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Energy Gases: The Methane Age and Beyond

Nebojša Nakićenović

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IIASA
International Institute for Applied Systems Analysis □ A-2361 Laxenburg □ Austria
Telephone: +43 2236 715210 □ Telex: 079 137 iiasa a □ Telefax: +43 2236 71313

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Abstract

The combustion of fossil fuels results in the emissions of gases and pollutants that produce adverse ecological effects. Evidence is also accumulating that suggest they may also cause global climate change. The combustion gases that are connected with global climate change are primarily carbon dioxide (CO_2) and to a lesser degree methane (CH_4) (see Cole this volume). All of these gases already occur in low concentrations in the atmosphere and, in fact, together with other greenhouse gases, such as water vapor, have made the earth habitable. The risk, however, is that the additional emissions of greenhouse gases associated with energy-use and other human activities are rapidly increasing the atmospheric concentrations of these gases and may therefore lead to an additional global warming during the next century. While the greenhouse gases that result from energy-use are the most important cause of these concerns, the energy gases also offer a potential solution to this problem.

Natural gas consists mostly of methane and is a very potent greenhouse gas if released into the atmosphere, but after combustion occurs, the amount of carbon dioxide resulting is much smaller per unit primary energy in comparison to other fossil energy sources. Natural gas emits roughly one-half of the carbon dioxide in comparison to coal for the equal amount of energy. Thus, a possible shift to a methane economy during the next decades offers a genuine mitigation strategy. Beyond that, natural gas could pave the way for more environmentally compatible energy systems of the distant future that could use hydrogen and electricity, both of which are carbon-free energy carriers, that could be produced by non-fossil sources of primary energy. This transition to the methane age and beyond to carbon-free energy systems would enhance the reduction of other adverse impacts on the environment by human activities.

In fact, carbon dioxide emissions represent the largest mass flow of waste in comparison to all other anthropogenic activities. Current energy-related carbon dioxide emissions are in the order of 6 gigatons of carbon (GtC) or more than 20 $GtCO_2$. This is more than 20 times larger than, for example, global steel production of about 700 megatons (Mt). Decarbonization is a notion that denotes reduction of carbon dioxide emissions per unit primary energy and unit economic activity, and dematerialization refers to the

*Dr. Nebojša Nakićenović is 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.

reduction of materials used per unit economic activity. Decarbonization would also help reduce the emission of other energy pollutants and wastes, and it would also enhance the dematerialization in general. Other measures that would lead to decarbonization, in addition to a shift to methane economy, include efficiency improvements and energy conservation, carbon removal and storage or a shift to carbon-free sources of energy, such as solar and nuclear energy.

From Resource Scarcity to Decarbonization

In the aftermath of the so-called energy crisis of the early 1970s, a number of studies have been conducted to assess the long-term national and global energy prospects. In the wake of increasing energy prices and serious supply shortages, most of these studies focused on securing the long-term supply. Often they resulted in calls for commercializing large amounts of nonconventional fossil resources, such as oil shales, promoting nuclear power and fusion. A number of studies also considered renewable energy sources and solar energy as additional strategies for enhancing the supply of energy in the long run. In any case, the paradigm of oil shortage and depletion of conventional fossil resources predominated.

As the sophistication of methodological approaches for analyzing energy futures increased, research also shifted to the questions of improving efficiency, end-use of energy and enhancing conservation. The studies became more balanced in treating supply and demand. Today, the predominate question is how to reduce the adverse impacts of energy-use in the world while allowing for sufficient increase of energy services in the developing countries. This is a formidable task considering that global population is expected to double during the next century and that 80 percent of humanity shares less than 20 percent of global wealth. At the same time, it is becoming increasingly evident that the fossil energy resources are much more abundant than it was anticipated in the 1970s and early 1980s. Both resources and reserve bases of oil and natural gas have increased and, in fact, new natural gas discoveries have outpaced oil. The absolute finiteness of energy resources does not appear to be a problem facing humanity in the next few hundred years. The question is rather how to utilize the available energy resources in supplying adequate services while arresting the further environmental degradation and global warming.

Figure 1 illustrates this dilemma of the need to increase energy services and reduce the adverse impacts of energy-use. It shows per capita emissions of carbon dioxide and methane for the major world regions. The height of the bars gives the carbon dioxide and methane per capita emission in tons of carbon equivalent, while the width of the bars shows the population of the region. Four main sources of the greenhouse gas emissions are shown: carbon dioxide emissions resulting from coal, oil and natural gas consumption, and the last division represents the combined carbon dioxide emissions of all non-fossil sources, such as biomass burning and also includes all of the anthropogenic methane sources, both energy and non-energy.

The combined carbon dioxide and methane emissions are clearly the highest in the industrialized countries reaching 6 tons of carbon (tC) equivalent per capita in North America and Australia, and are not much lower in some parts of the former Eastern Europe and Soviet Union. For example, the eastern states of Germany that constituted the former German Democratic Republic had almost the same per capita carbon dioxide emissions as the United States, but had a much lower standard of living and energy services. This was due to the high degree of inefficiency of the energy systems, a very high share of coal in the energy mix and a high level of material use per unit economic activity in general. This similar situation still exists in the economies of Eastern Europe, Russia and the other Commonwealth Republics.

In contrast to the energy-intensive economies in Eastern Europe, Japan and Western European countries achieve much higher levels of economic activities with a substantially lower per capita energy consumption and greenhouse gas emissions. The standards of living in most of the West European countries are comparable to those of the United States meanwhile the emissions of greenhouse gases are half as large. The variation is in the order of 3 tC equivalent per capita in the more efficient industrial countries to twice that amount in North America. These regions constitute about 20 percent of the world population today.

The other 80 percent of the world population accounts for only 20 percent of the global carbon dioxide and methane emissions. Figure 1 clearly shows this disparity in the emissions levels. For example, China with one billion people has combined carbon dioxide and methane emissions that barely exceed 1 tC per capita. It is also of interest to observe that the structure of the emissions is different in most developing countries in comparison to the industrialized countries. Using China again for an example we see that most of the emissions are due to coal consumption, non-fossil carbon dioxide and methane emissions indicating low shares of oil and natural gas in the primary energy mix. As the developing countries continue to grow, the total emissions will increase and if the development process continues, per capita emissions will most likely also increase. The current plans in India and China are to expand the coal production and use reaching perhaps 3 Gt in a few decades. This source of carbon dioxide alone would represent half of the current total emissions. Therefore, it is quite apparent that the economic and social development in the world are strong determinants of future greenhouse gas emissions. The potential risks of climate change, on the other side, suggest a need to slow down the growth of emissions and even decrease them in the next century. There is a need to reconcile this opening gap between the energy needs for development and reduction of emissions as a precaution to guard against global warming.

Energy Intensity and Decarbonization

Global emissions will continue to increase along with further economic development and population growth in the world. The most important determinants of future energy-related carbon dioxide emissions could be represented as products of the following factors: population growth, per capita value added, energy per value added and carbon emissions per energy on one side, and total carbon dioxide emissions on the other side of the identity (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 percent per year. The longer-term historical growth rates since 1800 have been about 1 percent

[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 CO_2 emissions can be described by changes in these four factors.

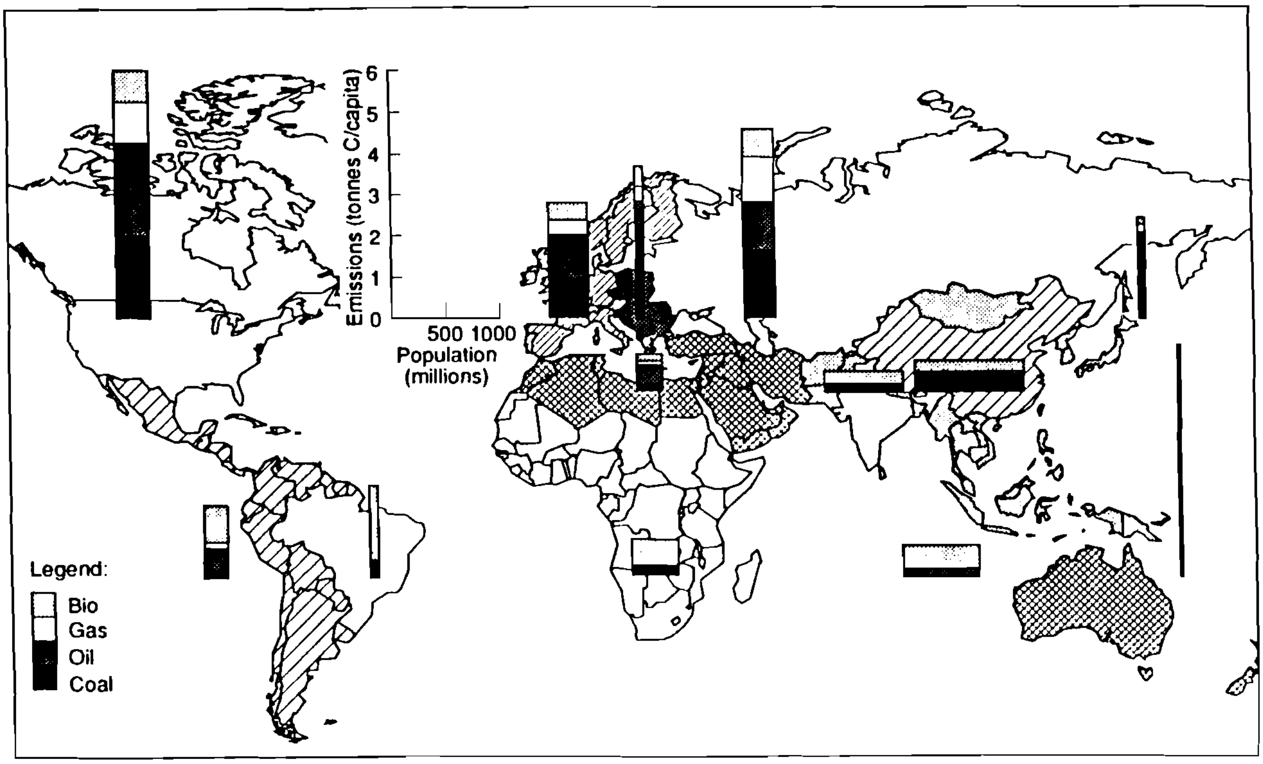

Figure 1: Industrial CO_2 and other greenhouse gas emissions per capita, versus population, for different world regions and by energy source in tons of carbon per capita. Other greenhouse gases include CO_2 from deforestation and anthropogenic methane emissions (1 kg CH_4 = 21 kg CO_2).

