Long-Term Strategies for Mitigating Global Warming

Nebojša Nakićenović, Arnulf Grübler, Atsushi Inaba, Sabine Messner, Sten Nilsson, Yoichi Nishimura, Hans-Holger Rogner, Andreas Schäfer, Leo Schrattenholzer, Manfred Strubegger, Joel Swisher, David Victor, and Deborah Wilson

RR-93-11
July 1993

Reprinted from *Energy* (1993) **18**(5):401–609.

International Institute for Applied Systems Analysis • Schlossplatz 1 • A-2361 Laxenburg • Austria
Tel: (+43 2236) 807 • Fax: (+43 2236) 71313 • E-mail: publications@iiasa.ac.at • Web: www.iiasa.ac.at

Reprinted with permission from *Energy* (1993) **18**(5):401–609.

Energy Vol. 18, No. 5, p. 401, 1993
Printed in Great Britain. All rights reserved

0360-5442/93 $6.00 + 0.00

Long-Term Strategies for Mitigating Global Warming†

Nebojša Nakićenović,‡ Arnulf Grübler,
Atsushi Inaba, Sabine Messner, Sten Nilsson,
Yoichi Nishimura, Hans-Holger Rogner, Andreas Schäfer,
Leo Schrattenholzer, Manfred Strubegger, Joel Swisher,
David Victor, and Deborah Wilson

International Institute for Applied Systems Analysis
A-2361 Laxenburg, Austria

(Received 19 June 1992)

Abstract – This special issue reviews technological options for mitigating carbon dioxide (CO_2) emissions. The options analyzed include efficiency improvements, renewable energies, clean fossil and zero-carbon energy technologies, carbon sequestration and disposal, enhancement of natural carbon sinks (halting deforestation, afforestation, and other sink enhancement options), and geo-engineering measures to compensate for increases in CO_2 concentrations. Reduction potentials, costs, and the relative contribution of individual options, as well as their limiting factors and possible timing of introduction and diffusion, are discussed. The study concludes with a discussion of methodological issues and of trade-offs and constraints for implementation strategies to mitigate anthropogenic sources of change in the global carbon cycle.

---

†The research reported in this special issue was carried out by the Environmentally Compatible Energy Strategies (ECS) Project at the International Institute for Applied Systems Analysis (IIASA). Support by the Global Industrial and Social Research Institute (GISPRI), Japan, and the Japan Industrial Policy Research Institute (JIPRI) for part of the research reported here is gratefully acknowledged. Special thanks go to Lourdes Cornelio, Val Jones, Lilo Roggenland, and Ewa Delpos for their help in the preparation of the manuscript.

‡To whom all correspondence should be addressed.

Energy Vol. 18, No. 5, pp. 403–419, 1993
Printed in Great Britain. All rights reserved

0360-5442/93 $6.00 + 0.00

Chapter 1

Introduction†

The overall objective of the study described in this special issue was to evaluate the potential contribution of innovative technologies toward global stabilization and the eventual reduction of energy-related emissions of carbon dioxide CO_2. The study included four related tasks.

First, a review was made of various options and measures for mitigating energy-related CO_2 emissions with emphasis on their technological and economic characteristics. The measures analyzed in the study ranged from efficiency improvements, renewable sources of energy, new fossil and nuclear energy, to CO_2 removal and storage, and the enhancement of natural carbon sinks.

Second, an assessment was made of selected national and international studies that deal with energy-related CO_2 mitigation options. The main findings of these studies have been incorporated into the analysis of CO_2 mitigation. This task was enhanced by two international workshops held at IIASA in March 1991 and October 1992 that reviewed the other studies and the technological options being considered in leading research organizations in a number of countries. A summary of the first workshop was published in an earlier special issue of *Energy* (Nakićenović and John, 1991), and of the second one in *IIASA Options* (Nakićenović, 1992).

The third task was to assess the potential contribution of innovative technologies toward mitigating CO_2 emissions. The assessment focused on second- and third-generation technologies that are likely to become available and diffuse during the next century. This task included analyzing the relationship between such innovative technologies and the enabling systems that might be necessary for their successful introduction. Further, an evaluation of the possibilities for their transfer to other parts of the world was also performed.

The final task was to analyze the total mitigation potential of innovative technologies within the context of energy chains (encompassing the whole energy system from the production of primary energy to energy end-use). The analysis was subject to a reference scenario of future energy development formulated specifically for this study. This Environmentally Compatible Energy Scenario (ECS'92) describes a "dynamics-as-usual" future energy development that incorporates longer-term historical rates of technological and economic change, based on earlier IIASA energy studies and modeling approaches. The relative costs and CO_2 emissions of alternative future energy chains are compared with those in the reference scenario. The comparative assessment is based on the CO_2

---

†Nebojša Nakićenović with contributions by David Victor (Section 1.6), Arnulf Grübler, and Leo Schrattenholzer.

database (CO2DB), which incorporates about 400 mitigation technologies (Messner and Strubegger, 1991). The results are summarized in cost curves.

It must be emphasized that the choice of particular measures and technological examples described in this study are not exhaustive; the objective was to prove the feasibility of developing accurate and systematic representations of mitigation and reduction technologies. The study is intended to provide an up-to-date review and assessment of technologies, together with their technical, economic and environmental characteristics. The study also focuses on the issues of when and where future technologies might become applicable.

Finally, it is important to note that the study does not take any particular position with respect to the issue of possible global warming as a result of increasing emissions of anthropogenic greenhouse gases. Instead, it investigates response strategies directed at energy systems and energy use that will be required to arrest and eventually to reduce these emissions. It is especially noteworthy that many of these strategies could have multiple benefits and thus might be of interest even if the dangers of global warming turn out to have been exaggerated.

1.1 Global Energy and CO_2 Emissions

Since the first measurements of atmospheric CO_2 concentrations were taken in 1958 on Mauna Loa, Hawaii, annual averages have portrayed a steady increase from about 315 ppm to more than 350 ppm today. This corresponds to an average increase of more than one ppm per year. In 1988 the atmospheric CO_2 concentration increased by 1.8 ppm or by about 3.8 Gigatonnes (Gt) of carbon. Most of this increase is due to anthropogenic sources of CO_2 such as fossil energy use and deforestation. The emissions of other greenhouse gases are also increasing, but global warming is primarily a CO_2 problem. CO_2 accounts for about 50% of the anthropogenic sources of global warming, followed by methane with about 20%. In 1988 global CO_2 emissions were about 7.6±1.5 Gt of carbon and sinks were about 3.8±1.5 Gt resulting in the annual increase of 3.8 Gt of carbon. Fossil energy consumption contributed more than two thirds of all anthropogenic sources of CO_2 or about 5.5 Gt of carbon. The largest single source of carbon emissions from fossil fuels is coal (about 60% of all fossil-fuel emissions), followed by oil (around 30%) and gas (less than 10%).

