DECARBONIZING THE GLOBAL ENERGY SYSTEM

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NORTH-HOLLAND

Decarbonizing the Global Energy System

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ABSTRACT

The study analyzes the long-term decarbonization of the global energy system, i.e., the decrease of the carbon emissions per unit of primary energy. Decarbonization appears as a continuous and persistent trend throughout the world, albeit occurring at very slow rates of approximately 0.3% per year. The study also discusses driving forces of the associated structural changes in energy systems such as technological change. Decarbonization also occurs at the level of energy end use and trends for final energy are shown. The quest for higher flexibility, convenience, and cleanliness of energy services demanded by consumers leads to decarbonization trends in final energy that are more pronounced than those of the upstream energy sector. The study concludes with a discussion of the implications for long-term scenarios of energy-environment interactions suggesting that decarbonization and its driving forces may still be insufficiently captured by most models and scenarios of the long-term evolution of the energy system.

Introduction

Two important factors determine the level of energy-related CO_2 emissions: the absolute level of energy demand, and the structure of the energy system (energy supply and end use). In this article, we focus on a discussion of changes in the structure of energy supply, which historically have led to a "decarbonization" of the global energy system.

Decarbonization means a decrease in the specific amount of carbon (or CO_2) emitted per unit of primary energy consumed. Structural changes in energy supply lead to decarbonization because the emission factors of different fuels vary—they are 1.25 tons of elemental carbon (tC) per ton oil equivalent (toe) for wood, 1.08 tC/toe for coal, 0.84 for oil, and 0.64 for natural gas [1]. Atmospheric CO_2 is an important greenhouse gas that helps to regulate the temperature regime of our planet. Without greenhouse gases global mean temperature would be some 30 degrees lower, and life as we know it would be impossible. Anthropogenic carbon emissions leading to an increase in atmospheric concentration of CO_2 are a potential source of change in the radiative balance of the atmosphere resulting in possible global warming and climate change [2]. Related political concerns have led to a Framework Convention of Climate Change [3] that calls for stabilization of greenhouse gas concentrations at levels that would prevent dangerous anthropogenic interference with the climate system. Hence a better understanding of

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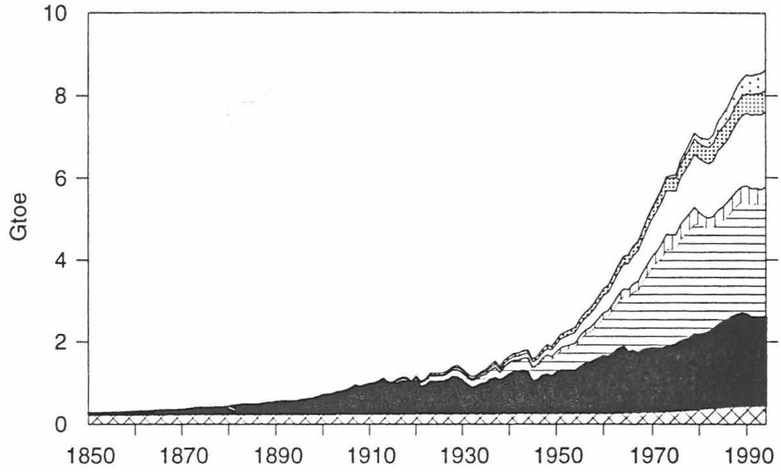

Fig. 1. Global primary energy consumption by source (in Gtoe): nuclear (*stippled*); hydro (*shaded*); gas (*open*); oil (feedstocks) (*vertical lines*); oil (*horizontal lines*); coal (*solid*); wood (*diamonds*).

past decarbonization trends and of possible future conditions for reducing the carbon intensiveness of the global energy system is of particular interest.

The article has the following structure. We start with a presentation of the data sources used for the long-term historical analysis of decarbonization. We then analyze long-term decarbonization trends of primary energy consumption and the main driving forces of the observed structural changes in energy systems such as technological change. We than analyze decarbonization trends for final energy, i.e., the mix of energy carriers actually demanded by industrial and private consumers. We conclude that the quest for higher flexibility, convenience, and cleanliness of energy services demanded by consumers leads to decarbonization trends of final energy that are more pronounced than those of the energy sector upstream. Finally, we discuss the implications of our analysis for long-term scenarios of energy-environment interactions, suggesting that decarbonization and its driving forces may still be insufficiently captured by most models and scenarios of the long-term evolution of the energy system.