per year. Most of the population projections expect at least another doubling during the next century e.g., World Bank (Vu, 1985) and United Nations Projections (1990). 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. In contrast, energy intensity per unit value added has been decreasing at a rate of about 1 percent per year since the 1860s and at about 2 percent 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 percent per year.

Figure 2 shows the extent of decarbonization in the world as the change in the ratio of average carbon dioxide emissions per unit of energy consumed. It occurred due to the gradual replacement of carbon rich by carbon poorer sources of energy. First, wood and coal were replaced by oil and later natural gas and more recently to a lesser degree by nuclear energy. Figure 2 also illustrates decarbonization rates implicit in a number of global energy scenarios. For example, the United States Environment Protection Agency's Rapidly Changing World (RCW) scenario actually anticipates an increase of carbon intensity in the world, and thus a trend reversal of the historical development (EPA, 1990). This is primarily due to a heavy reliance on coal in this scenario. The Intergovernmental Panel on Climate Change (IPCC) has developed a whole range of scenarios, the median one is shown in Figure 2 and anticipates continuation of the current level of carbon emissions per unit energy consumed in the world (IPCC, 1992). The Environmentally Compatible Scenario (ECS'92) developed at IIASA in 1992 (Nakićenović *et al.*, 1993) and the World Energy Council scenario (WEC, 1992) represent a continuation of the historical trends

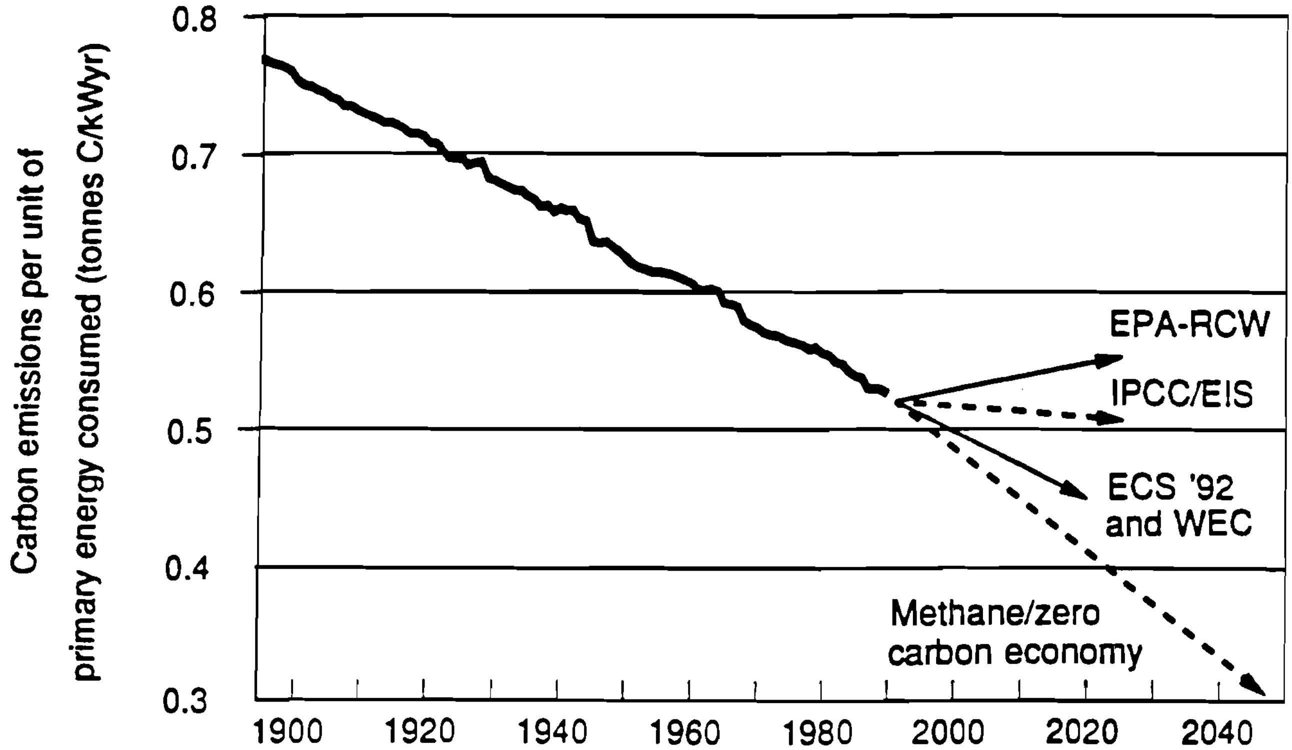

Figure 2: Global decarbonization of energy since 1900 and scenarios for the future in tons of carbon per kilowatt year (tC/kWyr) of energy. Four future scenarios are shown: EPA's rapidly changing world, the IPCC Energy and Industry Subgroup's median scenario and IIASA's Environmentally Compatible Scenario as well as the World Energy Council's reference scenario with basically the same carbon intensity of energy. The lower dashed line symbolizes the need to achieve lower emissions.

and thus, a certain degree of decarbonization in the future. The lower dashed line with the arrow into the future in Figure 2 symbolizes the need to achieve even higher rates of decarbonization in order to off set future population and economic growth in the world. A scenario that relies on the higher contribution of energy gases in primary energy consumption could achieve this goal and such a scenario will be described in this paper. To stabilize energy-related carbon emissions at current levels of almost 6 GtC for a primary energy demand between 15 and 18 Terawatt years (TWyr) by the year 2020, compared to 12 TWyr in 1992, the rate of decarbonization would have to range between 0.8 and 1.4 percent per year, i.e., two to four times the rates achieved in the past.

In addition to the decarbonization in energy, one must also consider the reduction of energy intensity in economic activities as a second factor that is also causing a decrease in the carbon dioxide emissions mentioned above. Figure 3 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 toward 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. 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