Most of the CO_2 increase is due to the historical emissions in the now industrialized countries of the "North". With only 25% of the world's population, these countries currently account for 72% of the global energy-related CO_2 emissions. This is illustrated in Figure 1-1, which shows the shares of fossil energy-related emissions by 13 world regions in 1988. Because of the long residence time of CO_2 in the atmosphere of between 50 and 300 years, a substantial part of present emissions will continue to contribute to additional global warming for many decades to come.

Using a simple model of the global carbon cycle it is possible to estimate the historical contribution of different regions and countries to the current concentrations (see Fujii, 1990). This result is illustrated in Figure 1-2. It clearly shows that the developing countries have caused less than 16% of the CO_2 concentrations due to past consumption of fossil energy. Although the historical responsibility for the CO_2 problem clearly rests with the industrialized countries, future emissions are expected to increase most rapidly in the developing countries.

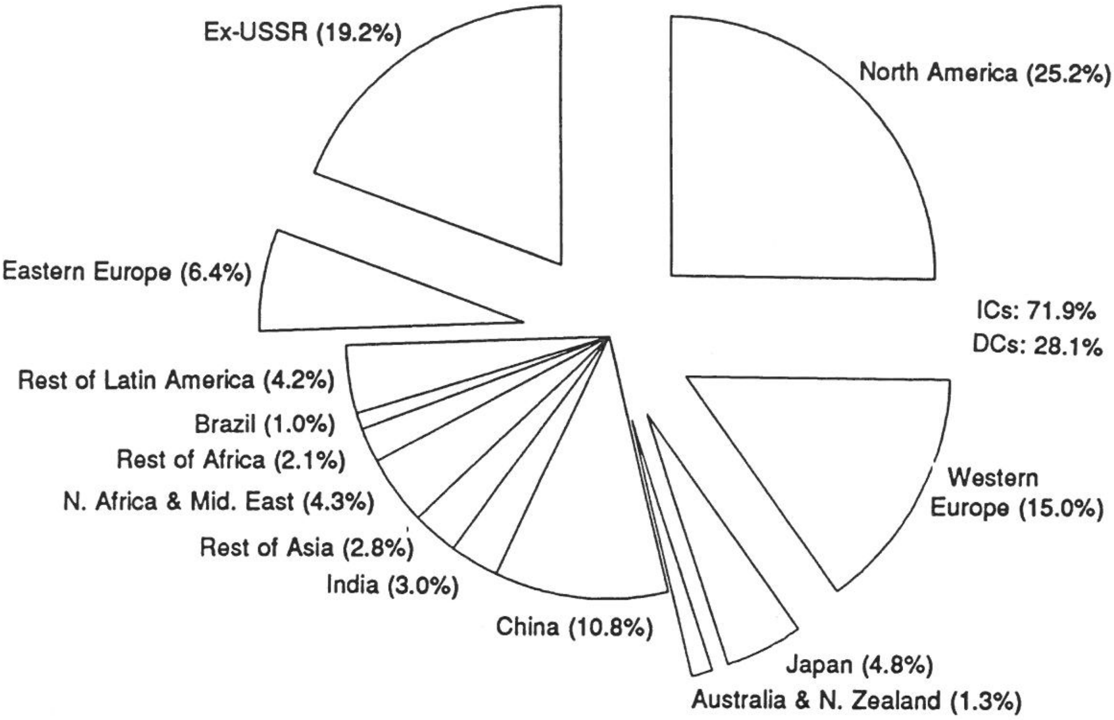


Figure 1-1. Shares of fossil energy-related CO_2 emissions by 13 world regions in 1988 (%).

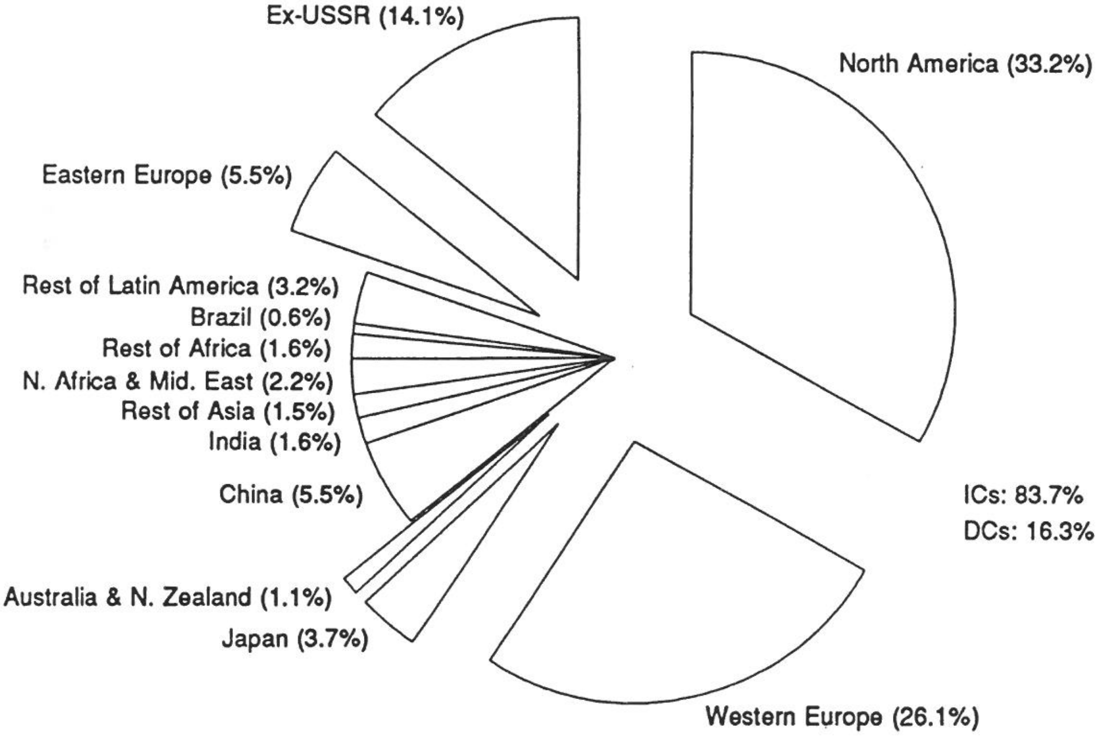


Figure 1-2. Contributions of the 13 world regions to the historical increase in atmospheric CO_2 concentrations due to fossil energy consumption since 1800 (%).

