THE FUTURE OF ENERGY GASES
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Energy Gases—The Methane Age and Beyond

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CONTENTS

ABSTRACT

The combustion of fossil fuels results in the emissions of gases and pollutants that produce adverse ecological effects. Evidence is also accumulating that suggests 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 additional global warming during the next century. Although 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; however, after combustion occurs, the amount of resulting carbon dioxide 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 an 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 in distant future that could use hydrogen and electricity, both of which are carbon-free energy carriers, that could be produced by nonfossil 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 into the environment in comparison to wastes from all other anthropogenic activities. Current energy-related carbon dioxide emissions are on the order of 6 gigatons of carbon (GtC) or more than 20 $GtCO_2$ per year. This is more than 20 times larger than, for example, annual global steel production of about 700 megatons (Mt). Decarbonization is a notion that denotes reduction of carbon dioxide emissions per unit primary energy and per unit economic activity, and dematerialization refers to the 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 a methane economy, include efficiency improvements and

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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 1970's, a number of studies have been conducted to assess 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 these studies resulted in calls for commercializing large amounts of nonconventional fossil energy resources, such as oil shales, and 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 energy 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 fossil energy resources are much more abundant than it was anticipated in the 1970's and early 1980's. 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.

This dilemma of the need to increase energy services and reduce the adverse impacts of energy-use is illustrated in figure 1. It shows per capita emissions of the greenhouse gases carbon dioxide and methane for the major world regions.

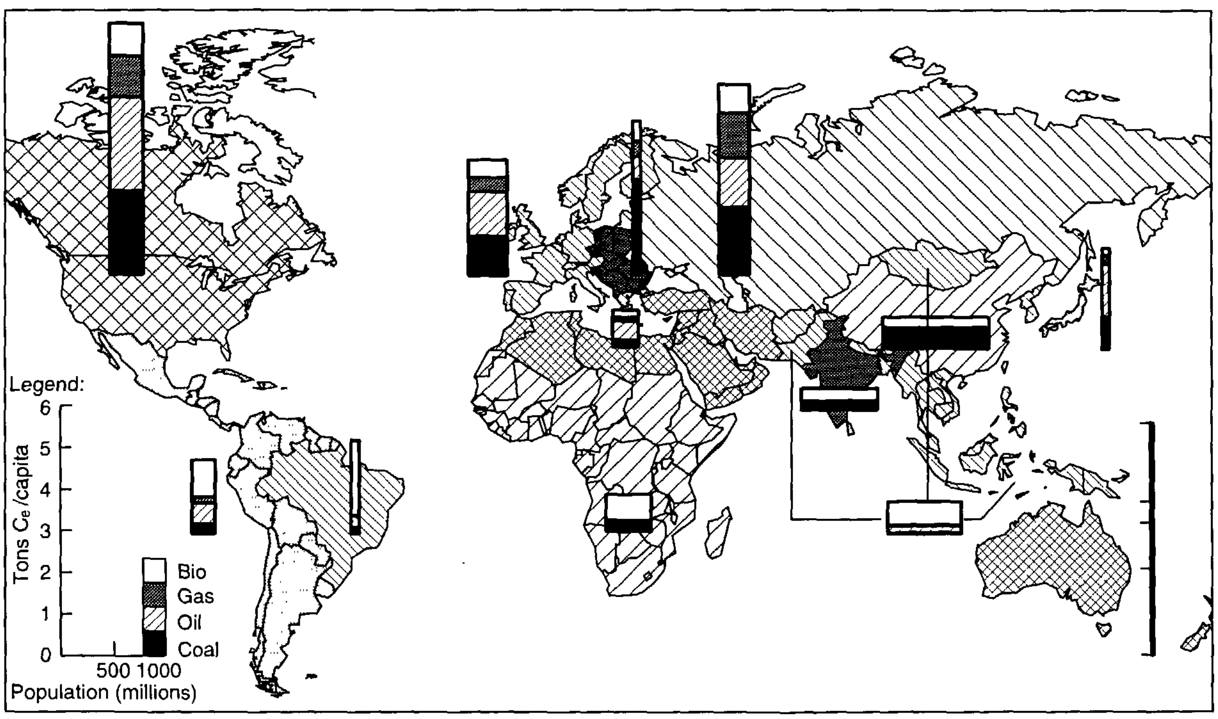

Figure 1. CO_2 and CH_4 greenhouse-gas emissions per capita versus population for different world regions and by energy source in 1988. Height of bars gives carbon dioxide and methane emissions per capita in tons of carbon equivalent, and width of bars shows regional population. Four main sources of the greenhouse gas emissions are shown: carbon dioxide emissions resulting from (1) coal, (2) oil, and (3) natural gas consumption, and (4) the combined carbon dioxide emissions of all nonfossil energy sources, such as biomass burning, and also all of the anthropogenic methane sources, both energy and nonenergy. (1 kg CH_4=21 kg CO_2). C_e=total greenhouse-gas emissions in tons of carbon.

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 not much lower in some parts of Eastern Europe and the former 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. A similar situation still exists in the economies of Eastern Europe, Russia, and the other Commonwealth (former Soviet) Republics.