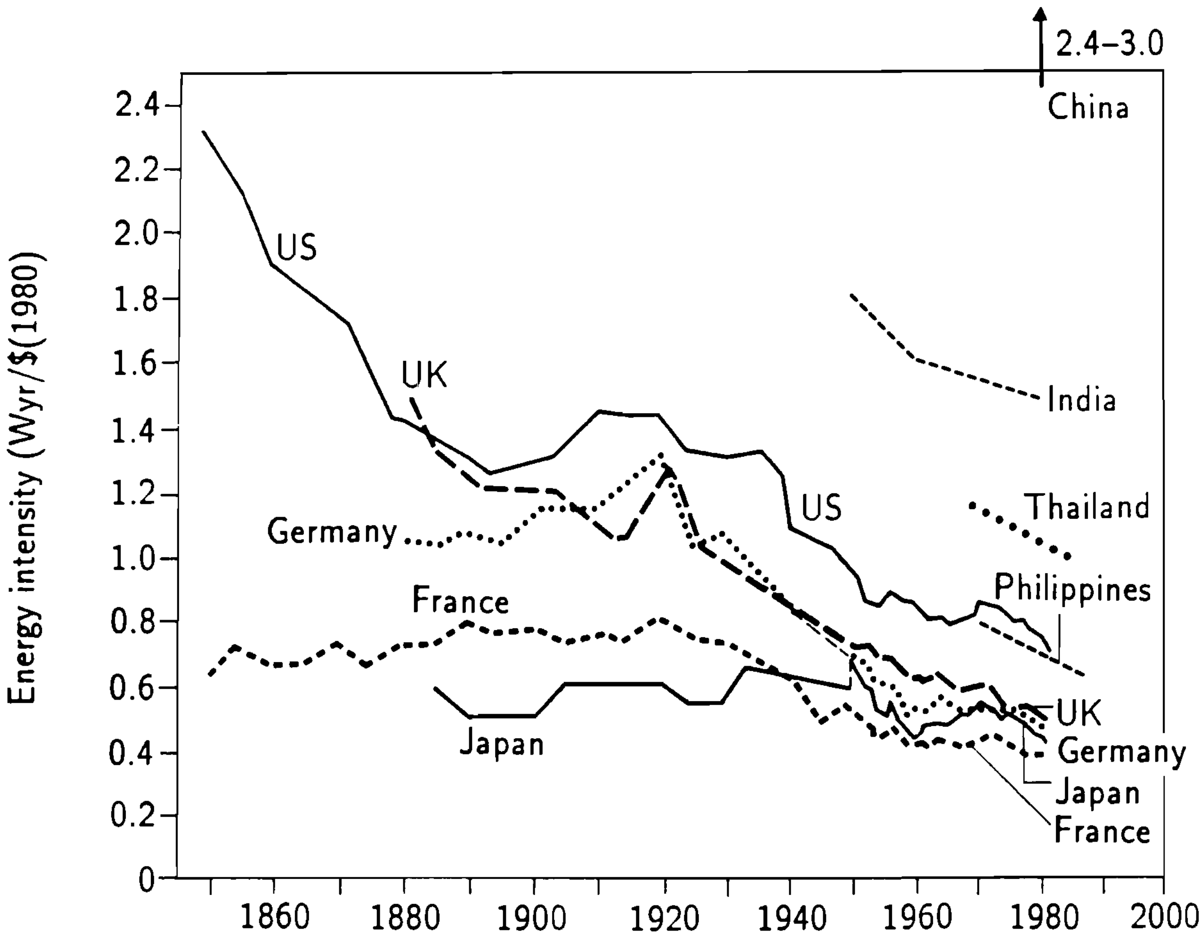

Figure 3: Primary energy intensity, including biomass, of value added in Wyr per constant GDP in 1980 dollars. Primary electricity is accounted as 1 Wyr = 8.76 kWh (equivalence method).

are similar to those of the United States about a century ago. The reforming countries of Eastern Europe and the former Soviet Union have relatively high energy intensities ranging between the United States and India on the high end.

Figure 4 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 highest 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 of value added has been about 1.3 percent per year because decarbonization of energy occurs at about 0.3 percent per year and reduction of energy intensity of value added at about 1 percent per year. This falls short of what is required to offset the effects of global economic growth, with rates of about 3 percent per year. This means that the global carbon dioxide emissions have been increasing at about 1.7 percent per year during most of this century. Today, global carbon dioxide emissions are still increasing at close to 2 percent per year implying

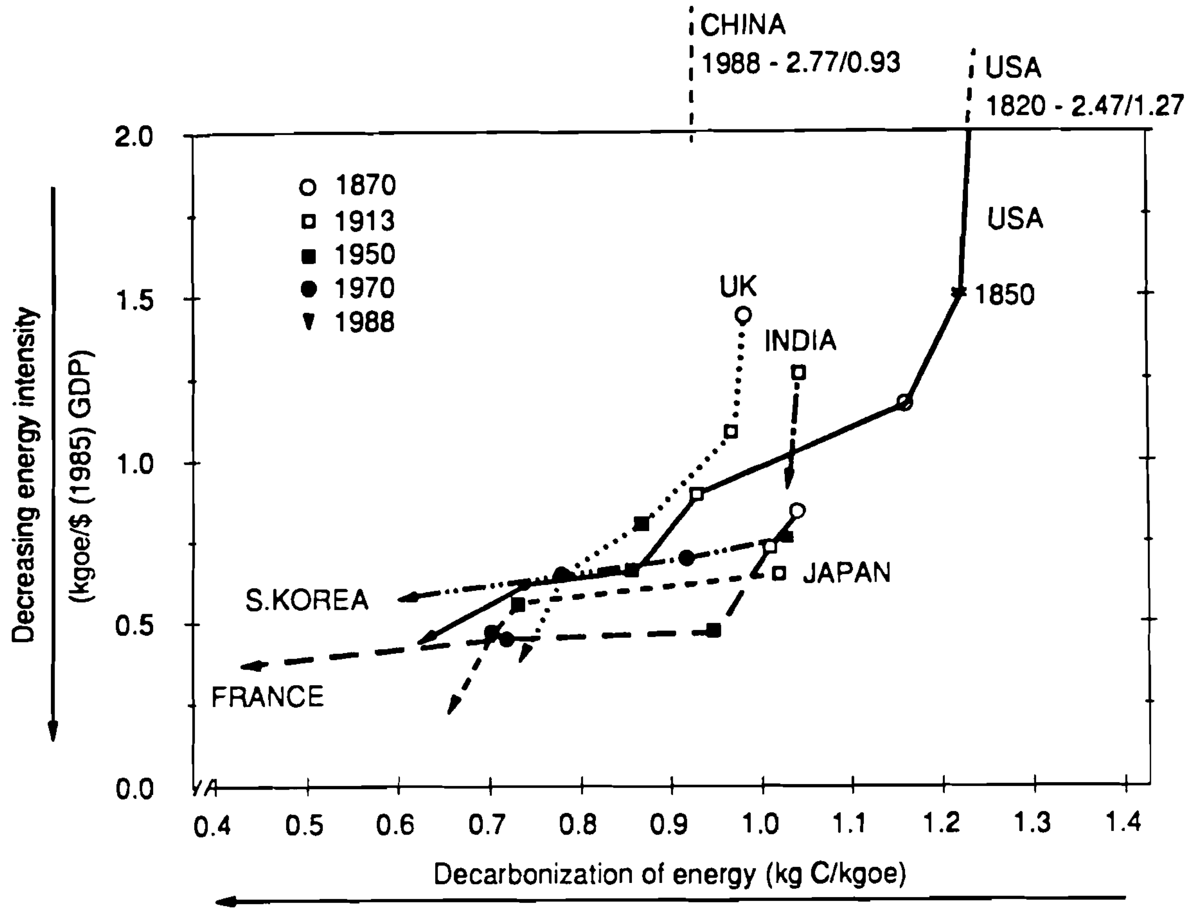

Figure 4: Global decarbonization and deintensification of energy in kg of C per kg oil-equivalent (kgoe), and in kgoe per $1000 GDP (Grübler, 1991).

a doubling before the 2030s and this is in fact quite close to the emissions levels projected in some of the global scenarios.

Figure 5 gives an overview of the major energy scenarios for the world. It shows the current energy-related carbon emissions of almost 6 GtC in 1990 and the anticipated development of emissions during the next three decades. It shows the EPA's RCW scenario with highest emissions exceeding 10 GtC by 2020 (EPA, 1990). It shows again the IPCC mid-range scenario with slightly lower emissions, although it should be mentioned here that the lowest IPCC scenarios actually lead to a reduction of global emissions with respect to 1990 during the next the century (IPCC, 1992). Figure 5 also shows the WEC reference scenario and the ECS'92 scenario from IIASA in the lower range (Nakićenović *et al.*, 1993).

The shaded area represents what could be called "the consensus view" of future energy emissions. This range of emissions is based on assessments of the International Energy Workshop (IEW). Since 1981, Stanford University and IIASA have jointly organized a series of IEW Workshops with the aim of comparing energy projections made by different groups around the world and analyzing their differences (Manne and Schrattenholzer, 1992). The projections are analyzed on the basis of a standardized poll. The median response derived from the polls corresponds, in our interpretation, to the "consensus view" and reflects the "conventional wisdom" of the international energy community. These projections mostly describe surprise-free, business-as-usual, middle-of-the-road scenarios.

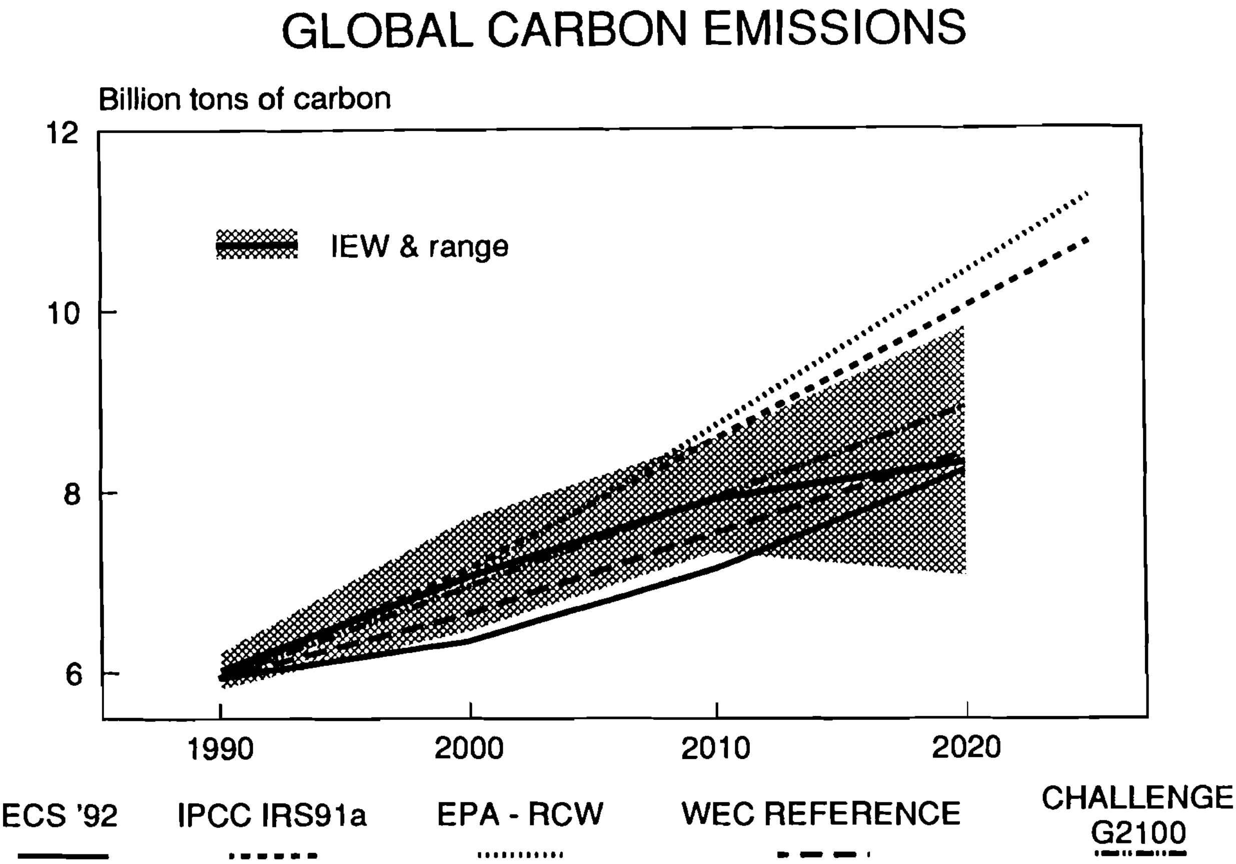

Figure 5: Global primary energy consumption 1990–2020; range of IIASA's IEW projections and the scenarios including EPA's RCW, WEC reference scenario, IPCC/IRS91a, IIASA's ECS'92 and IIASA's CHALLENGE G2100.