Historical Decarbonization Trends

DATA SOURCES

Figure 1 shows the growth in global primary energy use since the mid-19th century by primary energy source. The data set used in our subsequent analysis of energy decarbonization is an update of earlier estimates of historical energy consumption by Marchetti and Nakićenović [4, 5], based on BP statistics [6] for the period 1965 to 1994. Similar data sets have also been developed by Etemand and Luciani [7] for primary energy production since the beginning of 19th century and by a number of authors for energy consumption during the 20th century based on statistics of the League of Nations and later the United Nations [8–10]. Such data sets have also been used for estimating historical carbon emissions for carbon cycle models [11, 12] and for intergenerational carbon accounting [13, 14].

The data cover the consumption of fossil fuels in form of coal, oil, and natural gas, as well as the non-fossil[1] sources hydropower and nuclear energy. Hydro and nuclear

[1] Current energy systems are dominated by the use of fossil fuels. Therefore, hydropower and nuclear energy also entail some carbon emissions, as consumption of fossil fuels (and CO_2 emissions) is required for

are—following a customary convention in the energy industry—accounted for by the so-called "substitution method", i.e., as the fossil primary energy equivalent required to generate the same amount of electricity in a fossil fuel power plant with a current global average conversion efficiency of 38.6 percent [15]. Because production and trade of these commercial energy forms are well documented (not at least because energy has always been a preferred object of government taxation), we estimate that our data set records historical energy consumption within an uncertainty range of perhaps less than ±10%.

Estimates of fuelwood consumption are also included in our data set. Fuelwood was an important energy source of the industrialized countries during the early phase of their development and is important today in many developing countries. Unfortunately, the estimates are associated with large data uncertainties. For the period since 1961, data are from the United Nations Food and Agriculture Organization statistics [16]. For earlier periods we use the estimates of Marchetti and Nakićenović [4] that are largely based on the work of Putnam [17]. If harvested on a sustainable basis, fuelwood does not contribute directly to a net accumulation of CO_2 in the atmosphere, i.e., forest regrowth occurs at least at the same rate as fuelwood consumption, absorbing released CO_2 from the atmosphere. At present, no reliable estimates exist about the fraction of fuelwood that is harvested sustainably. As most of fuelwood consumption is in developing countries, where also deforestation rates are substantial, perhaps as much as half of the global current fuelwood use may lead to a net accumulation of carbon in the atmosphere. Global fuelwood use is estimated [16] at about 0.4 Gtoe (giga, or billion, tons of oil equivalent), or less than 5% of total energy use. However, the related carbon fluxes are smaller when compared with emission estimates from land-use changes and deforestation. Current fuelwood use may be releasing globally some 0.5 GtC (giga, or billion tons, elemental carbon), compared with some 1.6 ± 1 GtC estimated as annual release from land-use changes and deforestation [2]. The cumulative historical fuelwood consumption from 1850 to 1990 based on our data set is about 35 Gtoe, which corresponds to some 44 GtC cumulative emissions, compared with cumulative land-use emissions of 122 ± 40 GtC for the same time period [2]. In view of large uncertainties associated with net atmospheric accumulation of carbon emissions from burning of fuelwood, we report emissions and carbon intensities both including and excluding fuelwood. The former case may be considered as "gross" emissions, whereas the latter may be considered as minimum estimate of "net" emissions contributing directly to atmospheric concentration increases. (A similar accounting convention is also adopted for nonenergy feedstocks, discussed below).

Other noncommercial energy forms are not considered in our analysis, due to the absence of reliable estimates of current and historical consumption. They include human and animal work, agricultural residues and other biomass, dung, etc. Estimates in the literature put their current contribution to global energy consumption at between 0.5 to 0.7 Gtoe (i.e., between 6 to 8% of total primary energy use) [15, 18]. Associated carbon emissions should not generally lead to substantial atmospheric concentration increases. The released carbon is sequestered through renewed biomass and foodcrop growth.

The estimates of fossil fuel consumption reported in Figure 1 and used in our analysis also include nonenergy feedstocks (e.g., used for manufacture of plastics). Globally,

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the manufacture of steel, cement, etc. Emissions are mainly embodied in plant and equipment, but also originate from plant operation (e.g., gasoline and diesel use for cars, trucks, etc.). These emissions are difficult to determine accurately, especially at the global level and are of second order magnitude. In addition, emissions occur outside the energy sector proper (i.e., in manufacturing or the transport sector). These type of indirect emissions are not considered separately here.