In contrast to the energy-intensive economies of Eastern Europe, Japan and Western European countries achieve much higher levels of economic activities with substantially lower per capita energy consumption and greenhouse gas emissions. The standard of living in most of the Western European countries is comparable to that of the United States, however, the emissions of greenhouse gases are half as large in Western Europe. In the more efficient industrial countries of Western Europe and Japan, emissions are on the order of 3 tC equivalent per capita, whereas they are 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, nonfossil 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 coal production and use, with emissions 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 economic and social development in the world are strong determinants of future greenhouse gas emissions. The potential risks of climate change, on the other hand, 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: (1) population growth, (2) per capita value added, (3) energy per value added, (4) carbon emissions per energy on one side, and (5) total carbon dioxide emissions on the other side of the identity (Yamaji and others, 1991). Two of these factors are increasing and two are declining at the global level. [$CO_2=(CO_2/E)\times(E/GDP)\times(GDP/P)\times P$, 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.]

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 per year. Most population projections expect at least another doubling during the next century; for example, the World Bank (Vu, 1985) and United Nations (1991) projections. 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 1860's and at about 2 percent per year in most countries since the 1970's. Carbon dioxide emissions per unit of energy have also been decreasing but at a much lower rate, about 0.3 percent per year.

Figure 2 shows the extent of global decarbonization of energy since 1900, as the change in the ratio of average carbon dioxide emissions per unit of energy consumed. Decarbonization occurred owing to the gradual replacement of carbon-rich sources of energy by carbon-poorer sources of energy. First, wood and coal were replaced by oil and later by 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 (EPA) Rapidly Changing World (RCW) scenario actually anticipates an increase of carbon intensity in the world and thus a reversal of the historical development trend (Environment Protection Agency, 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 (Intergovernmental Panel on Climate Change, 1992). The Environmentally Compatible Scenario (ECS'92) developed at International Institute for Applied Systems Analysis (IIASA) in 1992 (Nakićenović and others, 1993) and the

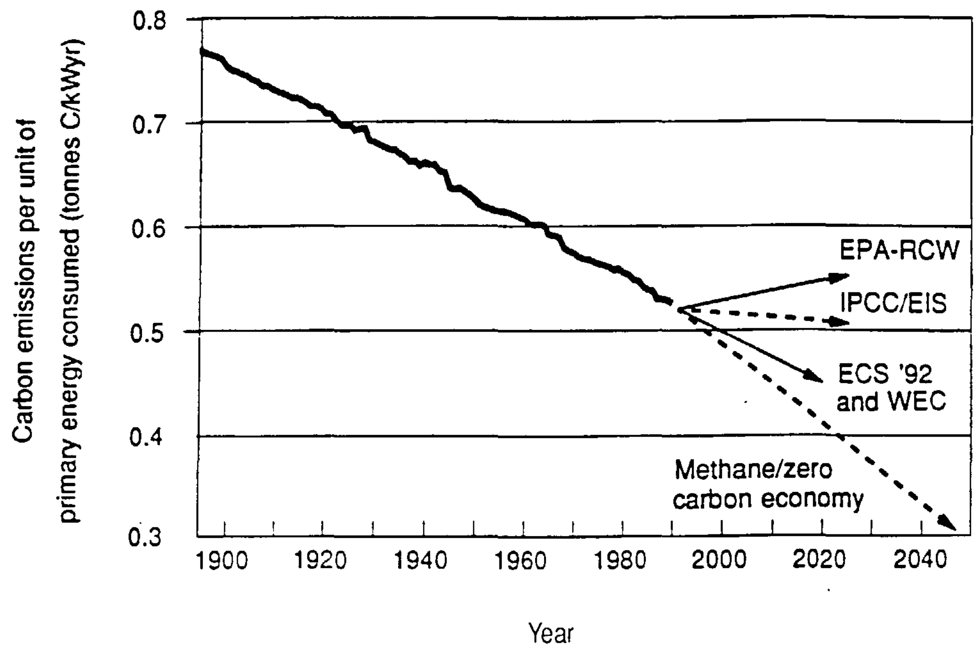

Figure 2. Global decarbonization of energy since 1900 and scenarios for the future in tonnes of carbon per kilowatt year (tC/kWyr) of energy. Four future scenarios are shown: (1) Environmental Protection Agency's (EPA) Rapidly Changing World scenario, (2) the Intergovernmental Panel on Climate Change (IPCC) Energy and Industry Subgroup's median scenario, and (3) the International Institute for Applied Systems Analysis (IIASA) Environmentally Compatible Scenario '92, as well as (4) the World Energy Council's (WEC) reference scenario, which has essentially the same carbon intensity of energy as ECS '92. The lower dashed line shows the further reduced emissions of a methane/zero-carbon economy.

World Energy Council scenario (World Energy Council, 1992) represent a continuation of the historical trends 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 offset 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 annual 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 from 0.8 to 1.4 percent per year (two to four times the annual rates achieved in the past).

In addition to energy decarbonization, 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 1940's. The energy intensity of India and its present improvement rates 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, between those of the United States (lower) and India (higher).