According to the results of the most recent IEW poll (Manne and Schrattenholzer, 1992), today's projections anticipate a more modest growth of global primary energy consumption between now and the year 2020 than the long-term trend of 2 percent per year. The IEW median projection corresponds to an average annual growth rate of 1.4 percent, which would lead to an absolute increase from 11.8 to 18 TWyr/yr.

Together the IEW projections comparisons show that the energy community is anticipating a substantial increase in global carbon dioxide emissions during the next 30 years, the median represents an increase of more than 30 percent. On the other hand, the international assessments such as the IPCC process clearly point to the need to reduce the emissions to the extent possible. Furthermore, the Framework Convention on Climate Change that was signed by 153 countries at the Rio de Janiero Summit in 1992, to be ratified in the near future, calls for reduction of emissions as a precautionary principle toward arresting climate change (International Negotiating Committee, 1992).

Carbon Dioxide Mitigation

There are basically three courses of action as far as energy is concerned in this context. First is to mitigate the emissions in the future, the second is to deal with the adverse impacts of climate change such as to compensate for incurred damages, and the last one is to adapt to climate change such as to learn to live in warmer weather. All of these alternatives are surrounded by numerous uncertainties. Mitigation measures and options have been studied in greater detail than impacts and adaptation. In this paper, mitigation strategies that involve greater use of energy gases in the future with the intention of reducing emissions of greenhouse gases will be considered. For completeness, a brief overview of other mitigation options will be given. The technological and economic measures to minimize energy-related greenhouse gases emissions include efficiency improvements, conservation, enhanced use of low-carbon fuels, carbon-free sources of energy and other options such as afforestation, enhancement of natural carbon sinks and creation of new ones. Thus, they encompass the whole energy system from primary energy extraction to actual energy-use including various conversion, transport, distribution and end-use systems.

Four types of technological strategies can be distinguished for stabilizing and eventually also reducing energy-related carbon dioxide emissions. The first is an incremental one, emphasizing energy efficiency improvements (see also Mills, this volume). In this case, devices or operational practices are replaced by more efficient ones without major changes in the technology of the device itself or technologies upstream of the energy chain. For example, this could mean replacing a refrigerator or a gas-fired power plant by more efficient vintages while using the same electricity and fuel supply chains. Three other strategies are more radical. They include changes in technologies design and operational practices with and without changes in the energy chains. These are changes in technological "trajectories". In the simplest case, the end-use technology is changed but with the same upstream energy chain, e.g., switching from a gasoline to diesel car. Alternatively, the end-use and conversion technologies may stay the same but the primary energy input changes, such as switching from an oil to a gas-fired combined-cycle power plant. Finally, it is possible to change the trajectories of end-use, conversion and primary energy supply technologies (e.g., the whole energy chain), such as switching from a gasoline car with oil as the primary energy source to an electric vehicle with photovoltaic panels.

There is a clear ranking of the four different technological strategies with regard to costs (Nakićenović *et al.*, 1993). The incremental improvements have the lowest cost because they do not require changes in technological trajectories. These are also the easiest to implement and take the shortest time. They are followed by measures that involve a change in the primary energy source and those involving changes in end-use technologies. Generally, the most difficult and costly measures to implement will be those where both end-use and primary energy supply technologies have to be changed. Here, changes are required in all related components of the energy system, meaning that entirely new energy chains have to be developed and built: new energy supply systems, infrastructures, diffusion of new end-use devices and delivery outlets.

A similar conclusion also holds for carbon removal and disposal technologies. The more remote from the disposal site and diluted the source of emissions, the more difficult and expensive are the carbon control measures. Again, demand-side measures such as improved efficiency and emission avoidance altogether are cheaper than post-combustion scrubbing of stack gases which, in turn, is cheaper than carbon removal from the atmosphere by e.g., micro-algae carbon fixation. From this perspective, it is not surprising that most assessments of mitigation options identify energy efficiency improvements and end-use demand management measures amongst the most cost-effective measures, followed by fuel substitution. More traditional energy supply-side measures, or even extensive industrial and infrastructural restructuring measures, are generally more difficult to implement and are certainly also more expensive.

In this paper, implications for carbon dioxide and methane emissions of increasing reliance on combustion of natural gas in the future are considered. Although, natural gas (mostly methane) results in lower specific carbon dioxide emissions than other fossil fuels it has not been explored in detail as a mitigation strategy for arresting global warming. Often, reservations are expressed in connection with wider use of natural gas because methane is a potent greenhouse gas. We will demonstrate that a stronger reliance on natural gas in the future would lead to relatively modest increases in carbon dioxide emissions compared with scenarios that are based on more traditional mitigation strategies. We will also show that methane emissions do not pose a major problem provided that leakage rates could be maintained at least at levels of up to 4 percent or reduced in the future.

Methane as an Energy Gas of Choice

A global scenario with a major share of natural gas in primary energy is of interest for several reasons. First, the historical replacement of coal by oil and later by natural gas points in this direction. Primary energy substitution (Marchetti and Nakićenović, 1979 and Nakićenović, 1990) suggest a likelihood that natural gas would in fact become globally the major source of energy during the next century. Second, new markets for natural gas appear to be opening also because it is more desirable than other fossil fuels with respect to the environment. Methane has the highest hydrogen to carbon atomic ratio and lowest carbon dioxide emissions of all fossil fuels. The historical transition from wood to coal to oil and to gas resulted in gradual decarbonization of energy or to an increasing hydrogen to carbon ratio of global energy consumption. Natural gas also highly desirable from the point of regional environment because of minimal sulfur dioxide and particulate emissions. Third, recent 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 Earth's crust (see Wymar; Gold; Korvalkin; this volume). There is an increasing evidence of multiple economic and geopolitical benefits from a worldwide shift to natural gas (Lee *et al.*, 1988).

Figure 6 shows primary energy substitution in the world. The competitive struggle between five main sources of primary energy is dynamic and quite regular so that it can be described by relatively simple rules (Marchetti and Nakićenović, 1979; Nakićenović 1979 and 1986). The dynamics of this process are captured by logistic equations that describe the rise of new energy sources and the senescence of old ones. The substitution process clearly indicates the dominance of coal as the major energy source between the 1880s and 1960s after a long period during which fuel wood (and other traditional energy sources) were in the lead. The massive expansion of railroads, the growth of steel, steamships and many other sectors are associated with and based on the 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 modern industries.