TABLE 1
1990 Global Primary Energy Use and Carbon Emissions (in Mtoe and MtC)

	Mtoe[a]	MtC[b]
Coal	2,239	2,418
Oil[c]	3,137	2,629
Gas	1,768	1,133
Nuclear[d]	440	–
Hydro[d]	481	–
Total commercial (1-5)	8,065	6,180
Energy use only[e]	7,657	5,838
Fuelwood	424	531
Total (6 + 8)	8,489	
Other noncommercial energy	<700	NA

[a] All values refer to lower heating values (LHV).
[b] For emission factors see Reference 1 and text.
[c] Crude oil and oil products. Includes international bunker fuel and nonenergy feedstocks.
[d] Substitution equivalent based on efficiency of fossil electrictiy generation of 38.6% (see Reference 15).
[e] Excludes 408 Mtoe (342 MtC) feedstock uses. Data source: References 15 and 28.

these nonenergy uses of energy (mostly oil products) amount to some 0.4 Gtoe and correspond to 0.3 GtC. Related carbon emissions are difficult to estimate, as atmospheric releases can be delayed substantially (for instance when plastic produced decades ago is burned in an incinerator after the end of its useful life; in case of buried wastes such delay times may extend even to centuries). This uncertainty, together with the fact that feedstocks constitute a raw material rather than an energy use, is reflected in our analysis by reporting numbers both including and excluding feedstock uses. This is similar to the concept of "gross" and "net" emissions discussed above for fuelwood use.

Table 1 summarizes global energy and carbon fluxes of our data set. Data are given in million toe and tC respectively for the year 1990 in order to facilitate comparisons with other studies, notably of the Intergovernmental Panel on Climate Change (IPCC) [18].

RATES OF DECARBONIZATION

For selected years, Table 2 summarizes key indicators of primary energy use, carbon emissions, and the resulting carbon intensities. As outlined in the previous section, we adopt two accounting conventions: including all energy streams and emissions ("gross" values), as well as excluding (sustainable) fuelwood use and nonenergy feedstocks ("net" values).

TABLE 2
Global Primary Energy Use (Mtoe), Carbon Emissions (MtC), and Carbon Intensities (tC/toe)

	Primary energy (Mtoe)		Carbon emissions (MtC)		Carbon intensity (tC/toe)	
	Net[a]	Gross[a]	Net[a]	Gross[a]	Net[a]	Gross[a]
1850	45	211	49	313	1.08	1.22
1920	939	1,173	947	1,239	1.01	1.06
1970	4,946	5,489	3,947	4,511	0.83	0.85
1994	7,785	8,610	5,839	6,716	0.75	0.78
Factor increase since 1850	173	41	119	21	0.7	0.6
%/year, 1850-1994	3.6	2.6	3.4	2.2	−0.3	−0.3

[a] "Gross" values include all forms of energy consumption and emissions; "net" values are excluding (sustainable) fuelwood and nonenergy feedstock uses.

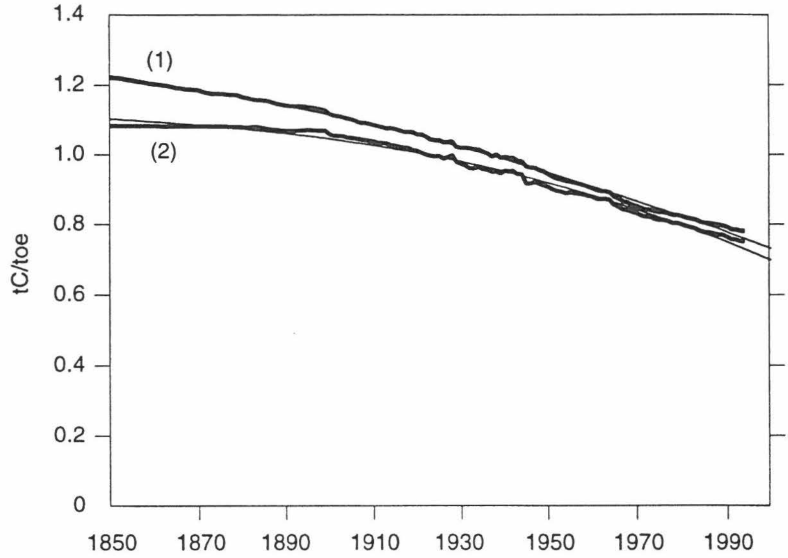

Fig. 2. Carbon intensities of global primary energy consumption In tC/toe): (1) "gross" intensity considering all energy forms and emissions; (2) "net" intensity excluding (sustainable) fuelwood and non-energy feedstocks.