Industrialized countries are in a position to achieve substantial emission reductions because they have relatively high per capita emission levels, larger economic and technological capabilities, and they are in a better situation to respond and adapt to climate change. The burden on the developing countries is twofold. While they need to increase their per capita energy consumption in order to improve the quality of life, they are also more vulnerable to the adverse consequences of climatic change. Figure 1-3 illustrates the wide variations in the current levels of per capita carbon emissions among various countries. They differ between the North and South by nearly a factor of 9 (3.3 tonnes of carbon per capita in developed countries versus 0.37 tonnes in developing countries). A persistent per capita emission gap remains (0.5–1.1 tonnes of carbon per capita in developing countries compared with 3.3 tonnes per capita in industrialized countries) even after including carbon emissions from tropical deforestation, currently estimated to range between 0.6 and 2.8 Gt carbon annually (IPCC, 1990; Houghton, 1990).

In any case, it appears unavoidable that with further development, global emissions will continue to increase for some time to come. The instrumental determinants of future energy-related CO_2 emissions could be represented as multiplicative factors in the hypothetical equation that determines global emission levels. The *Kaya identity* establishes a relationship between population growth, per capita value added, energy per value added and carbon emissions per energy on one side of the equation, and total CO_2 emissions on the other (Yamaji *et al.*, 1991).[1] Two of these factors are increasing and two are declining at the global level.

At present, the world's global population is increasing at a rate of about 2% per year. The longer-term historical growth rates since 1800 have been about 1% per year. Most of the population projections expect at least another doubling during the next century (see World Bank and UN 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% per year since the 1860s and at about 2% per year in most countries since the 1970s. CO_2 emissions per unit of energy have also been decreasing but at a much lower rate of about 0.3% per year.

Figure 1-4 illustrates the extent of this "decarbonization" in terms of the ratio of average CO_2 emissions per unit of energy consumed globally since 1860. The ratio decreases due to the continuous replacement of fuels with high carbon contents, such as coal, by those with lower carbon contents and most recently also nuclear energy. Figure 1-5 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 are similar to those of the United States about a century ago.

---

[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.

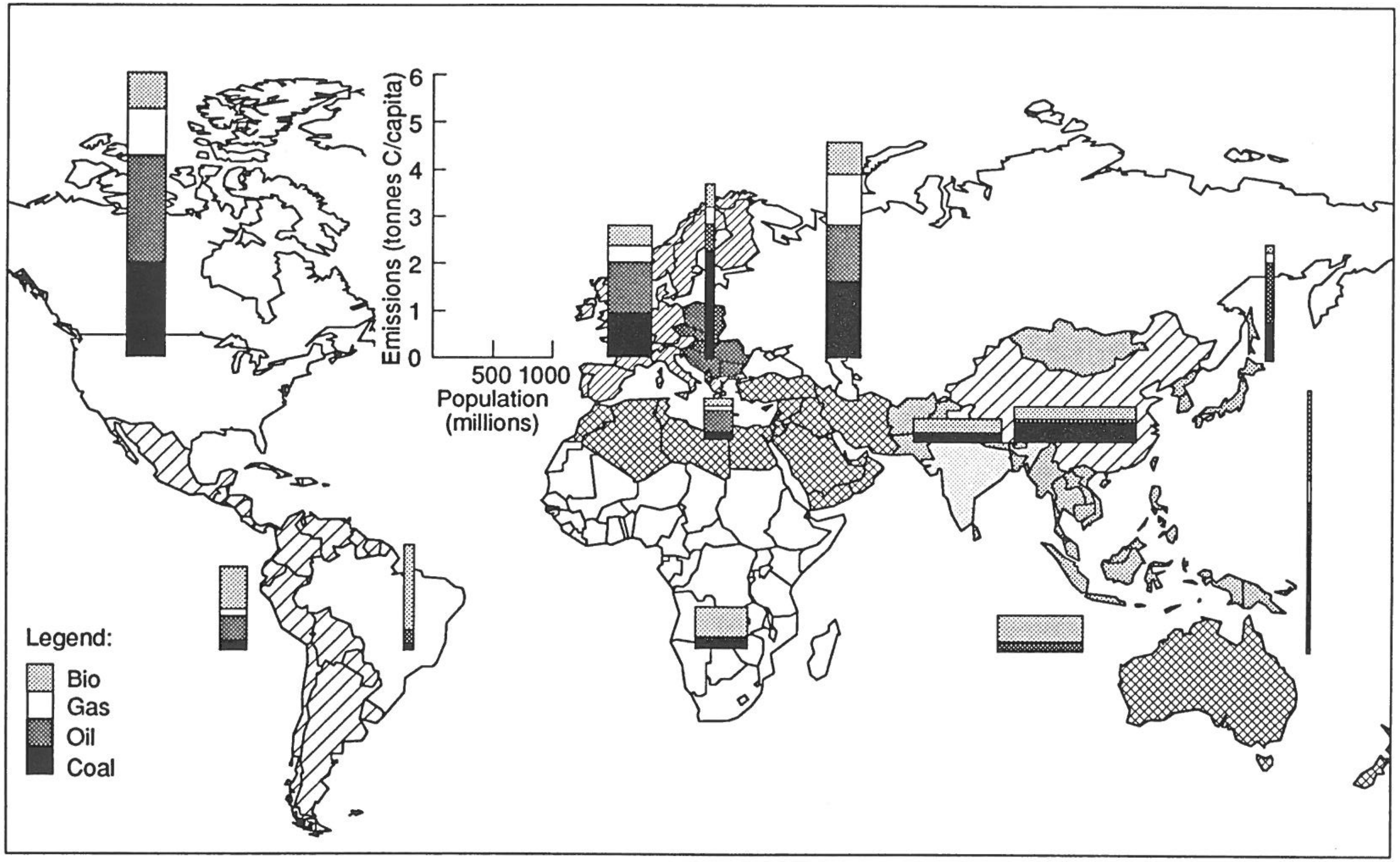


Figure 1-3. Industrial CO_2 and other greenhouse gas emissions per capita, versus population, for different world regions and by energy source (in tonnes of carbon per capita). Other greenhouse gases include CO_2 from deforestation and anthropogenic methane emissions ($1\,\mathrm{kg}\ CH_4 = 21\,\mathrm{kg}\ CO_2$).