Figure 6 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

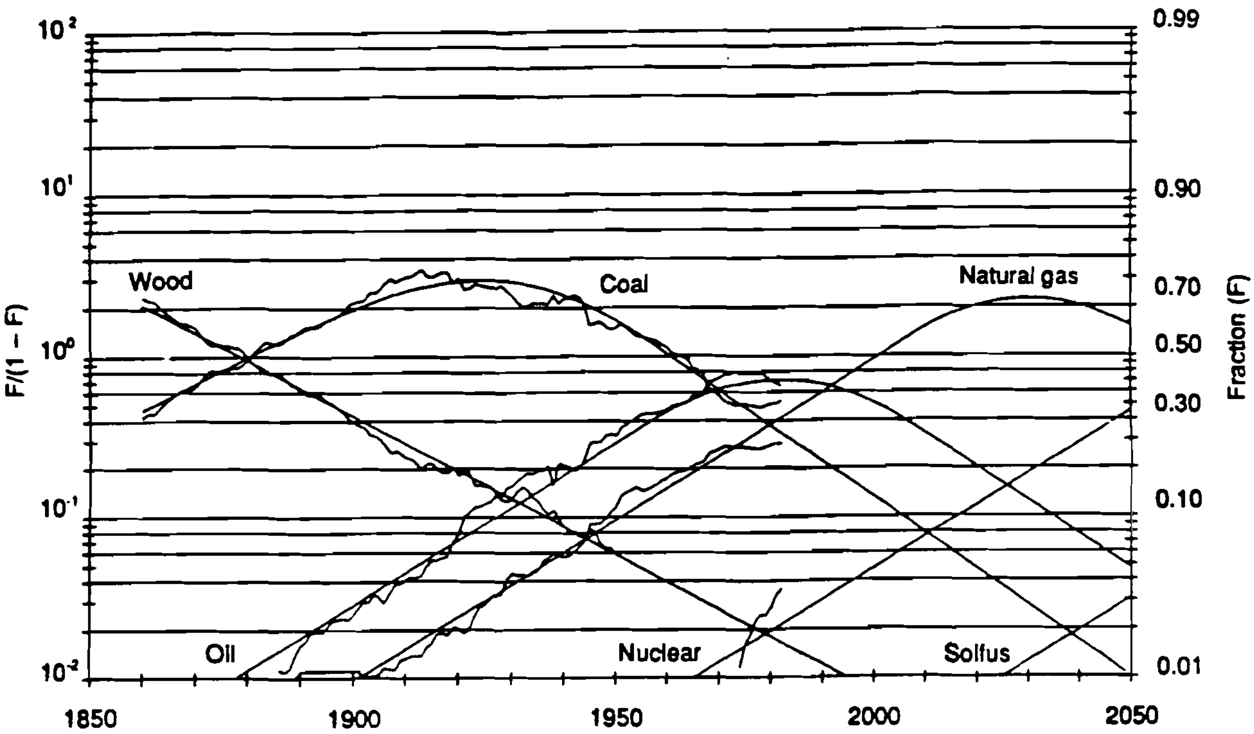

Figure 6: Global primary energy substitution. Smooth lines represent model calculations and jagged lines are historical data. "Solfus" is a term employed to describe a major new energy technology, for example solar or fusion.

such an explorative "look" into the future, additional assumptions are required because potential new competitors, such as nuclear, solar and other renewables, have not yet captured sufficient market shares to allow estimation of their penetration rates. In order to explore the behavior of the logistic substitution model when the competition between energy sources is extended into the future, we assume that nuclear energy would diffuse at comparable rates to oil and natural gas half a century earlier. This implies that the current share of nuclear energy in the world would be unchanged for a decade when growth would resume but at a lower rate than in the past. Nevertheless, such a scenario would require a new generation of nuclear installations and today such prospects are at best questionable. This leaves natural gas with the lion's share in primary energy during 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. "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 that natural gas would saturate (Marchetti and Nakićenović, 1979 and Nakićenović 1990).

Figure 6 demonstrates that the diffusion of new energy sources and the replacement of older by newer ones takes on the order of almost 100 years at the global level. All too often there is over-optimism about how rapid the diffusion of new technologies might be. The historography (history and geography) of technological change clearly demonstrates that the diffusion of innovations with some economic and social significance may take on the order of decades and sometimes even centuries. Longer periods are required for the pervasive transformation of economic activities by a whole cluster of technological and organizational innovations. The analysis of primary energy substitution and market penetration suggests that natural gas would 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, the primary energy substitution implies a gradual continuation of the decarbonization of energy in the world. The methane economy could represent a first step toward a carbon-free energy future. For this reason the dynamics of primary energy substitution is used as a scenario for determining carbon dioxide and methane emissions associated with a stronger reliance on natural gas as a fuel of choice in the future. This approach was employed more than 15 years ago to determine future energy-related carbon dioxide emissions scenarios and was used again a few years ago in a more comprehensive assessment of future carbon dioxide and methane emissions (Marchetti, 1979, Ausubel *et al.*, 1988 and Victor, 1990).

Market penetration and substitution analysis provides a method for calculating shares of different primary energy sources in the world. What is required is the scenario describing the levels of global primary energy consumption. Thereafter, the calculation of carbon dioxide emissions becomes a straightforward matter.[2]

We examine a methane economy scenario with two overall levels of energy consumption in the world, both are population driven and based on the World Bank estimates (Vu, 1985). One variant of the methane economy scenario, the "efficiency case", holds the per capita energy consumption at the current level so that the primary energy consumption increases the same as the world population. This leads to a primary energy consumption rate of about 20 TWyr/yr by the end of the next century when the population reaches 10 billion. The second variant, the "long wave case", stipulates another growth pulse in per capita primary energy consumption leading to a three-fold increase by the end of the next century and to staggering levels of global primary energy consumption. The two cases cover a large domain encompassing between them some of the highest and lowest projections from the literature. Figure 7 shows the primary energy consumption in the two variants of the methane economy scenario.

The carbon dioxide emissions are simply calculated as the product of the market shares of different energy sources (Figure 6), the scenario of global primary energy consumption (Figure 7) and individual emissions factors (given in footnote 2). Figure 8 shows the resulting carbon dioxide emissions for the two cases. In the efficiency variant, emissions stay roughly constant over the next 50 years, peaking shortly before 2050 and falling thereafter. The results of this case are close to the lowest of the IPCC scenarios and consistent with gradual stabilization of atmospheric carbon dioxide concentrations (IPCC, 1992). In the long-wave case, emissions peak steeply at a level close to 15 GtC per year shortly before 2050 and also decline thereafter falling to 7 GtC in the year 2100. The two cases bracket virtually all reasonable scenarios of primary energy consumption in the future while they result in substantially lower carbon dioxide emissions. Because the same market shares are used for both variants, the scenario has the same carbon intensity of energy in both cases. In fact, it achieves high decarbonization rates in the world, higher than those experienced in the past (Figure 2) and higher than assumed in majority of other energy and carbon dioxide projections.

[2]The following carbon dioxide emissions factors per unit energy (tce): Wood 0.844 tC/kWyr; coal 0.735 tC/kWyr; Oil 0.849 tC/kWyr and natural gas 0.442 tC/kWyr (Ausubel *et al.*, 1988).

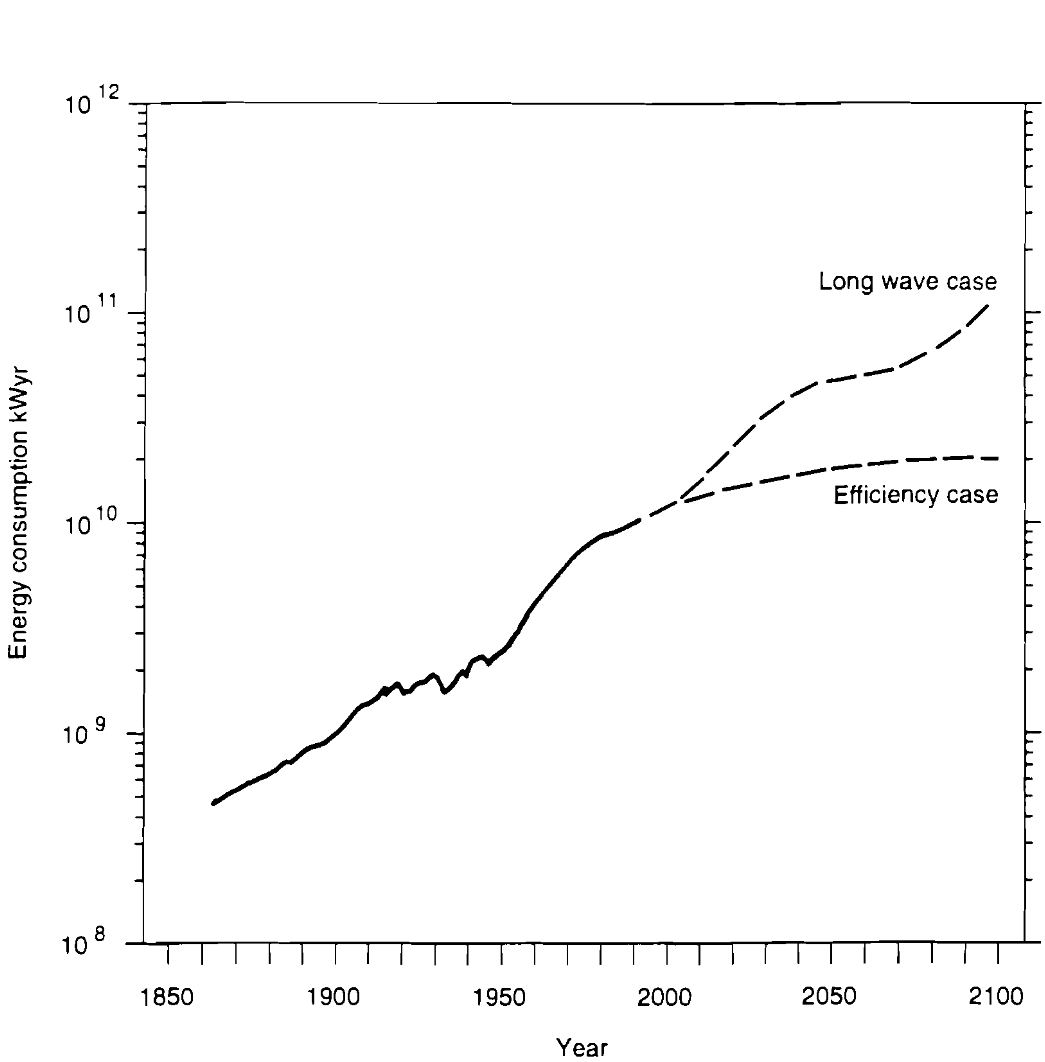

Figure 7: Primary energy consumption, historical data and the two variants of the methane economy scenario.