The tremendous expansion of (primarily fossil) energy use and emissions since the onset of the Industrial Revolution is evident from the data. Primary energy use has expanded by a factor of 170, and carbon emissions by a factor of 120 in the case of net values and by factors of 40 and 20, respectively, in the case of gross values. During the 1850 to 1994 period, cumulative emissions released to the atmosphere are close to 300 GtC. Coal is by far the dominant source (132 GtC), followed by oil (86 GtC, including feedstocks), fuelwood (44 GtC), and natural gas (30 GtC).

The key observation however, is that carbon emissions have expanded at a slower pace than primary energy use, leading to the observed "decarbonization" of the global energy system. (The term "decarbonization" to our knowledge was first coined by Yoichi Kaya and Kenji Yamaji [19, 20] describing short-term structural change trends in OECD energy systems. Longer term and global analyses of decarbonization were first performed at IIASA [21, 22].)

The carbon intensity of primary energy use today is some 30 to 40% lower than in the mid-19th century. Table 2 however also illustrates that this long-term structural change is rather slow with 0.3 average improvement rate per year, and nearly one order of magnitude lower than the rate of increase in energy use.

Figure 2 illustrates the two decarbonization trends, calculated from our data set. Despite fundamental changes in both energy supply and end use (see discussion in the section below), decarbonization trends are surprisingly regular and nonlinear. This is a feature observed for many dynamic, self-organizational systems. We used a three-parameter logistic curve [23] to fit the data. It describes the historical development rather well.

The assumption that the curve parameters are uncorrelated (and hence traditional measures of statistical uncertainty are applicable) cannot be supported according to Debecker and Modis [24]. The parameter uncertainties of our estimates (using the observations over the entire period 1850 to 1994), assuming a 10% data error and a 90% confidence

TABLE 3
Decarbonization Trends: Logistic Parameters and Uncertainties

	"Gross" carbon intensity	"Net" carbon intensity
K (tC/toe)	1.16–1.36	1.01–1.25
t_0 (year)	2003–2011	2018–2028
Δt (years)	−305– −337	−208– −228
R^2	0.998	0.991

Where K, t_0, and Δt denote the parameters of a logistic curve, in particular the asymptote (K), the inflection point (t_0), and the growth rate parameter (Δt), that denotes the time (in years) to go from 1 to 50, or (because of the symmetry condition) from 10 to 90% of K. As we describe a declining trend, the parameter Δt is negative.

level, are derived from the look-up tables of parameter uncertainties obtained with Monte Carlo simulations in [24] and are given in Table 3.

Figure 2 also suggests that decarbonization trends are continuous and without trend reversals, although there seems to be a certain slowdown since the early 1970s. Figure 2 also shows that the time scales involved in decarbonization are very long indeed. If historical trends should continue, a phase-out of fossil fuels would occur only late in the 22nd century. This implies that we might be only half-way through the fossil fuel age. This contrasts the perceptions every since the 1950s about forthcoming resource depletion or a rapid technology-led transition away from fossil fuels [17, 25] (see also the contribution of Jean-Marie Martin in this special issue on this topic).

Before turning to a discussion of the driving forces of decarbonization, let us briefly summarize some major implications. The long-term decarbonization trends indicate that the global energy system is moving in the right direction. This gives reason to be cautiously optimistic that the process of development, and the resulting economic growth, increased energy needs, and emissions, could be reconciled with a precautionary policy of avoiding large-scale human interference with the radiative balance of the atmosphere. The task of controlling energy-related carbon emissions, as daunting as it may appear from today's, or a short-term perspective, may in fact turn out to be less obstructive if indeed an acceleration of long-term structural change trends is called for rather than departure in an entirely new direction. Conversely, it will simply not suffice to rely on "autonomous" structural change toward carbon-freer energy systems especially considering the slow historical rates of decarbonization of 0.3% per year. They are dwarfed by historical and anticipated future growth rates in energy use and resulting carbon emissions. Substantial acceleration of decarbonization will thus entail both ambitious technological and policy changes. Their effectiveness will depend also on our understanding of the forces that have led to historical rates of decarbonization and how these may evolve in future.

Driving Forces

STRUCTURAL CHANGE

Before the Industrial Revolution, the energy system relied on harnessing natural energy flows, and animate and human power, to provide energy services in the form of heat, light, and work. Power densities and availability were constrained by site-specific factors, with mechanical energy sources limited to draft animals, water, and windmills. The only form of energy conversion was from chemical energy to heat and light, through burning fuelwood, for example, or tallow candles. Energy consumption typically did not exceed 0.5 toe per capita per year.