Figure 4 shows the decarbonization and energy deintensification achieved in a number of countries since the 1870's. It illustrates salient differences in the policies and structures of energy systems among countries. For example, Japan and France have achieved the highest levels 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

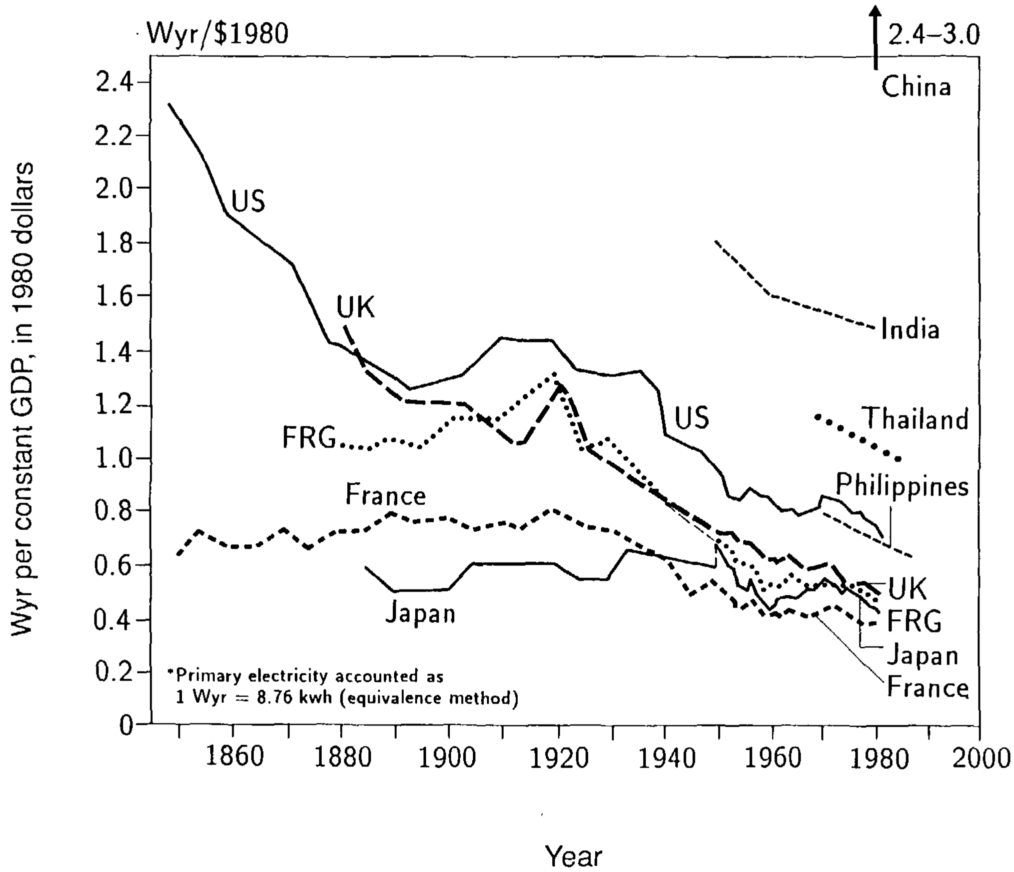

Figure 3. Primary energy intensity, including biomass, of value added in kilowatt year (Wyr) per constant gross domestic product (GDP) in 1980 dollars. Primary electricity is accounted as 1 Wyr=8.76 kWh (equivalence method).

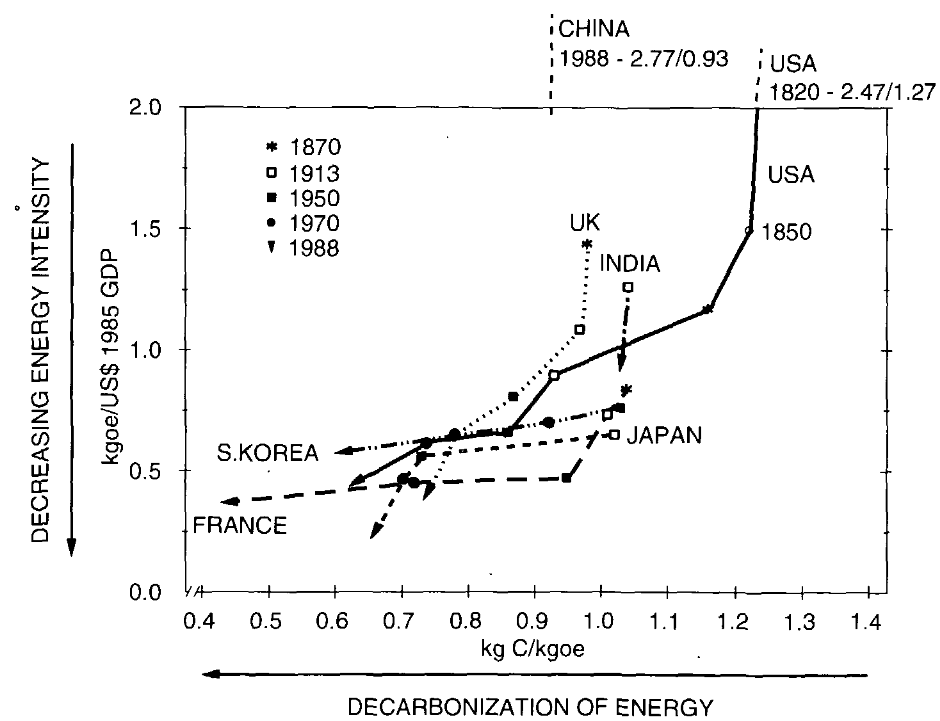

Figure 4. Global decarbonization and deintensification of energy in kilograms of carbon per kilogram of oil equivalent (kgC/kgoe), and in kgoe per $1,000 gross domestic product (GDP) (Grübler, 1991).