Energy Scenarios and Decarbonization

Table 1 summarizes the structure of current primary and final energy supply and resulting carbon emissions as well as a range of scenarios for the period 2020 to 2025. As a measure of the degree of decarbonization, we calculate the primary energy carbon intensity, i.e., total energy-related carbon emissions divided by the total primary energy consumption. The efficiency case of the methane economy scenario is compared with five other scenarios.

Two views of the future emerge from Table 1 (see also Figure 2). One view implies a discontinuity in the historically observed trend of decarbonization of energy systems. Instead, the fuel mix becomes more carbon intensive. This is due to increased reliance on coal and synthetic fuel production in the scenarios. The EPA's RCW and (to a lesser degree) the IPCC/EIS scenario are examples (EPA, 1990 and EIS, 1991). A second view adopts basically a "dynamics-as-usual" perspective, which is a continuation of historical trends in energy decarbonization as, for instance, reflected in the ECS'92 scenario

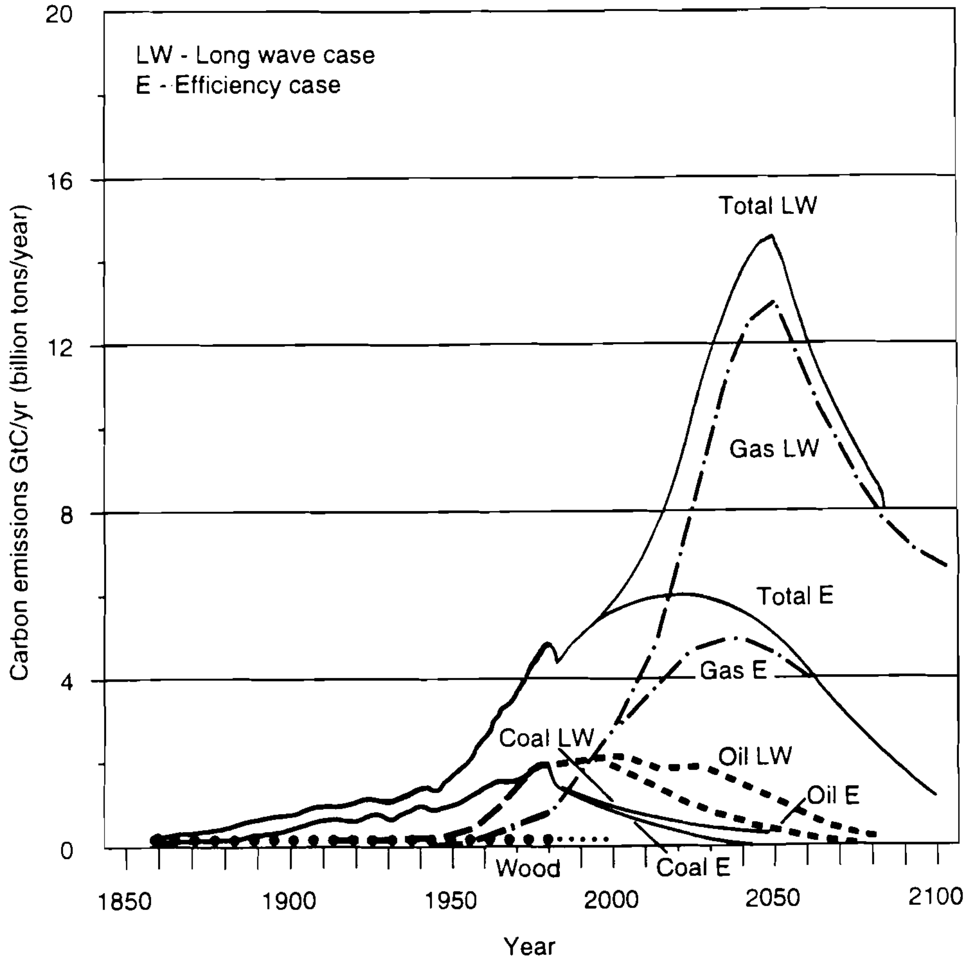

Figure 8: Global carbon dioxide emissions in GtC/yr, historical data and the two variants of the methane economy scenario, E denotes the efficiency and LW the long-wave variant.

(Nakićenović *et al.*, 1993) or the recent reference scenario of the World Energy Council (WEC, 1992). However, these improvements, as impressive as they are especially in comparison with other scenarios, are not sufficient to reverse the rising trend in global energy-related carbon emissions. Both scenarios still result in global emissions between 8.1 and 8.4 GtC by the year 2020.

In comparison, the methane economy scenario is more dynamic. Carbon intensity falls because the increased natural gas use "bridges" the time period to a massive market penetration of zero-carbon energy sources such as solar or nuclear in the second half of the 21st century. Table 1 reproduces the efficiency variant of the methane economy scenario. The implied energy efficiency improvement strategy results in a primary energy demand of only some 15 TWyr by the year 2025.[3] This, together with a drastic shift in the energy supply structure (natural gas accounts for 68 percent of primary energy

[3]Traditional biomass uses (currently estimated at 1.5 TWyr) are excluded in the scenario. If included, total energy demand would be quite close (10 to 15 percent lower) to the ECS'92 or the WEC scenario.

Table 1: Primary and final energy supply, carbon emissions and carbon intensity, 1990 and scenarios for the period 2020 to 2025, in TWyr and GtC.

	1990	IPCC/ EIS 2025	EPA- RCW 2025	WEC- reference 2020	IIASA ECS'92 2020	"CH_4 economy" 2025[a]	RIGES 2025
Primary energy supply, TWyr							
Coal	2.94	7.56	8.73	4.55	3.87	0.53	2.82
Oil	4.19	7.07	4.96	5.26	6.20	1.92	2.43[c]
Gas	2.22	5.48	3.09	3.95	3.92	10.59	2.95[c]
Non-fossil	2.35	4.53	3.70	5.16	4.10	2.30[b]	7.06[c]
Total	11.70	24.64	20.49	18.92	18.10	15.34[b]	>15.26[c]
Final energy consumption, TWyr							
Coal	1.22	3.28	4.09	n.a.	1.58	n.a.	2.16
Oil	3.52	5.89	5.12	n.a.	5.06	n.a.	2.43
Gas	1.42	4.04	2.52	n.a.	2.54	n.a.	1.87
Electricity & heat	1.10	3.61	2.81	2.59	2.29	n.a.	2.42
Other	1.20	1.08	–	n.a.	1.37	n.a.	3.52
Total	8.46	17.90	14.54	n.a.	12.85	n.a.	12.40
Carbon emission, GtC							
Final energy use	3.02	7.77	7.31	n.a.	5.12	n.a.	3.95
Energy sector	2.48	4.68	3.81	n.a.	3.53	n.a.	1.02
Total[a]	5.50	12.45	11.12	8.40	8.06	6.16	4.97
Carbon intensity (tC/kWyr)							
Primary energy	0.470	0.505	0.547	0.444	0.445	0.402	>0.330
Final energy	0.357	0.434	0.503	n.a.	0.398	n.a.	0.319

[a]Efficiency scenario.
[b]Excluding biomass.
[c]For oil, gas, geothermal, and intermittent renewables only secondary energy equivalent. Primary energy requirements, therefore, would be higher. This uncertainty also affects the primary energy carbon intensity.

supply by 2025), is reflected in carbon emissions of 6.2 GtC, i.e., basically a stabilization of current emission levels.

A Renewables-Intensive Global Energy Scenario (RIGES) has been suggested by Johansson *et al.*, (1992). Final energy demand of 12.4 TWyr is similar to the ECS'92 scenario described above. RIGES suggests that renewables would be competitive against fossil fuels and could penetrate massively as primary energy supply. Sustainable biomass and other renewables account for close to 43 percent of primary/secondary energy supply (>15.3 TWyr) by the year 2025.[4] It must be emphasized, however, that such a rapid market penetration of non-fossils in this scenario is without precedent for any primary energy source in history. For comparison, it took about 80 years for the market share of oil to grow to 40 percent of the global primary energy supply. The carbon emissions in RIGES would amount to 5 GtC per year, i.e., result in a stabilization (even slight reduction) of current energy-related carbon dioxide emissions.

[4]Primary energy production is only given for biomass and coal. For nuclear and hydro we have assumed a substitution equivalent based on the average efficiency of fossil electricity generation in the scenario (40 percent). For oil, gas, geothermal, and intermittent renewables only secondary energy equivalents are given. This also explains why the primary energy carbon intensity of RIGES is not presented in Figure 2.