Two "grand transitions" have since shaped structural changes in the energy system at all levels. The first was initiated with a radical technological end-use innovation: the

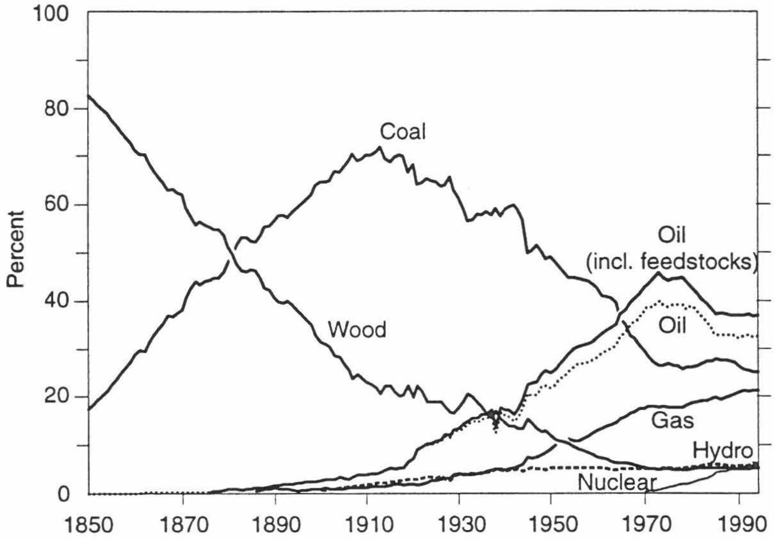

Fig. 3. Structural change in global primary energy (percent shares by source).

steam engine powered by coal. The steam cycle represented the first conversion of fossil energy sources into work; it allowed the provision of energy services to be site independent, because coal could be transported and stored as needed; and it permitted power densities previously only possible in exceptional locations of abundant hydropower. Stationary steam engines were first introduced for lifting water from coal mines, thereby facilitating increased coal production. Later, they provided stationary power for what was to become an entirely new form of organizing production: the factory system. Mobile steam engines, on locomotives and steam ships, enabled the first transport revolution, as railway networks were extended to even the most remote locations and ships converted from sail to steam. Characteristic energy consumption levels during the "steam age," approximately the mid-19th century in England, were about 2 toe per capita per year. By the turn of the 20th century coal had replaced traditional non-fossil energy sources and supplied virtually all the primary energy needs of industrialized countries.

The second grand transition was the greatly increased diversification of both energy end-use technologies and energy supply sources. Perhaps the most important single innovation was the introduction of electricity as the first energy carrier that can be easily converted to light, heat, or work at the point of end use. A second key innovation was the internal combustion engine, which revolutionized individual and collective mobility through the use of cars, buses, and aircraft. Like the transition triggered by the steam engine, this "diversification transition" was led by technological innovations in energy end use, such as the electric light bulb, the electric motor, the internal combustion engine, and aircraft. However, changes in energy supply have been equally far reaching. In particular, oil emerged from being an expensive curiosity at the end of the 19th century to the dominant global position it has occupied for the last 30 years.

Figure 3 illustrates these two grand transitions by showing the changing shares of different primary energy sources in the global energy supply (from Figure 1). The long-term structural changes include the long transition away from traditional renewable energy forms (fuelwood) toward fossil fuels; the emergence and eventual saturation of coal, when it supplied about two-thirds of global energy needs by the eve of World War I;

the introduction of oil and later on natural gas, first as a by-product of oil production and more recently as an energy carrier in its own right; the peak in the market share of oil in the 1970s; and finally a slow-down in the dynamics of change in the primary energy supply structure during the last two decades. This reduced dynamism may be partly due to the increased regulatory interest received by the energy sector in recent decades, partly due to oil's attractiveness for the transportation sector where demand has risen steadily, and partly due to a delayed switch in power generation away from coal and oil to natural gas (through misguided regulation).

In essence, the historical structural changes in the global energy system were triggered by numerous technological changes ranging from energy supply to energy end-use. The transition from fuelwood to coal, from coal to oil, and more recently toward gas and other grid-dependent energy forms such as electricity are embedded in much more far-reaching transformations in the technological, economic, and institutional base of modern economies that are interrelated, interdependent, and mutually cross-enhancing [26]. Freeman and Perez [27] (see also Chris Freeman's contribution to this special issue) have developed a particularly convincing metaphor to describe such changes in "techno-economic paradigms," and it is easy to associate particular of these paradigms with its dominant energy system and carrier from the coal-based steam economy of the 19th century to the oil and petrochemical based "Fordist mass production and consumption paradigm" [27] of economic development since World War II.