year—decarbonization of energy occurs at about 0.3 percent per year and reduction of energy intensity of value added occurs at about 1 percent per year. This falls short of what is required to offset the effects of global economic growth of about 3 percent per year. This means that 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 a doubling before the 2030's, 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 increase of emissions during the next three decades. It shows the EPA's RCW scenario with highest emissions exceeding 10 GtC by 2020 (Environmental Protection Agency, 1990). It shows again the Intergovernmental Panel on Climate Change (IPCC) midrange scenario with slightly lower emissions, although it should be mentioned that the lowest IPCC scenarios actually lead to a reduction of global emissions with respect to 1990 during the next the century (Intergovernmental Panel on Climate Change, 1992). Figure 5 also shows the WEC reference scenario and the ECS'92 scenario from IIASA to be in the lower range of emissions (Nakićenović and others, 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.

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 comparisons of projections 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

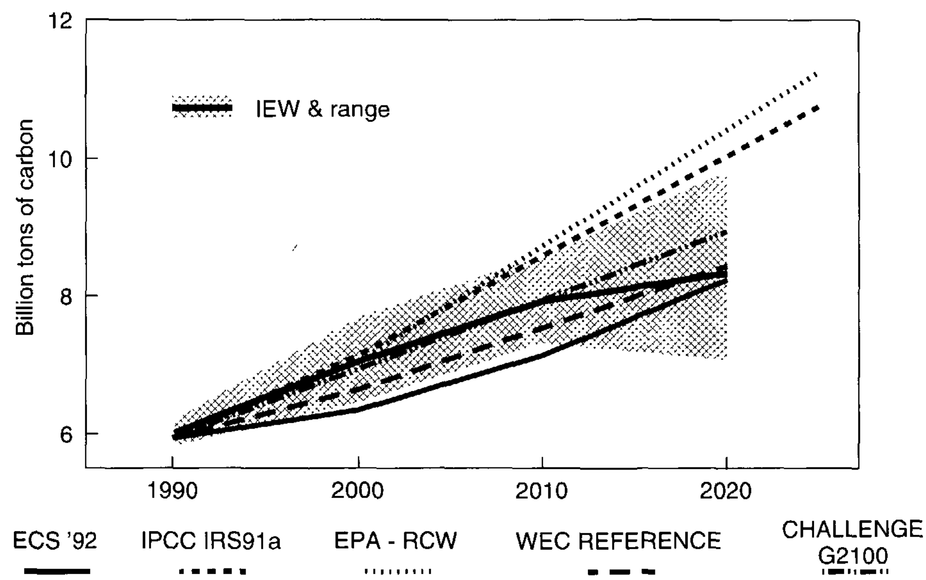

Figure 5. Global primary energy consumption 1990–2020. Range of the International Institute for Applied Systems Analysis International Energy Workshop (IIASA IEW) projections, including the Environmental Protection Agency Rapidly Changing World (EPA RCW) scenario, the World Energy Council (WEC) reference scenario, the Intergovernmental Panel on Climate Change scenario (IPCC IRS91a), the International Institute for Applied Systems Analysis Environmentally Compatible Scenario (IIASA ECS'92), and the International Institute for Applied Systems Analysis (IIASA) Challenge G2100. See text for discussion of shaded areas.

30 percent. On the other hand, international assessments such as that by the IPCC clearly point to the need to reduce the emissions to the fullest 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 to deal with carbon dioxide emissions: (1) mitigate the emissions in the future, (2) deal with the adverse impacts of climate change and compensate for incurred damages, and (3) adapt to climate change and learn to live in the 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 gas 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 the creation of new sinks. Thus, the mitigation strategies 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 in the energy supply chain. For example, this could mean replacing a refrigerator or a gas-fired power plant by a more efficient model, while using the same electricity and fuel supply chains. Three other strategies are more radical. They include changes in technological 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, for example, switching from a gasoline to a 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 (in other words, 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 and others, 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 are cheaper than post-combustion scrubbing of stack gases, which, in turn, is cheaper than carbon removal from the atmosphere by micro-algae carbon fixation or other technologies. From this perspective, it is not surprising that most assessments of mitigation options identify energy efficiency improvements and end-use demand-management measures among 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, the implications of carbon dioxide and methane emissions from 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 to 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 4 percent of gas consumption or less in the future.