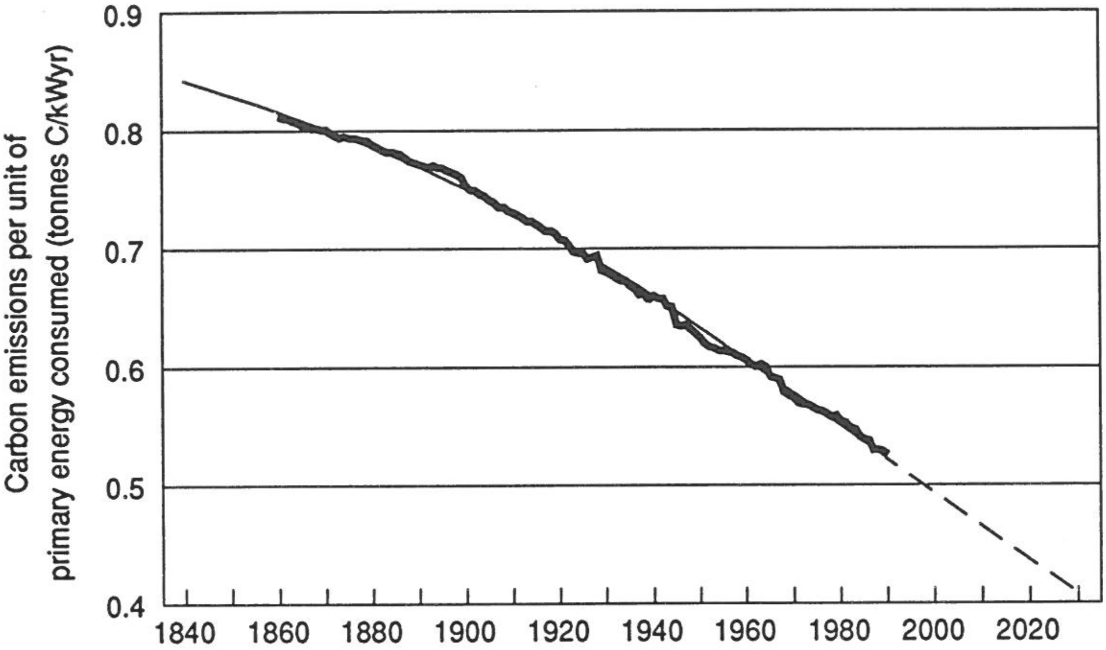


Figure 1-4. Global decarbonization of energy since 1860 (in tonnes of carbon per kWyr of energy).

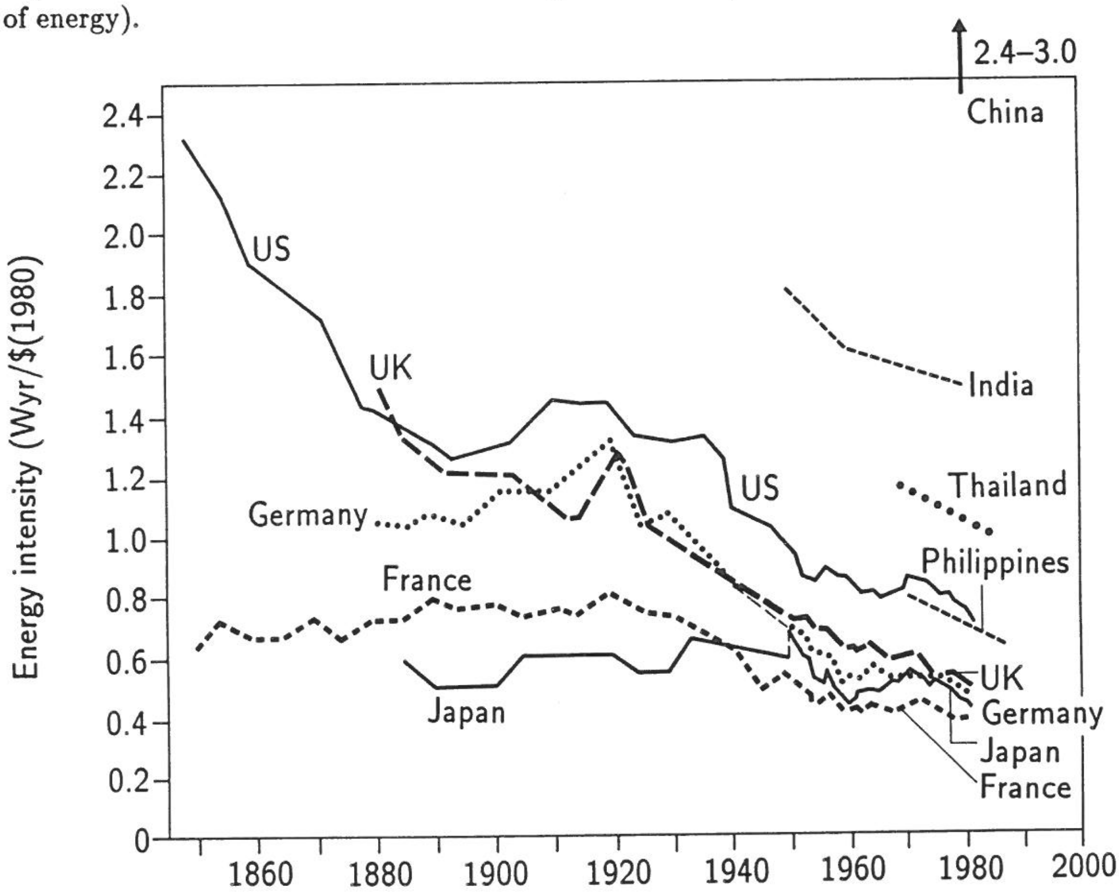


Figure 1-5. Primary energy intensity (including biomass) of value added (in Wyr per constant GDP in 1980 dollars). Primary electricity is accounted as 1 Wyr = 8.76 kWh (equivalence method).