The "grand" energy transition have facilitated far reaching structural changes in employment, the spatial division of labor, and international trade. These are associated with modernizing traditional economic and social structures and include concurrent structural changes like industrialization, urbanization, monetization of the economy, but also important changes in the requirements imposed on the energy sector. The historical structural changes in energy supply in particular have led to increased energy "quality," in terms of flexibility, convenience, and cleanliness. Better quality together with improved technologies of energy end-use has been a main driver, together with economic structural change, for improvements in energy efficiency and aggregate energy intensities (energy needs per unit of economic output). Although improvement rates can vary significantly over time and between different countries (see the contribution of Chris Freeman in this special issue), long-term aggregate improvement rates range in the order of 1 percent per year [15].

In essence, our interpretation of the long-term decarbonization trend of the energy system is the result of a combination of continuous technological change and the quest toward ever higher energy quality.

ENERGY END-USE

In our discussion thus far we have concentrated on the decarbonization of the supply part of the energy system. We will now look at energy end use. Together with technological change, the drive to cleaner energy is an important factor in decarbonization along with changing consumer preferences and rising incomes.

Contrary to primary energy, energy end-use statistics are much more sparse, especially concerning longer term historical data. The most systematic international statistics are those of the International Energy Agency [28] covering the period since 1971. These shorter term trends are analyzed in Figure 4. The carbon intensities of final energy use (i.e., of the mix of fuels actually demanded by consumers) are analyzed for selected world regions (as used in [15]). As for primary energy, two data sets are given including and excluding fuelwood and nonenergy feed-stock uses. The data are not plotted as time

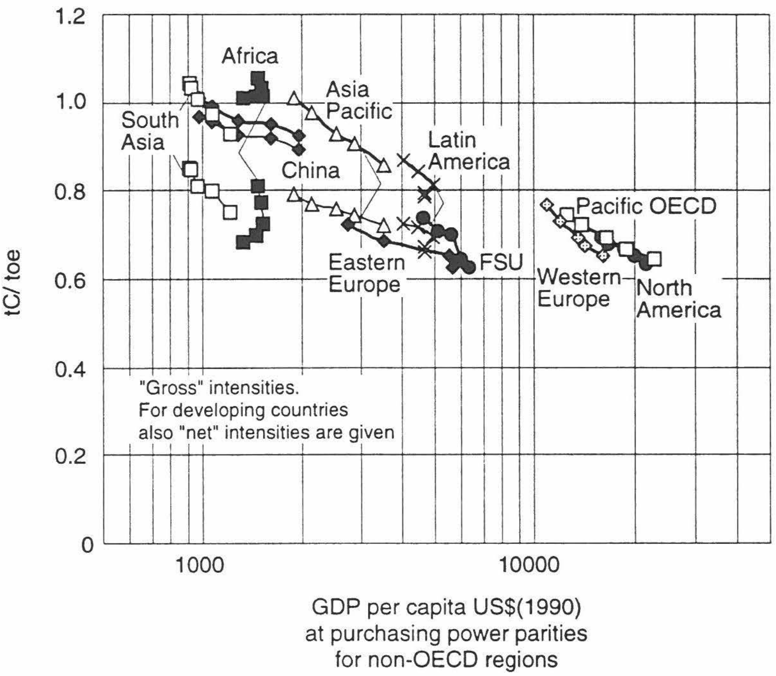

Fig. 4. Carbon intensities of final energy versus degree of economic development (GDP per capita, at purchasing power parities), 1971–1991.

trends, but as a function of the degree of economic development, measured by per capita GDP and adjusted for purchasing power differences for developing economies and those undergoing transition to a market economy (Eastern Europe and the FSU, the former Soviet Union). This "development metric" intends to give some insights into the longer term evolution of the (now) industrialized countries, that also began their development path many decades ago at similar levels of per capita income and energy use structures as are prevailing in the developing countries today.

Three observations on Figure 4 are noteworthy: first, is the considerable heterogeneity between different regions; second, is the persistent trend toward lower carbon intensities with rising per capita income; third, are the much lower carbon intensities of final energy (below 0.7 tC/toe) compared with primary energy [29]. The lower carbon intensities for final energy are the result of changes in the fuel structure that consumers demand (private and industrial alike): increasing shares of high quality energy forms like electricity, district heat, gas, and liquids. This trend is particularly pronounced in high-income economies. Conversely, the final energy consumption structure of low income (i.e., developing) countries is dominated by the use of solids with a high carbon content: fuelwood and coal. In turn, these have virtually disappeared as end-use fuels in high income countries (with the notable exception of some coal use in metallurgical industry).