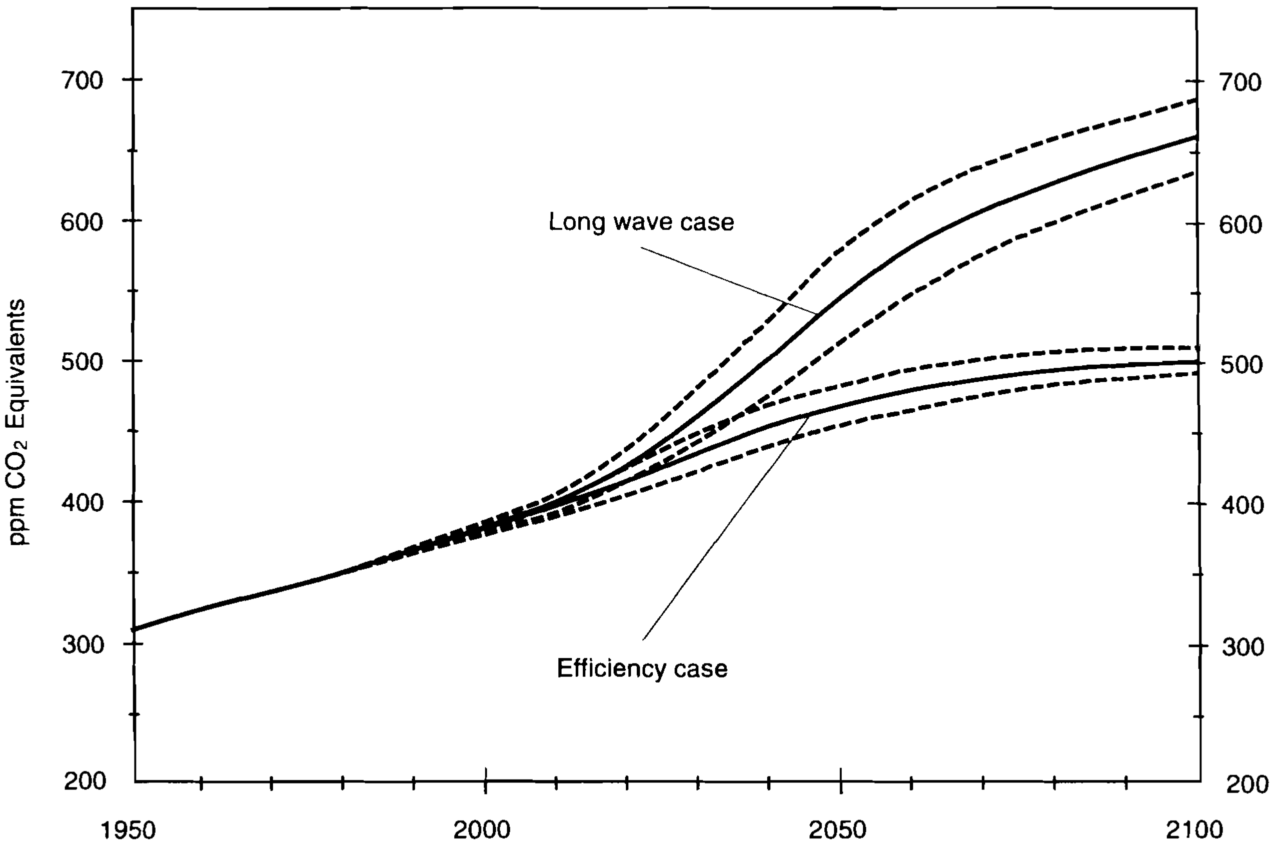

Figure 9: Atmospheric CO_2 and CH_4 concentrations from methane economy scenario expressed as CO_2 equivalents in ppm. Simple models of CO_2 and CH_4 concentrations and different values for CH_4 forcing have been used for estimating CO_2 equivalents of CH_4 concentrations. Higher set of curves are for the long wave and lower ones are for the efficiency case. The lower dotted curves show only CO_2 emissions, solid lines are CO_2 and CH_4 emissions for 2.5 percent leakage, and higher dotted curves for 4 percent leakage and high CH_4 forcing.

Methane and Carbon Dioxide Emissions

Carbon dioxide is the major energy-related source of global warming and the most important single greenhouse gas. Methane is also a natural constituent of air, arising from many natural processes. Recent increases in the concentration of atmospheric methane is usually attributed to diverse anthropogenic activities such as the growth of animal population, rice production and organic waste depositories. However, using methane in the energy system also contributes to the atmospheric increases. Major energy-related sources of methane come from coal mining, oil and natural gas production and natural gas transport, distribution and end-use (see Clayton and others, this volume).

Figure 9 shows the atmospheric carbon dioxide concentrations that result from the methane economy scenario corrected for the methane leakage. Simple models of atmospheric carbon dioxide and methane concentrations have been used (Ausubel *et al.*, 1988; Victor, 1990; and Grübler and Fujii 1991). For carbon dioxide, the airborne fraction of close to a half of annual emissions was used together with a slow decay of atmospheric concentrations. Methane leaks from the natural gas extraction, supply and distribution system are assumed to be 2.5 percent and methane is assumed 24 times as effective as carbon dioxide in greenhouse forcing on volume basis. The dotted lines in Figure 9 are for two additional calculations, one without leakage of natural gas (methane emissions from coal are included) and a methane forcing of 16 (low case), and the other with 4 percent leakage and a methane forcing of 32 (high case).[5] The atmospheric concentrations of carbon dioxide and methane are given in ppm of CO_2 equivalents. For this calculation, methane concentrations are converted to CO_2 equivalents using the methane conversion factors discussed above and methane atmospheric lifetime of 9.6 years.

This sensitivity analysis of methane emissions inclusion indicates that the methane economy scenario yields substantial reductions in greenhouse gas emissions and that it is robust even when large methane leaks are included. However, it is also evident that the role of methane leaks is not trivial. As energy-use increases, especially in the long wave variant, the problem of methane leaks becomes more important (Victor, 1990). This means that the greenhouse forcing due to increased levels of energy consumption with the same structure of the energy system is not linear. The finding identifies the additional advantage of lower energy scenarios toward the absolute and relative reduction of greenhouse gas emissions.

The required acceleration of the rate of decarbonization over the ones achieved historically and projected for the future in most energy scenarios illustrates the difficulty of achieving stabilization of energy-related carbon emissions under the premises of population growth and economic development. Very massive restructuring of future energy systems alongside vigorous efficiency improvement efforts will be required to come close to such a global target.

Methane Economy as a Bridge to Hydrogen

The analysis of the methane economy scenario has demonstrated that it achieves substantial carbon dioxide emissions reductions during the next century compared with alternative scenarios that rely more on other fossil energy sources in the future. As such the methane economy could make a significant contribution toward emissions reduction, but it is important to observe that most of the carbon dioxide would be originating from natural gas. Thus, further mitigation in this scenario would have to be focused on natural gas itself. This means that ways have to be investigated for limiting carbon emissions associated with natural gas use.

There are basically two alternative approaches in reducing carbon dioxide emissions from methane use, one is to remove carbon after combustion and the other before. In the first case, the most promising technologies involve carbon scrubbing from flue gases. There are three main scrubbing processes that could be used: chemical and physical absorption, cryogenic distillation, and membrane separation (Nakićenović, 1993). Chemical absorption process is widely used to remove SO_x and NO_x from flue gases and there are a few pilot plants with carbon dioxide removal by the same method. The various absorbents include potassium carbonate and amines. Scrubbing would clearly increase energy costs. The mono-ethanol-amine process would for example increase electricity costs by perhaps 80 percent leading to carbon dioxide mitigation costs of about $140 per tC removed (Blok

[5]Two methane forcing factors compared to carbon dioxide are used to encompass the range given in the literature, the high factor of 32 and low one of 16 (Victor, 1990).

et al., 1991 and Nakićenović, *et al.*, 1993). The major problems associated with scrubbing are to reduce the costs and minimize losses in plant efficiency due to the energy spent in separating carbon dioxide from flue gases. Further, scrubbing processes are more suited for larger concentrations of carbon dioxide as in power-plant flue gases. They are less suited for distributed combustion of natural gas in individual homes and end-use devices. Thus, scrubbing would be applicable on larger-scales mostly in electricity generation.

The other alternative would be to remove carbon from natural gas prior to consumption leaving hydrogen as the energy carrier. The basic process would involve methane steam reforming followed by a shift reaction and physical absorption or other separation of carbon dioxide. Hydrogen would then be transported to the user and converted to desired energy form, heat or work, without any carbon dioxide emissions. This is clearly a more elaborate mitigation strategy than carbon scrubbing, but it offers greater possibilities in the long run including a bridge to the "hydrogen" economy after the saturation in natural gas contribution to global energy supply. The strategy offers an evolutionary transition from current reliance on carbon-intensive mix of fossil fuels via methane to carbon-free energy system of distant future.

Both scrubbing and removal pose the question what to do with accumulating amounts of carbon that is not released into the atmosphere. The amounts of carbon generated by scrubbing alone would be truly enormous. As was mentioned above, global emissions from energy-use amount to close to 6 GtC per year and electricity's share is about 2 GtC or about 7 $GtCO_2$ per year. The amount of carbon dioxide generated today in electric plants alone dwarfs all possible market demands. Thus, an important question is how such a large mass flow can be managed. There are two possibilities: to utilize carbon to the maximum degree possible in other activities, or to store the collected streams in permanent disposal sites. The possible uses include enhanced oil recovery, chemical feedstocks, building materials, carbonization of beverages, food conservation, sewage treatment, fertilizers in greenhouse horticulture, fire extinguishing equipment, and gas welding. Of all of these potential commercial uses of collected carbon dioxide only the first three provide permanent means of disposal, but the involved quantities would be limited compared with potential disposal requirements.

Additionally, carbon dioxide may also be permanently stored in natural underground reservoirs, such as aquifers or depleted natural gas fields, or alternatively deposited in the deep ocean. It is difficult to estimate the quantities of accumulated carbon dioxide that could be stored in aquifers, gas and oil fields with any degree of certainty. The potential capacity might be as high as 750 GtC (Nakićenović *et al.*, 1993). It is clear, however, that this is a rough estimate and not a practical storage capacity for future carbon emissions, but the orders of magnitude involved show that current levels of carbon emissions are storable at least during the next half a century or even longer. Thus, the storage potential is indeed large by any standards.