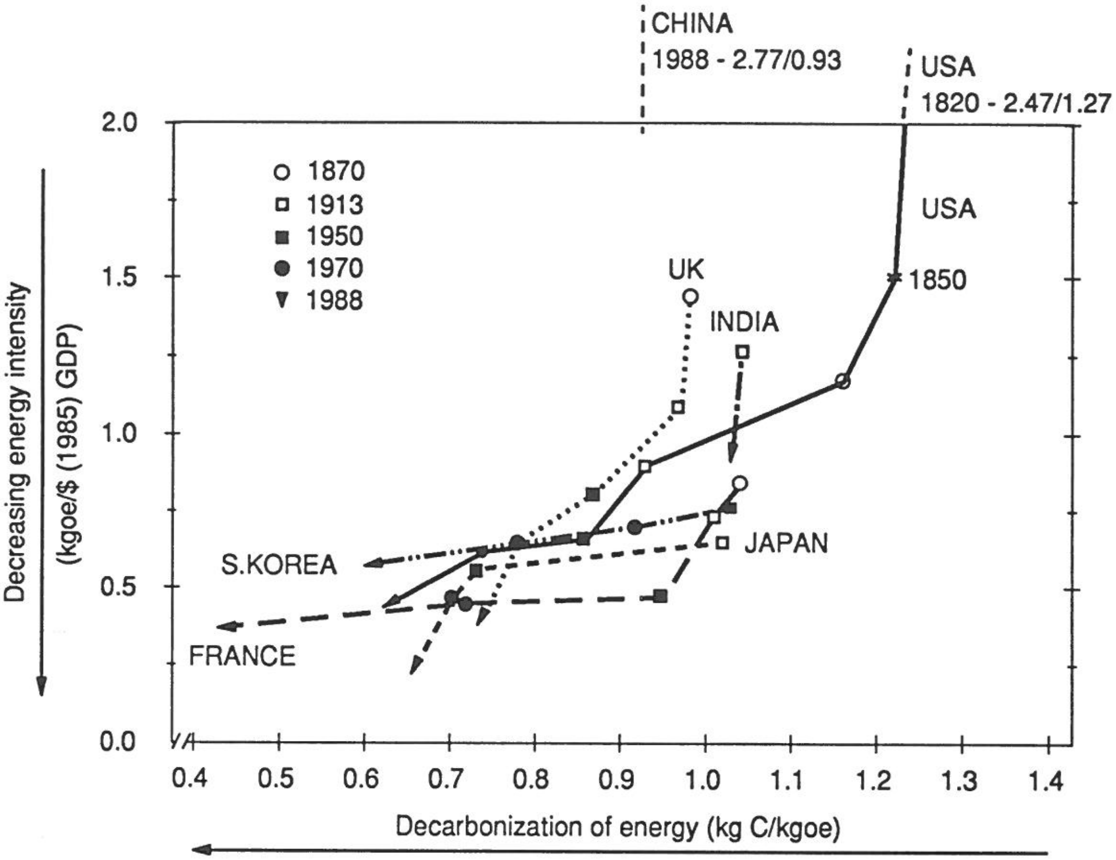


Figure 1-6. Global decarbonization and deintensification of energy (in kg of C per kg oil-equivalent (kgoe), and in kgoe per $1000 GDP) (Source: Grübler, 1991).

Figure 1-6 shows the degrees of decarbonization and energy deintensification achieved in a number of countries since the 1870s. It illustrates salient differences in the policies and structures of energy systems among countries. For example, Japan and France have achieved the largest degrees of decarbonization; in Japan this has been achieved largely through energy efficiency improvements over recent decades, while in France largely through vigorous substitution of fossil fuels by nuclear energy. All countries have achieved high levels of decarbonization through the replacement of coal first by oil, and later by natural gas.

At the global level, the joint reduction in carbon intensity per unit value added has been about 1.3% per year since the mid-1800s. This falls short by about 1.7% of what is required to offset the effects of global economic growth, with rates of about 3% per year. This means that the global CO_2 emissions have been increasing at about 1.7% per year. A number of national CO_2 reduction plans have been announced, aiming to stabilize and in some cases even reduce CO_2 emissions. The Framework Convention on Climate Change is another important international accord designed to curb the total growth of other emissions. Today, global CO_2 emissions are still increasing at close to 2% per year implying a doubling before the 2030s. Before we discuss possible measures and options for the mitigation of future CO_2 emissions we will first briefly review the future emission levels projected by different energy studies.

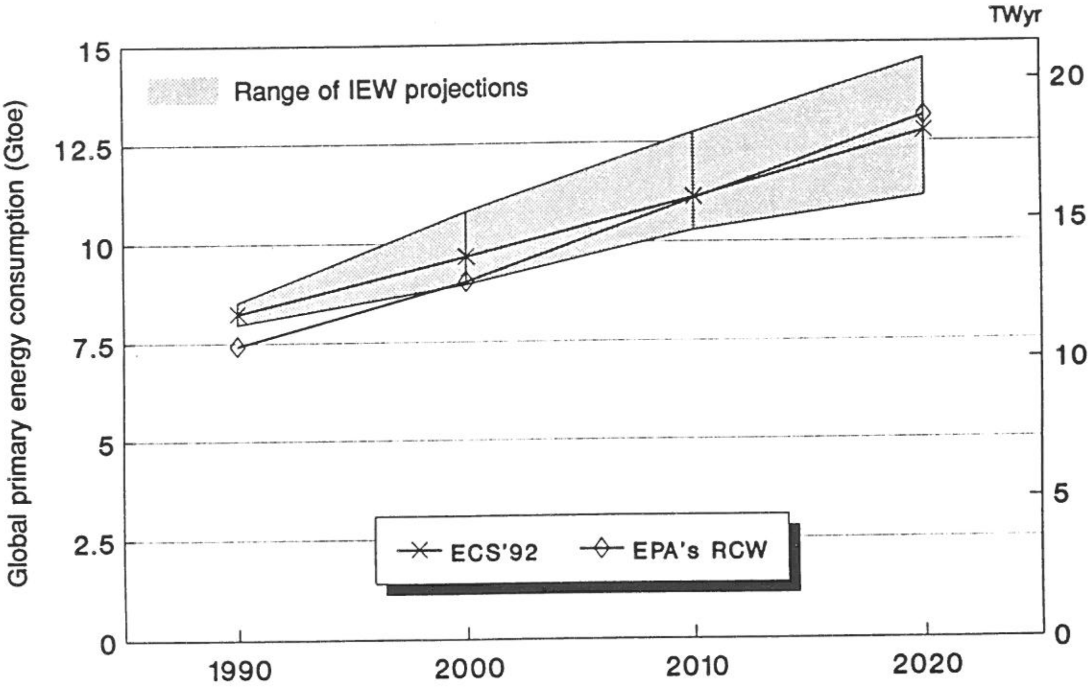


Figure 1-7. Global primary energy consumption 1990–2020; range of IEW projections and the scenarios of ECS'92 and the EPA's RCW.

1.2 The Consensus View of Future Energy and Emission Scenarios

Since 1981, Stanford University and IIASA have jointly organized a series of International Energy Workshops (IEW) with the aim of comparing energy projections made by different groups around the world and analyzing their differences (Manne and Schrattenholzer, 1992). These 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 (slightly more than 2% per year). The IEW median projection corresponds to an average annual growth rate of 1.4%, which would lead to an absolute increase from 8.3 to 12.7 GToe (11.8 to 18 TWyr/yr). Figure 1-7 shows the range of these IEW projections in comparison with two reference scenarios (described more fully in Chapter 8): the US EPA's RCW (Rapidly Changing World) scenario and the ECS'92 scenario developed for this study. The figure shows that the ECS'92 scenario falls just below the median of the IEW projections. The EPA's RCW (for which there seem to have been some calibration problems for the year 1990) moves toward the high end of the IEW range.