The decarbonization of final energy is thus more pronounced than that of primary energy. This is in fact no surprise considering that the carbon intensities of primary energy systems are also influenced by factors such as resource endowments, trade, and geopolitical supply diversification considerations. To an extent, the energy sector "compensates" part of the decarbonization that occurs as a function of changing economic and consumer preferences toward high quality fuels. Part of this is due to technological reasons (e.g., electricity as an end-use fuel is carbon-free but entails emissions at the point of its generation); part is due to policy measures (e.g., restrictions to use clean natural gas in electricity generation have only recently been lifted in the United States and by the European Communities). Nevertheless, the persistent and converging trend toward cleaner fuels and lower carbon intensities that seems to accompany economic development is an additional reason for cautious optimism concerning continuing improvements in the future that could assist climate protection efforts.

This outlook is however shared only by comparatively few studies and scenarios of the future. The "mainstream" viewpoint, as formulated for instance in the scenarios of the IPCC, rather seems to both neglect continued shifts toward higher quality fuels in energy end-use and anticipate long-term stagnation or even deterioration of decarbonization of energy supply. The latter trend emerges in the scenarios primarily as a result of perceived resource scarcities and postulated slow development of alternative energy sources and would lead global energy systems of the 21st century back to the beginnings of the Industrial Revolution: to a coal-based economy.

Scenarios of the Future

Exactly 100 years ago, in April 1896, Svante Arrhenius published an article, "On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground" [30]. It was the first comprehensive study to analyze the "greenhouse effect" and to assess the implications of elevated concentrations of CO_2 (carbonic acid in the terminology of Arrhenius) in the atmosphere. He quantified the CO_2 emissions quoting estimates of his colleague Prof. Högborn indicating consumption of some 500 million tons of coal worldwide (and assessed them to equal the carbon uptake by weathering of rocks). The greenhouse effect and the potential of anthropogenic interference of CO_2 emissions from burning of fossil fuels are thus known to science for 100 years. (Cf. the discussion of "discovery by accident" versus an "attention management problem" by Tom Schelling and Harvey Brooks in this special issue.)

What would have been Arrhenius' scenario for future increases in these anthropogenic emissions? We do not known, as the study (wisely perhaps) presented the calculations parametrically for a range of CO_2 concentration levels from 200 to 900 ppmv (parts per million by volume), compared to the then estimated prevailing level of about 300 ppmv. And 100 years later, CO_2 concentrations have reached 360 ppmv [2] and numerous scenarios exist that attempt to project emission levels far out into the future. The IPCC (IS92 series [31]) developed one of the most influential of these scenarios.

Figure 5 summarizes the results of a recent evaluation of the IPCC scenarios ([32] in [2]) comparing the carbon intensity of primary energy for the six IPCC scenarios (IS92a to IS92f) with the range from other scenarios published in the literature. The most significant finding for the IPCC scenarios is that after the middle of the 21st century carbon intensities stay constant for all of the six scenarios developed. This represents in our viewpoint a certain lack in scenario richness, especially in view of the stated purpose to explore a wide range of future possible developments through the scenario exercise. Figure 5 also shows the corresponding decarbonization trends of the recent scenarios of the World Energy Council [15] that try to capture a broader spectrum of future developments in the energy sector. There, only one scenario (A2) portrays a similar picture of stagnating improvements in decarbonization as depicted by the IPCC scenarios.

The IS92 scenario assumptions of driving forces in the domain of energy technologies and resource availability appear restricted, especially when compared with the wide variation in input assumptions like population and economic growth. As a result, all of the

