expressed in tons of carbon per ton of oil equivalent final energy (tC/toe).

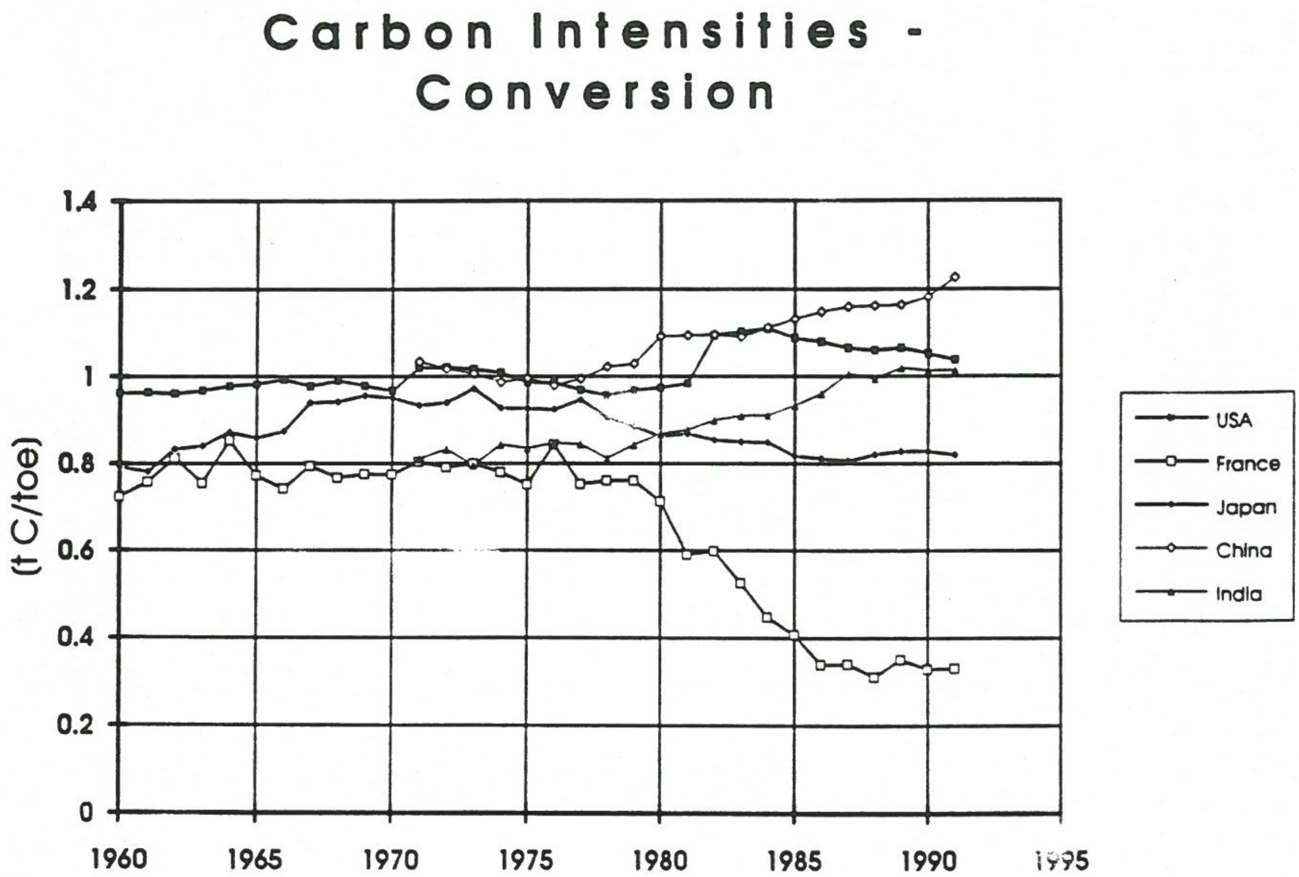

Figure 5: Carbon intensity of energy conversion for China, France, India, Japan, and the United States from 1960 to 1991, expressed in tons of carbon per ton of oil equivalent primary energy (tC/toe).