METHANE AS AN ENERGY GAS OF CHOICE

A global scenario in which a major share of primary energy is natural gas is of interest for several reasons: (1) The historical replacement of coal by oil and later by natural gas indicates such a trend. Primary energy substitution (Marchetti and Nakićenović, 1979; Nakićenović, 1990) suggests a likelihood that natural gas will become the major global source of energy during the next century. (2) New markets for natural gas appear to be opening because natural gas is more environmentally desirable than other fossil fuels. Methane has the highest hydrogen to carbon atomic ratio and the lowest carbon dioxide emissions of all fossil fuels. The historical transition from wood to coal to oil and to gas has resulted in gradual decarbonization of energy, or to an increasing hydrogen to carbon ratio of global energy consumption. Natural gas use is also highly desirable from a regional environment standpoint because of minimal sulfur dioxide and particulate emissions. (3) Recent assessments suggest that gas resources may be more abundant than was widely believed only a decade ago. New discoveries have outpaced consumption. Additionally, discoveries of gas hydrates and natural gas of ultradeep origin indicate truly vast occurrences of methane throughout Earth's crust (see Wyman; Gold; Kvenvolden; this volume). There is increasing evidence of multiple economic and geopolitical benefits from a worldwide shift to natural gas (Lee and others, 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, 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 1880's and 1960's 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 1960's, 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 2040's. For such an explorative "look" into the future, additional assumptions are required because potential new competitors, such as nuclear, solar, and other renewable energy sources have not yet captured sufficient market shares to allow estimation of their growth rates. 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 prospects for such

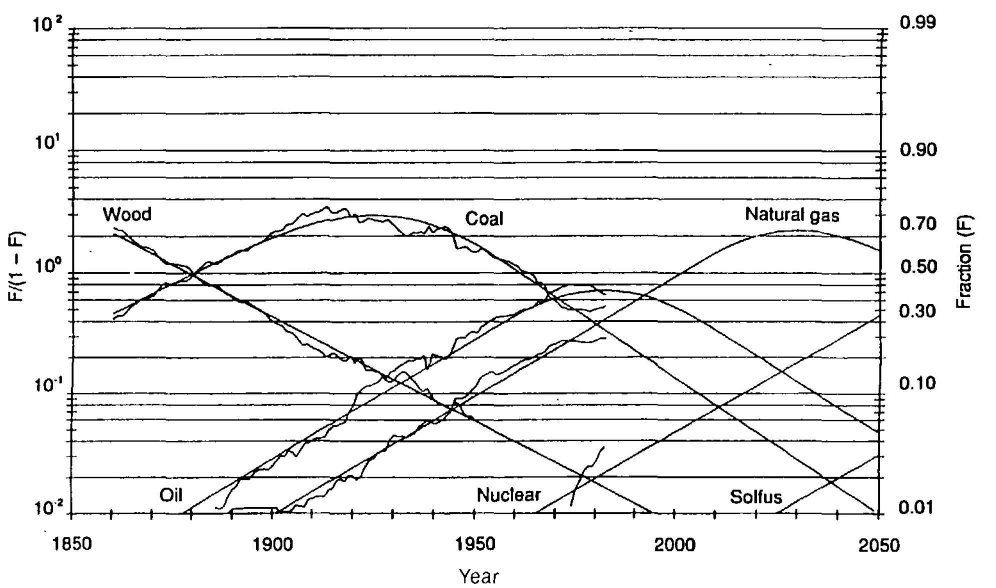

Figure 6. Global primary energy substitution. Smooth lines represent model calculations and jagged lines are historical data. "Solfus" is a term employed to describe a major new energy technology, for example solar or fusion.

installations are at best questionable. This leaves natural gas with the lion's share in primary energy during the next 50 years. In the past, new sources of energy have emerged from time to time, coinciding with the saturation and subsequent decline of the dominant competitor. "Solfus" is a term employed to describe a major new energy technology (for example solar or fusion) that could emerge during the 2040's at about the time that natural gas would reach maximum share of total energy (Marchetti and Nakićenović, 1979; Nakićenović, 1990).

Figure 6 demonstrates that the diffusion of new energy sources and the replacement of older energy sources 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 historiography (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 may 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 emission scenarios and was used again a few years ago in a more comprehensive assessment of future carbon dioxide and methane emissions (Marchetti, 1979; Ausubel and others, 1988; 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 a scenario describing the levels of global primary energy consumption. Thereafter, the calculation of carbon dioxide emissions becomes a straightforward matter; the following are carbon dioxide emissions factors per unit energy (kWyr): Wood 0.844 tC/kWyr; coal 0.735 tC/kWyr; oil 0.849 tC/k Wyr; and natural gas 0.442 tC/kWyr (Ausubel and others, 1988).

We examine a methane economy scenario with two overall levels of energy consumption in the world, both are population driven and based on World Bank estimates (Vu, 1985). One variant of the methane economy scenario, the "efficiency case," holds per capita energy consumption at the current level so that the primary energy consumption increases at the same rate as world population growth. 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 threefold 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 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 (fig. 6), the scenario of global primary energy consumption (fig. 7) and individual emissions factors (discussed above). Figure 8 shows the resulting carbon dioxide emissions for the two methane economy variants. 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 (Intergovernmental Panel on Climate Change, 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 and they result in substantially lower carbon dioxide emissions than other long-term