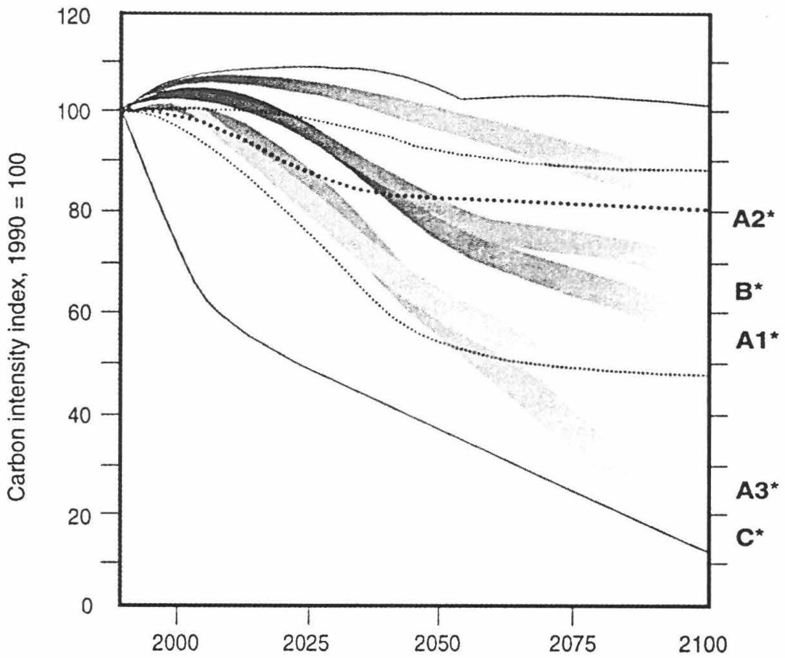

Fig. 5. Carbon intensity of primary energy, a comparison of future scenarios (index 1990 = 100): IS92a and range of IPCC scenarios (*dotted lines*); range of non-IPCC scenarios (*lines*); range of IIASA-WEC scenarios (*shaded lines, with asterisk*).

scenarios converge to quite similar long-term energy supply structures and hence to two clusters of carbon intensities, corresponding to the higher and the lower energy demand scenarios, respectively. A yet more pronounced scenario singularity can in fact also be observed for the geographical distribution of energy consumption (and emissions) in the IS92 scenario series (Table 4). Keeping in mind that scenarios are not intended as forecasts but rather are descriptions of alternative futures, it seems important to explore a wider spectrum of possibilities that illustrate possible tensions or congruences between economic development, energy consumption, and emissions on one side, and the preservation of the environment on the other. Technological change and changing consumer preferences

TABLE 4
Variations in the Basic Assumptions of the IPCC IS92 Scenarios (global data by 2100)

	Population (billions)	Emissions (GtC)	% Share of DCs in energy	% Share of coal in emissions	Carbon intensity (tC/toe)
IS92a	11.3	19.8	66	87	0.57
IS92b	11.3	18.6	68	93	0.55
IS92c	6.4	4.6	62	69	0.36
Is92d	6.4	9.9	67	84	0.33
IS92e	11.3	34.9	69	81	0.59
IS92f	17.6	25.9	65	84	0.64
Range	6.4–17.6	4.6–34.9	62–69	69–93	0.33–0.64
Minimum/maximum	2.8	7.6	1.1	1.3	1.8

Data source: Reference 31.

toward cleaner fuels that lead to decarbonization are certainly key parameters to explore in such future exercises.

Conclusion

The global energy system is decarbonizing, as measured by the reduction in the specific carbon emissions per unit of primary energy consumed. This trend appears continuous and persistent, albeit it proceeds at very slow rates of 0.3% per year. Should these historical trends continue, we might in fact be only half-way through the fossil fuel age that would draw to a close only late in the 22nd century.

The driving forces of decarbonization include both continued technological change in all domains of energy production, conversion, and end use as well as the quest for higher flexibility, convenience, and cleanliness of energy services demanded by consumers, especially as incomes rise. To an extent the energy sector "compensates" some of the more pronounced decarbonization trends in energy end use, reflecting resource endowments, technology availability, geopolitical considerations, as well as policy influence. Nevertheless, decarbonization is a pervasive phenomenon also in energy supply and conversion.

The long-term decarbonization trends indicate that the global energy system is moving in the right direction. This gives reason to be cautiously optimistic that development and the resulting economic growth, increased energy needs, and emissions could be reconciled with a precautionary policy of avoiding large-scale human interference with the climate system. The task of controlling energy-related carbon emissions, as daunting as it may appear from today's perspective, may in fact turn out to be less obstructive if indeed an acceleration of long-term structural change trends is called for rather than departure in an entirely new direction.

Conversely, it will simply not suffice to rely on "autonomous" structural change toward carbon-freer energy systems, especially considering the slow historical rates of decarbonization of 0.3% per year. They are dwarfed by historical an anticipated future growth rates in energy use and resulting carbon emissions. Substantial acceleration of decarbonization would thus entail both ambitious technological and policy changes. Whereas such changes are inherently difficult to anticipate, it is also a matter of fact that historically it was precisely structural changes that enabled us to improve quality and quantity of energy services. Such structural changes are rarely represented in studies of energy-environment interactions. This suggests that decarbonization and its driving forces may still be insufficiently captured in most models and scenarios of the long-term evolution of the energy system.

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