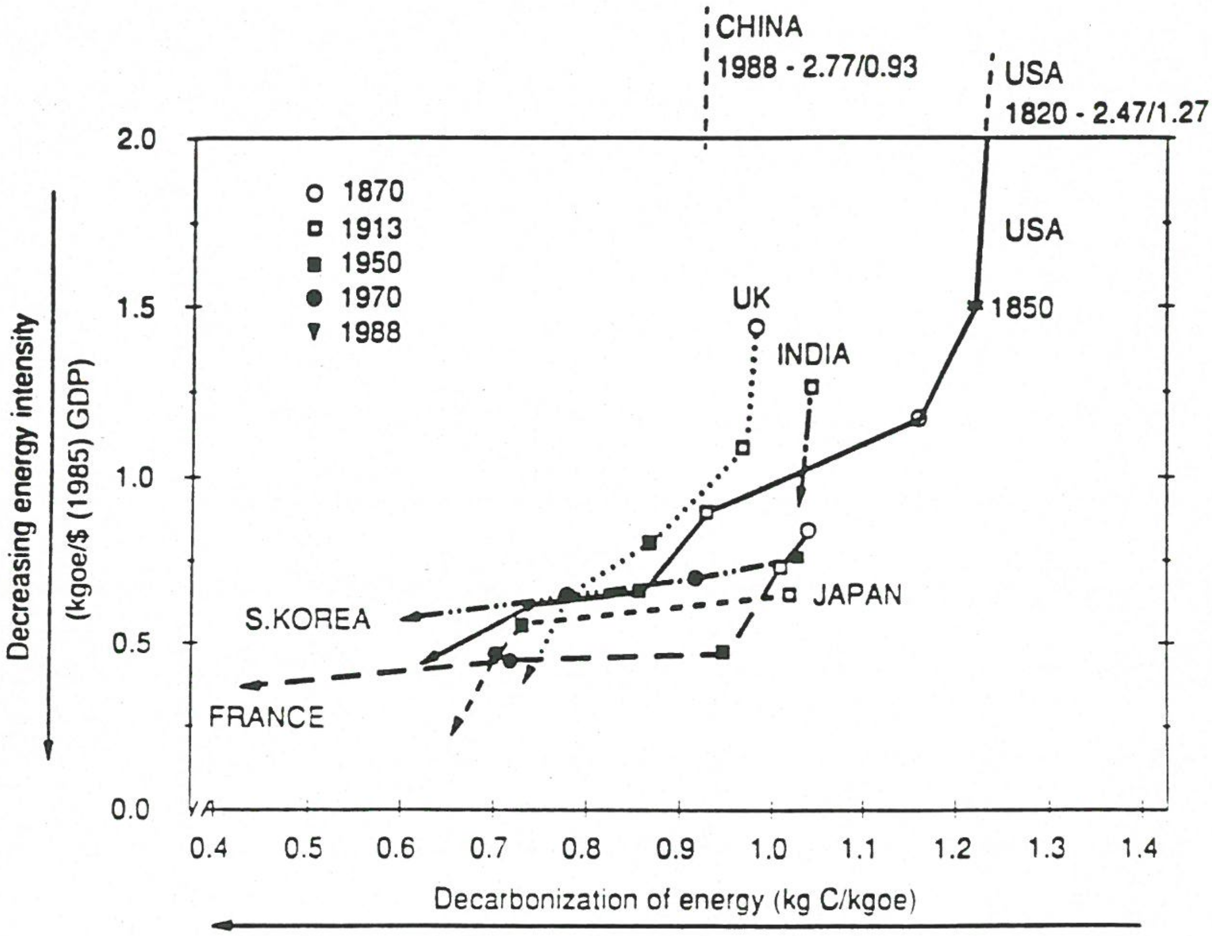

Figure 6: Global decarbonization and deintensification of energy from 1870 to 1988 expressed in kilograms of carbon per kilograms of oil equivalent energy (kgC/kgoe), and in kilograms oil equivalent energy per $1,000 per GDP in constant 1985 dollars.

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