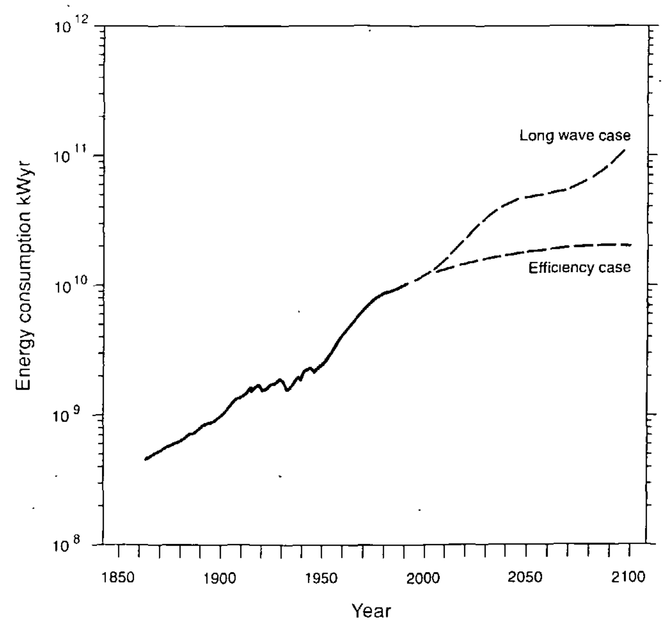

Figure 7. Primary energy consumption (historical data (solid line) and the two variants (dashed lines) of the "methane economy" scenario).

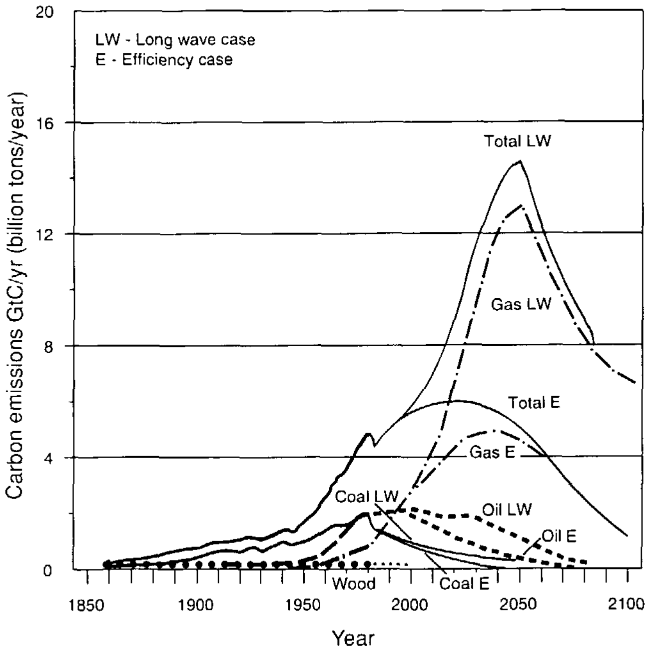

Figure 8. Global carbon dioxide emissions in gigatons of carbon per year (GtC/yr) (historical data and the two variants of the "methane economy" scenario). E, efficiency variant; LW, long-wave variant.

scenarios. Because the same market shares are used for both variants, the methane economy scenario has the same carbon intensity of primary energy consumption in both cases. In fact, the scenario achieves high decarbonization rates in the world, higher than those experienced (fig. 2) and higher than assumed in the majority of other energy and carbon dioxide projections.

ENERGY SCENARIOS AND DECARBONIZATION

Table 1 summarizes the structure of current (1990) 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 as 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 fig. 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 Energy and Industry Subgroup of Intergovernmental Panel on Climate Change scenario are examples (Environmental Protection Agency, 1990; Energy and Industry Subgroup of Intergovernmental Panel on Climate Change, 1991). A second view adopts basically a "dynamics-as-usual" perspective, which is a continuation of historical trends in energy decarbonization as, for example, reflected in the ECS'92 scenario (Nakićenović and others, 1993) or the recent reference scenario of the World Energy Council (World Energy Council, 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 8.06 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 energy 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; 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). This, together with a drastic shift in the energy supply structure (natural gas accounting for 68 percent of primary energy supply by 2025), is reflected in the carbon emissions estimate of 6.16 GtC, which is basically a stabilization of current emission levels.

A Renewables-Intensive Global-Energy Scenario (RIGES) has been suggested by Johansson and others, (1992). In their scenario, the final energy demand of 12.4 TWyr is close to that in 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 (>15.26 TWyr) by the year 2025. (Primary energy production is only given for biomass and coal. For nuclear and hydropower 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.) It must be emphasized, however, that such a rapid market penetration of nonfossil energy sources in this scenario is without precedent for any primary energy source in history. For example, 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 4.97 GtC per year, a stabilization (even slight reduction) of current energy-related carbon dioxide emissions.

Table 1. Primary and final energy consumption, carbon emissions, and carbon intensity (1990 and scenarios for the period 2020 to 2025).