The most prominent international effort to analyze global greenhouse gas emissions, atmospheric concentrations, impacts and response strategies has been undertaken by the Intergovernmental Panel on Climate Change (IPCC, 1990). Within the IPCC, *inter alia*,

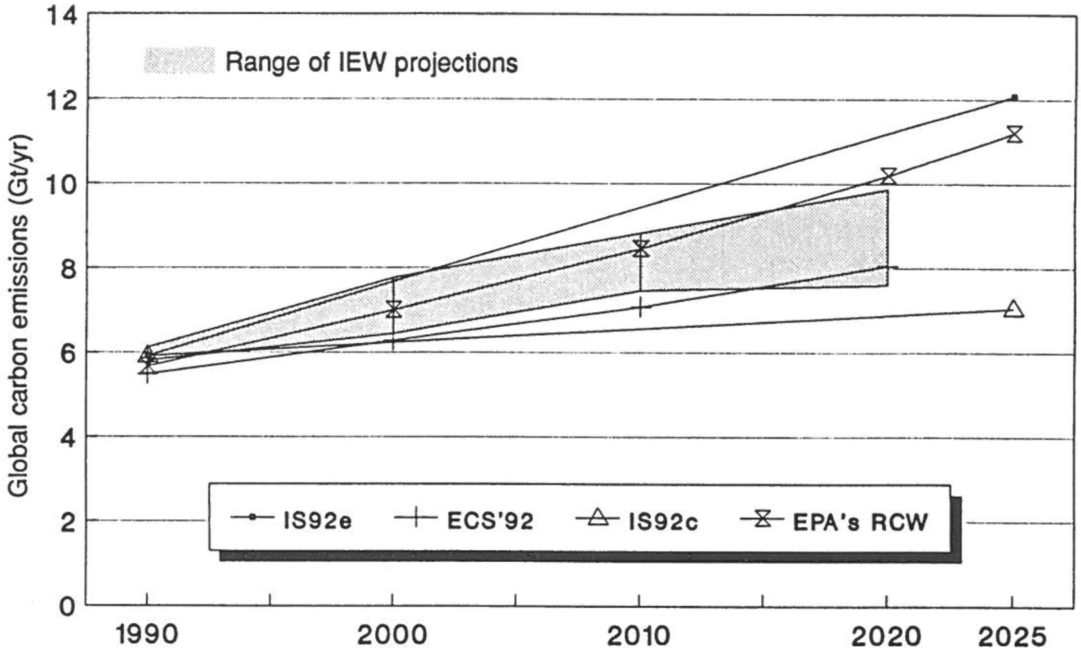


Figure 1-8. Global energy-related carbon emissions scenarios, 1990–2020; range of IEW projections, EPA's RCW, ECS'92, and range of IPCC scenarios (IS92c and e).

scenarios of possible future emissions are formulated corresponding to an atmospheric concentration equivalent of a doubling CO_2 over pre-industrial levels during the next century. Subsequently, additional emission scenarios were developed in which atmospheric concentrations of greenhouse gases are stabilized at a level less than a doubling of CO_2 equivalent and then further reduced. The IPCC (1992) has now significantly increased the range of scenarios to six, by defining two CO_2 emission scenarios above the old reference (IS90) and four below it. The CO_2 emissions (from energy production, conversion and end use, cement production, and deforestation) projected by these scenarios ranges from less than 5 to more than 35 Gt of carbon in the year 2100. The main factors underlying this variability are population, economic growth, and the availability of fossil energy resources. As a merely quantitative classification, two of the six IPCC scenarios could be described as "high" (IS92e and f), two as "business-as-usual" (IS92a and b), and two as "Low" (IS92c and d). The assumptions leading to total emissions of some 10 Gt of carbon in the year 2100 (in IS92c) include a world population of not more than 6.4 billion, average annual economic growth rates of 1.2% between 1990 and 2100, and primary energy availabilities favoring nuclear energy over to fossil fuels. In contrast, the low case (IS92d), in which less than 5 Gt of carbon are emitted annually, includes higher economic growth (2% per annum up to the year 2100) but also a high availability of renewable energy sources, combined with powerful international agreements on emission controls.

Calibrating the IPCC scenarios to the actual 1990 emissions of fossil fuels makes them comparable with the IEW poll responses up to the year 2020. In Figure 1-8, the two extreme IPCC scenarios (IS92c and e), the EPA's RCW and ECS'92 are plotted, together with the IEW range. This comparison shows that the new low IPCC scenario is still optimistic, but much closer to the IEW range than its older cousins. In particular, annual emissions in all new scenarios rise between 1990 and 2020. At the same time, the high scenario (IS92e) seems very high by IEW poll standards. Likewise, the exponential growth of the EPA's RCW scenario moves it close to the IPCC high scenario (IS92e) by 2020.

1.3 Alternative Views

In contrast to the business-as-usual scenarios that attempt to describe likely developments, typical energy efficiency scenarios are *normative* or *prescriptive*, and thus describe a desirable future. An innovative action program to arrest global warming adopted by Japan describes desirable emission reductions in the future and prescribes specific targets for the stabilization of CO_2 emissions in Japan (Ogawa, 1991). This is in stark contrast with the scenarios that describe "hands-off" developments. The Japanese Action Program identifies a desirable emission trajectory to be reached through progress in developing innovative technologies such as solar, hydrogen and other new forms of energy, as well as the fixation of CO_2.

A well-known global normative energy scenario was described by Goldemberg *et al.* (1988). Their base case describes global primary energy use of 8 Gtoe (11 TWyr) in the year 2030. They conclude that a per-capita energy use of approximately 1 kWyr/yr in developing countries could "provide enough energy services not only to satisfy the basic human needs of the whole population but also to raise their standard of living to the level of Western Europe". Their results suggest that the industrialized countries could reduce their per-capita use of final energy – mainly by improving energy efficiency – from 4.9 to 2.5 kWyr/yr. Along with this low level of primary energy consumption are carbon emissions of just under 5 Gt in the year 2020, a bit lower than the current emission levels.

Soon after Goldemberg *et al.* published their analysis, other studies began to look specifically into measures to reduce CO_2 emissions. A prominent example is the report by the Office of Technology Assessment (OTA, 1991a), which assesses the US situation. In addition to a base scenario, the OTA defines two reduction scenarios, nicknamed Moderate and Tough. CO_2 reductions are measured against 1987 total US emissions. The authors of the OTA report express the opinion that the reductions of the Moderate scenario (31.3% of 1987 emissions, corresponding to an average annual reduction of 1.3%) can be achieved at a net saving, albeit with substantial shifts in the economy. The net savings of the Tough scenario are estimated at between $20 and $150 billion per annum (in 1987 dollars). The range of estimated benefits includes a reduction in CO_2 emissions of between 67 and 76% of 1987 emissions (4 and 5% per annum). Relative to the emissions in the Base scenario in 2015, these reductions correspond to 47 and 53%, respectively. In the Moderate scenario, the bulk of the savings potential (40%) is attributed to the residential and commercial sectors. These percentages drop to 28% in the Tough scenario, where the significant increase in saving potential is due to increased emission reductions in the transportation and industrial sectors. A large share of emission reductions in the Tough scenario is achieved by afforestation and use of biomass.