In comparison, the potential for carbon disposal in the deep ocean is vast. The global carbon cycle involves the annual exchange of around 200 GtC between oceans, the atmosphere and the biosphere. The large amount of carbon is "stored" in the oceans and is estimated to be about 36,000 GtC. As the largest carbon reservoir on Earth, the deep oceans might be a possible repository for the sequestered carbon. There are various disposal schemes: to pump carbon dioxide in high-pressure pipes to the ocean floor, to inject liquid carbon dioxide at depths of about 3 km that would then continue to sink, to release solid carbon dioxide (ice) that would sink by itself to the bottom, and to disperse carbon dioxide into a suitable thermohaline current that would carry it to the ocean bottom.

The gist of the original proposal by Marchetti (1976) was to generate a "gigamixer" by injecting carbon dioxide into sinking thermohaline currents that eventually reach the deep ocean where the carbon dioxide enriched water might reside for thousands of years due to the slow natural mixing. The concrete proposal involved the Gibraltar subduction undercurrent that would provide a storage capacity of 10 GtC per year, easily exceeding all energy-related sources of carbon dioxide generated in the methane economy scenario during the next half a century. In a more practical scheme, carbon dioxide collected in continental Europe could be transported by pipeline for disposal at Gibraltar. The theoretical mitigation potential of this scheme is vast since there are other sinking thermohaline currents including the subduction currents of Bab-al-Mandab in the Red Sea, the Weddell Sea, and the North Atlantic.

Clearly, all of these different schemes for storing carbon dioxide in either liquid or solid pools on the ocean floor or dissolved in the deep ocean still require concept proof before even a pilot project could be started. In any case, among the major outstanding uncertainties are the possible ecological effects of higher concentrations of carbon dioxide in the oceans and their effects on local chemistry in the vicinity of storage sites.

The methane economy scenario with carbon removal offers the opportunity for achieving global energy decarbonization and eventually eliminating carbon emissions altogether. Thus, methane fulfills most of the obvious future requirements for becoming the major source of energy. A bonus is that the reliance on natural gas can pave the way for a very clean hydrogen future. Figure 10 illustrates the possibility and timing of such an evolutionary transition from fossil fuels to hydrogen (see also Veziroglu and Barbin, this volume). It shows the decarbonization in the world as the increasing ratio of hydrogen to carbon in the average energy mix. The data show the actual hydrogen and carbon content of global primary energy consumption as specified in Figure 10 for wood, coal oil and natural gas. The change in hydrogen to carbon ratio is presented as a "substitution" process of hydrogen for carbon in the total primary energy consumption during the last century and as the continuation of this process in the future. The extrapolation in Figure 10 shows that, after this century, the hydrogen-to-carbon ratio may exceed the level of four-to-one, that can be achieved by the pure methane, implying that some additional hydrogen would be needed to supplement the increasing reliance on methane.

The possible way of both increasing the share of methane in global energy and hydrogen-to-carbon ratio is carbon removal and disposal. For example, methane could be separated into carbon dioxide and hydrogen in the proximity of the production site. This would require the development of large scale steam reforming processes but is conceivable that the separation could be achieved economically. The separated carbon dioxide could be reinjected into the depleted natural gas field or used for enhanced oil recovery and hydrogen could be piped like methane. Marchetti (1991) made such a proposal for Russian natural gas and hydrogen delivery to Europe and use of separated carbon dioxide for enhanced oil production in Ukraine. Initially, hydrogen could be added to the natural gas in the same pipeline and if required separated at consumption sites by membranes or other methods or simply used as mixture of methane and hydrogen. As the quantities of separated carbon and hydrogen increase it might become necessary to build dedicated hydrogen and carbon dioxide pipelines. In the first stages of the hydrogen economy of the distant future, separated carbon might have to be deposited in the deep ocean as the fluxes become

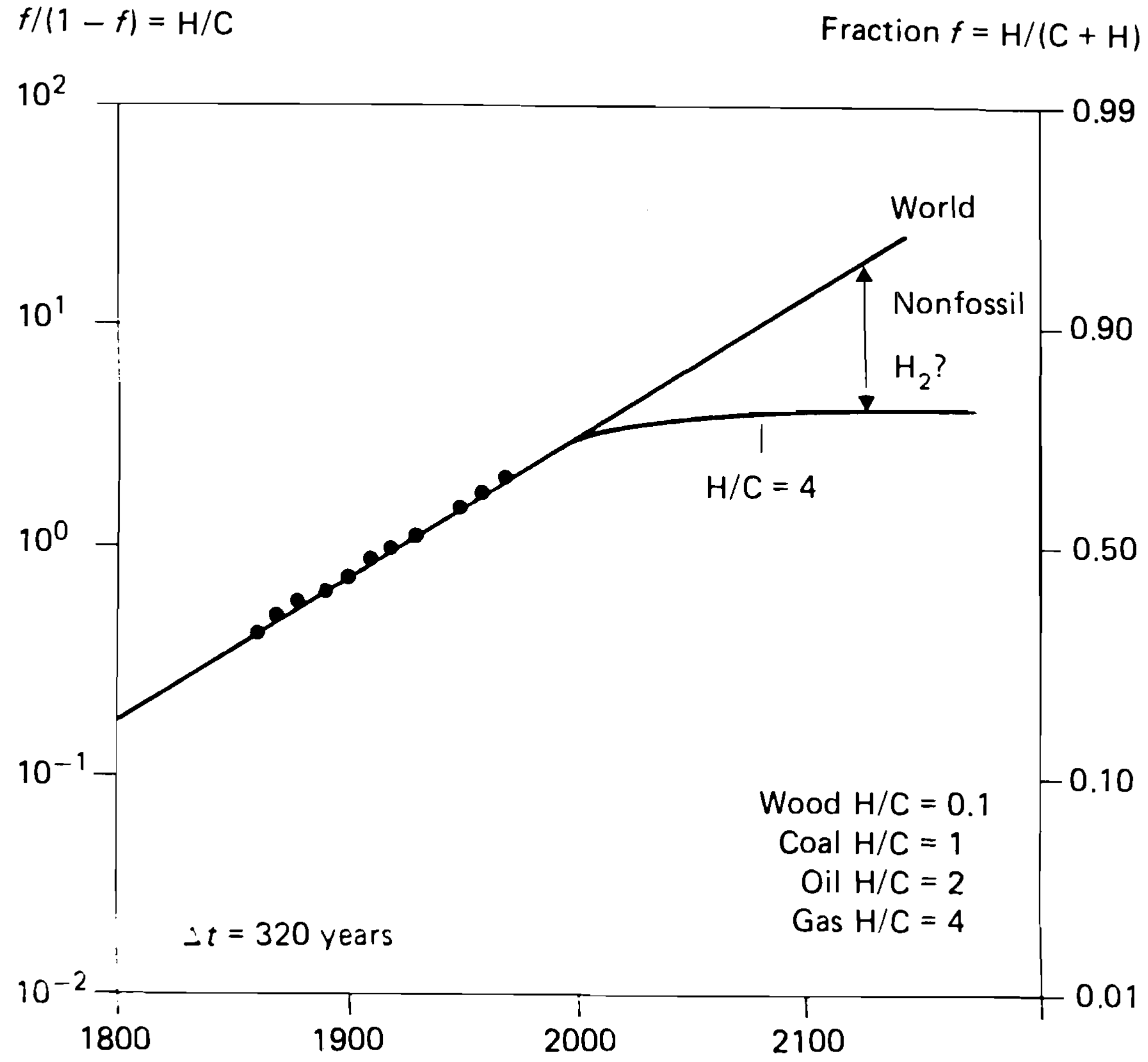

Figure 10: Hydrogen-to-carbon ratio of global primary energy including historical data and future projection (Marchetti, 1982).

too difficult to be absorbed by the declining oil production needs. Eventually, methane could be replaced as the source of hydrogen by carbon-free options, collectively called solfus (see Figure 6). Hydrogen and electricity would provide virtually pollution-free and environmentally benign energy carriers. To the extent that they might be produced from methane, the separated carbon would be contained within the energy sector or stored. As methane contribution to global energy needs saturates and subsequently proceeds to decline, carbon-free sources of energy would take-over eliminating the need for carbon handling and storage.

Conclusion

The findings in this paper confirm that energy gases could become means for reducing energy-related emissions of greenhouse gases. The issue of climate warming is likely to be a major planetary concern during the next century along with the needs to provide sufficient energy for further social and economic development in the world. Methane and later hydrogen offer the possibility for reconciling these conflicting objectives. The findings show that evolutionary development of the global energy systems toward larger contribution of natural gas is consistent with the dynamics of the past 130 years. Continuation of this process in the future leads to carbon dioxide and methane emissions that are low compared with other, more conventional scenarios. The reasons for the moderate emissions associated with the emergence of the methane economy are that natural gas emits less carbon dioxide than other fossil fuels and that the scenario assumes zero-carbon sources of energy, collectively called solfus, to develop under the wing of gas and become major sources of energy by 2100. The current phase in the development of the global energy system 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 that we must look, hope, and work for during the next decades is the production of hydrogen without fossil fuels (Ausubel *et al.*, 1988). 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 enhance the reduction of other adverse impacts of energy-use on environment in addition to substantial reductions of carbon dioxide emissions.

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