[IPCC/EIS 2025, Intergovernmental Panel on Climate Change Energy and Industry Subgroup's median scenario; EPA RCW 2025, Environmental Protection Agency's Rapidly Changing World scenario; IIASA ECS'92, International Institute for Applied Systems Analysis Environmentally Compatible Scenario '92; WEC reference, World Energy Council's reference scenario; RIGES 2025, Renewables-Intensive Global-Energy Scenario (Johansson and others, 1992). TWyr, terawatt year; GtC, gigatons carbon; tC/kWyr, tons of carbon per kilowatt year; --, no data; n.a., not applicable]

Category	1990	IPCC/ EIS 2025	EPA RCW 2025	WEC reference 2020	IIASA ECS'92 2020	"Methane economy" 2025[a]	RIGES 2025
Primary energy consumption (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	1.59	2.95[c]
Nonfossil	2.35	4.53	3.70	5.16	4.10	2.36[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 and 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.

METHANE AND CARBON DIOXIDE EMISSIONS

Carbon dioxide is the major energy-related source of global warming and the single most important greenhouse gas. Methane is also a natural constituent of air, arising from many natural processes. Recent increases in the concentration of atmospheric methane are usually attributed to diverse anthropogenic activities, such as the growth of animal population, rice production, and organic waste depositories. However, using methane as a source of energy 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 methane leakage. Simple models of atmospheric carbon dioxide and methane concentrations have been used (Ausubel and others, 1988; Victor, 1990; Grübler and Fujii, 1991). For carbon dioxide, an 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 to be 24 times as effective as carbon dioxide (by volume) in greenhouse forcing. 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 factor of 16 times that of carbon dioxide (low case) and the other with 4 percent leakage and a methane forcing factor of 32 times that of carbon dioxide (high case). 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). The atmospheric concentrations of carbon dioxide and

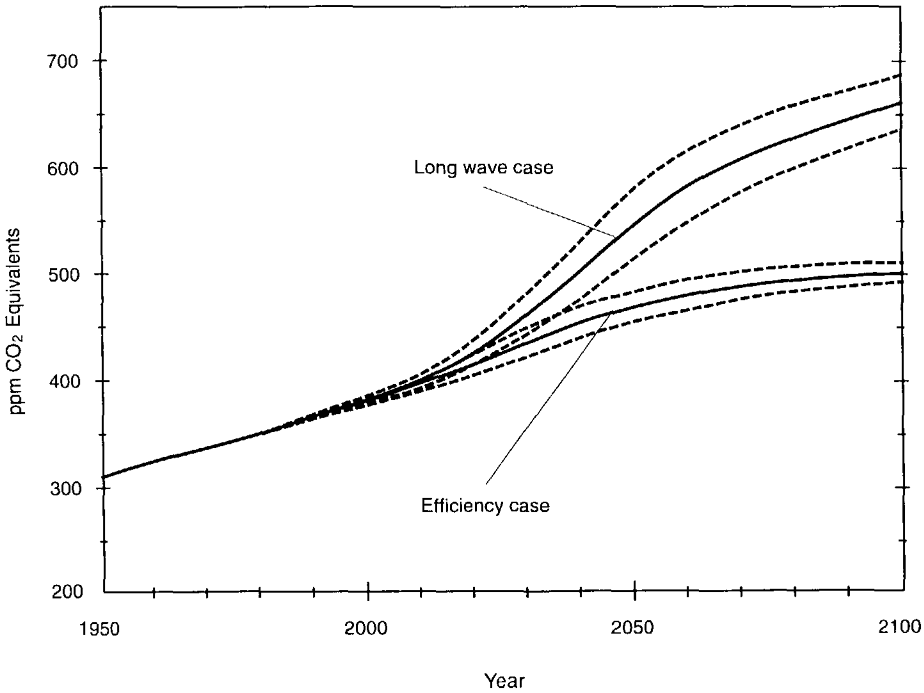

Figure 9. Atmospheric CO_2 and CH_4 concentrations from the "methane economy" scenario expressed as CO_2 equivalents in parts per million. Simple models of CO_2 and CH_4 concentrations and different values for CH_4 forcing have been used for estimating CO_2 equivalents of CH_4 concentrations. Higher set of curves are for the long-wave case and lower ones are for the efficiency case of the scenario. 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 are for 4 percent leakage and high CH_4 forcing.

methane are given in parts per million of CO_2 equivalents. For this calculation, methane concentrations are converted to CO_2 equivalents using the methane conversion factors discussed above and a 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, even when large methane leaks are included. However, it is acknowledged 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, owing to increased levels of energy consumption with the same structure of the energy system, is not linear. This finding identifies the additional advantage of lower energy scenarios toward the absolute and relative reduction of greenhouse gas emissions.

The lower rate of decarbonization in all scenarios, except the methane economy, over the rates achieved historically 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 along with vigorous efficiency improvement efforts will be required to come close to stabilizing global emissions.

METHANE ECONOMY AS A BRIDGE TO HYDROGEN

The analysis of the methane economy scenario has demonstrated that it achieves substantial carbon dioxide emission 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; however, 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 and others, 1993). The chemical absorption process is widely used to remove oxides of sulfur (SOx) and oxides of nitrogen (NOx) from flue gases, and there are a few pilot plants that remove carbon dioxide by the same method. The various absorbents include potassium carbonate and amines. Scrubbing would clearly increase energy costs. The monoethanol-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 and others, 1991; Nakićenović and others, 1993). The major problems associated with scrubbing are to reduce the costs and minimize losses in plant efficiency owing 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 powerplant 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 the 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 of the natural gas contribution to global energy supply. This mitigation strategy offers a transition from the current global reliance on a carbon-intensive mix of fossil fuels via methane to a carbon-free energy system in the distant future.