A major effort to study greenhouse gas (GHG) emission reductions in the developing world has been launched by the Asian Energy Institute (AEI, 1991). The first results show that greenhouse gas emissions can be reduced in the developing countries, but at a price. Major options to reduce CO_2 emissions for less than $100 per tonne of carbon include afforestation, the increased use of hydropower in China, efficiency improvements, coal washing in India, and generally the increased use of biomass fuels for electricity generation.

1.4 Carbon Emissions and Carbon "Wealth"

This brief comparison of IEW projections, IPCC, and the normative type of scenarios suggests that the "business-as-usual" type of development implies a substantial increase in global CO_2 emissions. Thus, there is a need to reduce the sources of greenhouse gases as much as possible and, at the same time, to enhance the natural sinks of CO_2. There is also the question of how the limited "resource" of future CO_2 releases should be allocated. In some sense, this is analogous to the concerns about limited global fossil resources during the 1970s.

During the 1970s, the focus of many global energy studies was on resource availability and the possible time horizons for introducing new energy supply sources. Today, the predominant question is whether it will actually be possible to continue consuming energy at current or even higher rates in the future. What is dramatically different is the (possible) shift from resource to environmental constraints. The ultimate global resource could be the environment rather than the recoverable energy reserves and resources. The fortunate fact is that the "carbon wealth" of the Earth is large indeed. As technology and production economics improve, it will be possible to tap even larger fractions of the total resource base and part of the already known occurrences, implying an availability of fossil fuels for centuries rather than decades.

The carbon content of the total fossil resource base (some 3700 Gt) is about five times larger than the current atmospheric carbon loading of about 760 Gt (a more detailed discussion is given in Chapter 4). We have classified the global resource base (carbon wealth) by the estimated recovery costs and, in that way, have derived a global "carbon supply curve" as shown in Figure 1-9.

This figure shows that the real problem lies in the fact that as much as 3000 Gt of fossil energy resources could be recovered at relatively modest costs [below $20 per barrel oil-equivalent (boe), or for less than $180 per tonne of carbon]. If actually mined and used as fuel, this could triple the current atmospheric CO_2 concentration. This points to the urgent need to identify clean fossil energy technologies that could mitigate CO_2 emissions if larger shares of carbon wealth are ever consumed.

1.5 Second- and Third-Generation Technologies

In the long run there is a clear need to shift to energy sources with low carbon contents, such as natural gas, and ultimately to those without any carbon whatsoever, such as solar, nuclear and possibly in the far future to fundamentally new energy sources such as fusion. Technological and economic structural changes will also be important in improving efficiency and in reducing carbon emissions. All of these near, medium and far future options need to be assessed from the point of view of their availability, costs and potential contribution to mitigation. However, the problem is that some may be available in the near future albeit with uncertain costs, whereas others may not even be technically feasible today so that their availability as options is completely uncertain.

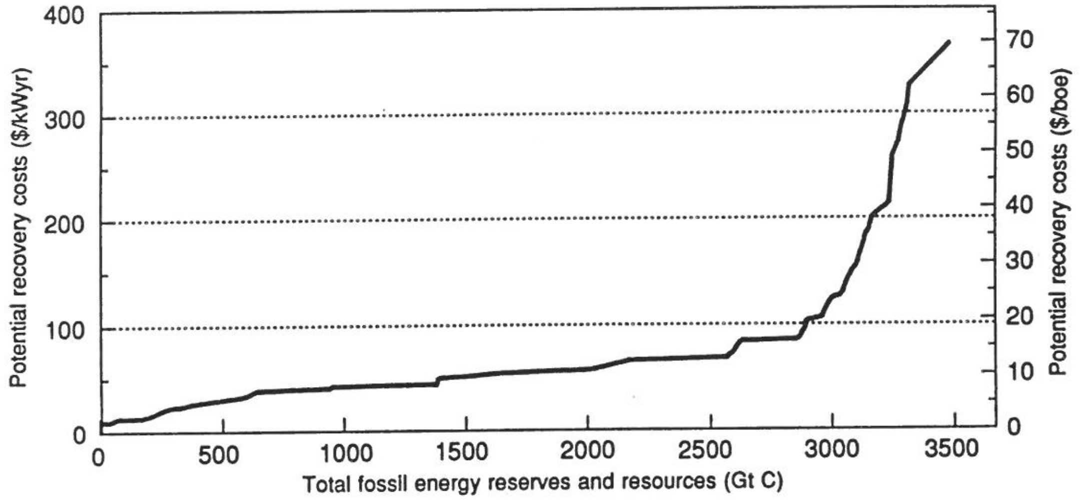


Figure 1-9. Global carbon supply curve, based on fossil reserves and resources, in Gt carbon (cumulative) versus potential recovery costs, in 1990 dollars per barrel (oil-equivalent). Costs include exploration, development, and extraction; modest technological improvements are considered.

There is therefore a need to introduce some classifications in the various mitigation options in order to guarantee a consistent assessment of their potential contributions.

In this study, we employ a very simple two-tier classification scheme by dividing all possible future technologies into two distinct groups: second- and the third-generation technologies. Second-generation technologies encompass all options that can be expected to make a "significant" contribution before the year 2030, and the third-generation technologies thereafter. More precisely, the notion of a "significant" contribution refers to the market share achieved by the new technology by 2030 or thereafter and is based on the characterization of technologies practiced in innovation and diffusion research. This two-tier classification is clearly very simplistic and represents a first attempt to separate the long-term from very long-term options. More sophisticated, multidimensional classification schemes will need to be developed in the future if the time horizon adopted in this study (more than a century) becomes more common practice. Such study horizons are dictated by the long time constants involved in the anthropogenic causes of climatic change. In all such cases it is no longer possible to group all options together since some are already practiced (perhaps on a very humble scale today, such as photovoltaic electricity), and some are not yet feasible (such as solar power satellites).

The rate at which new, efficient and less carbon-intensive technologies can be introduced depends, among other factors, on the vintage structure of the energy system, on annual market growth, on the policy and institutional barriers and incentives, on the relative merits in terms of the technical and environmental performance of new systems, and on the economic advantages to adopt or not. These are some of the more important factors that will determine the diffusion of new energy technologies.