Both scrubbing and removal generate large amounts of carbon that are not released into the atmosphere. The amounts of carbon generated by scrubbing alone would be truly enormous. As was mentioned above, global carbon dioxide emissions from energy use amount to close to 6 GtC per year, of which about 2 GtC or about 7 $GtCO_2$ per year is from electricity use. The amount of carbon dioxide generated today in electrical powerplants alone dwarfs all possible market demands for this carbon dioxide. Thus, an important question is how such a large mass flow can be managed. There are two possibilities: (1) to utilize carbon to the maximum degree possible in other activities or (2) to store the collected carbon in permanent disposal sites. The possible uses of carbon dioxide 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; however, the quantities utilized would be limited compared with the potential amounts of carbon dioxide requiring disposal.

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 and gas and oil fields with any degree of certainty. The potential capacity might be as high as 750 GtC (Nakićenović and others, 1993). It is clear, however, that this is a rough estimate and not a practical estimate of storage capacity for future carbon emissions, but the orders of magnitude involved show that capacity exists to store current levels of carbon emissions for at least the next half a century. 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 largest amount of the carbon is "stored" in the oceans and is estimated to be about 36,000 GtC. As the largest carbon reservoir on Earth, the deep ocean might be a possible repository for the carbon generated by scrubbing and removal. There are various disposal schemes: (1) to pump carbon dioxide in high-pressure pipes to the ocean floor, (2) to inject liquid carbon dioxide into the ocean at depths of about 3 km that would then continue to sink, (3) to release solid carbon dioxide (ice) that would sink by itself to the ocean floor, and (40 to disperse carbon dioxide into a suitable thermohaline current that would carry it to the ocean floor.

The gist of Marchetti's (1976) proposal to dispose of carbon dioxide 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, owing to the slow rate of natural mixing. The proposal involved using the Gibraltar subduction undercurrent and would provide a storage capacity of 10 GtC per year, which easily exceeds the volume of carbon dioxide generated by energy-related sources 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 because there are other sinking thermohaline currents including subduction currents in the Red Sea (Bab-al-Mandab current), 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. Among the major outstanding uncertainties are the possible ecological effects of higher concentrations of carbon dioxide in the oceans and their effects on local water chemistry in the vicinity of storage sites.

The methane economy scenario with carbon removal presents the possibility of achieving global energy decarbonization and eventually eliminating carbon emissions altogether. Thus, methane (natural gas) 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 Barbir, this volume). It shows global decarbonization 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 the 4:1 ratio that can be achieved by the use of pure methane, implying that some additional hydrogen would be needed to supplement the increasing reliance on methane.

A possible way of both increasing the share of methane in global energy and the 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 it 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 the 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 dioxide 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 dioxide might have to be deposited in the deep ocean, as the fluxes become too difficult to be absorbed by declining oil-production needs. Eventually, methane could be replaced as the source of hydrogen by carbon-free options, collectively called solfus (see fig. 6). Hydrogen and electricity would provide virtually pollution-free and environmentally benign energy carriers. To the extent that these energy carriers might be produced from methane, the separated carbon dioxide could be contained within the energy sector or stored. As the methane contribution to global energy needs saturates and subsequently proceeds to decline, carbon-free sources of energy would takeover, eliminating the need for carbon handling and storage.

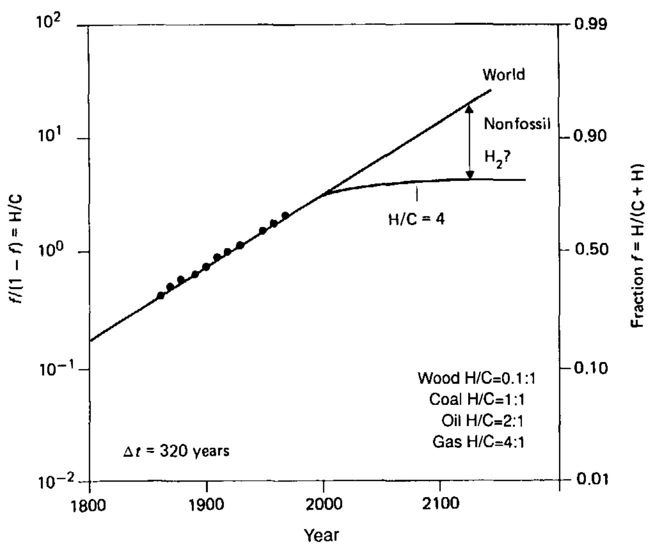

Figure 10. Hydrogen-to-carbon ratio of global primary energy including historical data and future projection (Marchetti, 1982).

CONCLUSION

The findings in this paper indicate that methane and hydrogen 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 need 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 system toward a larger use 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 the development of zero-carbon sources of energy, collectively called solfus, in the future and their major role in energy production 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 and others, 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-effect option because it would also enhance the reduction of other adverse impacts of energy use on the environment in addition to substantial reductions of carbon dioxide emissions.

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