1.5.1 Diffusion and Evolution of Technologies

One of the contributions of Schumpeter (1939) that is often cited with reference to technological change and economic development, is the distinction between invention, innovation and diffusion. According to this definition, invention concerns the first development of a new artifact or process, innovation entails its economic application, and diffusion describes its introduction by buyers or competitors (Dosi, 1991). Diffusion starts after the successful commercialization of a basic innovation, leading to the creation of a new process, product, or service. Eventually, some innovations replace their predecessors, and some become pervasive in that they lead to a host of interrelated new activities in many sectors, creating whole new industries, and thereby contributing to social and economic development. Electricity, automobiles or computers are examples of innovations that have changed many facets of everyday life.

The characteristic S-shaped diffusion pattern and the resulting rates of diffusion represent a macro aggregate of an underlying complexity of adoption causes. Diffusion phenomena are probably best conceptualized as proceeding through various stages of a "diffusion life cycle". Each stage is characterized by different market niches, different determinants of diffusion, and different relationships to other diffusion processes, both of a competitive and interdependent nature (Grübler, 1991a).

As a technology and its applications mature, the awareness of possible disadvantages become evident. Improvements then cover an increasingly smaller domain of technical and managerial possibilities. Saturation starts, and the problems associated with widespread and large-scale applications become important. The social and institutional responses are rather nonlinear and disruptive, and the awareness of social disadvantages and risks often increases rapidly, making further adoption unacceptable. The perceived disadvantages of further applications can outpace incremental improvements as the technological and social potentials appear to be exhausted. Further adoption is virtually blocked. During the periods when old systems saturate, new technoeconomic paradigms emerge; the old development trajectory associated with the previous generation of pervasive technologies and institutional forms is not only challenged, but in time is also replaced by the new solutions. Dosi *et al.* (1988) have identified innovation diffusion and the resulting technological change as a fundamental force in shaping the pattern of transformation of an economy. Technological change is both disruptive during the transition period (marked by fluctuations, frictions, and occasionally crises) and a source of order for the directions of change and the dynamic adjustment process as new technologies diffuse through national and international economies. The question is whether today we are at the brink of a paradigm change from a material and carbon-intensive development trajectory to a new one with a closed economic metabolism and a high degree of environmental compatibility. Closing the carbon cycle and general decarbonization would also be a salient characteristic of such a new development trajectory that could result from a globally pervasive technoeconomic paradigm shift.

The replacement rates of old technologies by new ones throughout an economy differ considerably. Studies of innovation diffusion indicate that larger systems such as infrastructures tend to be replaced by new ones at relatively slow rates. All too frequently there is over-optimism about how rapid the diffusion of new technologies might be. The historiography 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 whole clusters of technological and organizational innovations. For example, the replacement of older energy sources by newer ones took on the order of 80–90 years. Figure 1-10 shows that the diffusion of new energy sources and the replacement of the older by newer ones takes of the order of almost 100 years at the global

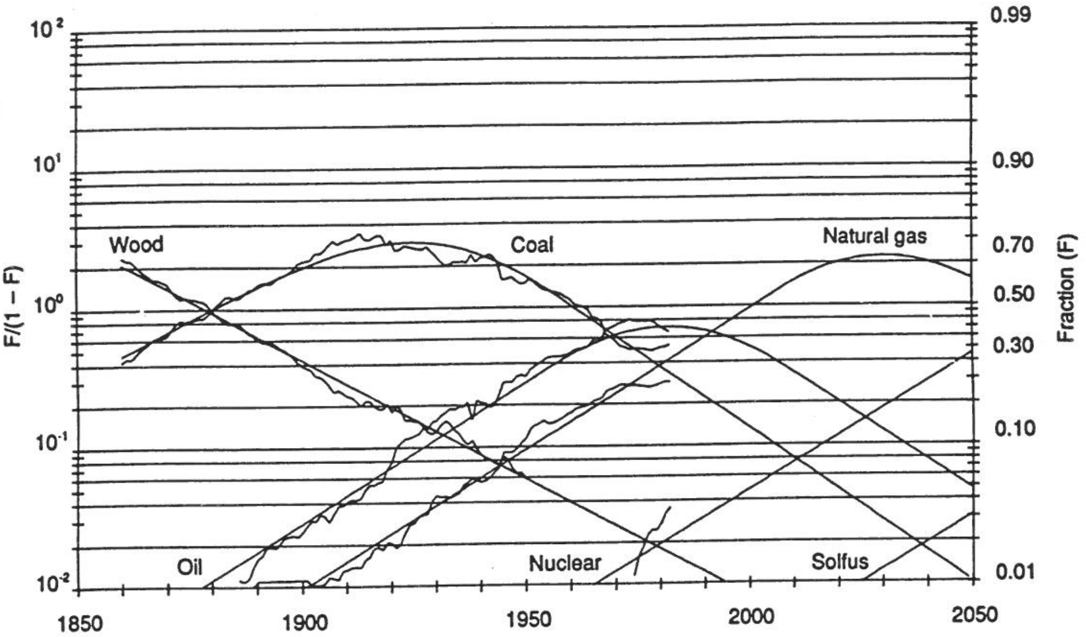


Figure 1-10. Global primary energy substitution.

level. The important issue in the context of the present study is to determine the rate at which new energy technologies can be expected to replace older ones, thereby once more reducing the overall carbon intensity and improving the efficiency of energy systems.

Technologies that are closer to the ultimate consumer have a shorter life span than infrastructures, so that replacement processes tend to be faster. For example, automobiles age much faster than power plants or housing stocks, and to a large extent this determines the rates of replacement. Vehicle fleets can be replaced in about three decades, as can locomotive rolling stock and railroad cars, whereas aircraft have a longer service life. Another extreme example is light bulbs, which could be replaced within a short time span of a few years. The mean duration for replacing most systems is about 30–40 years. If we assume that the new systems now being introduced are twice as energy efficient as those they are replacing, then in about 30 years overall efficiency could be twice as high as it is today. This implies an annual efficiency improvement rate of more than 2.3%. In addition, should demand grow so that the new systems are introduced faster than replacement needs, then improvement rates could be higher. In any case, the above examples illustrate that it will be difficult to achieve overall improvement rates of energy and carbon intensity higher than a few percent per year.

1.6 Policy and Institutional Dimension

This section gives an overview of the policy context within which less greenhouse-gas-intensive technologies might be developed and diffused worldwide. Section 1.6.1 reviews the many proposals regarding appropriate commitments to slow global warming. That is, how much of the emissions of greenhouse gases should be controlled, how to share the burden, and what balance needs to be struck between the mitigation of and adaptation to climatic change. Section 1.6.2 reviews proposals on the mechanisms for slowing global warming, especially those related to mitigation, and Section 1.6.3 very briefly discusses the institutional reforms that might accompany an effort to slow global warming. Finally, Section 1.6.4 discusses the actual policy efforts under way at the local, regional and global levels, with special attention to international negotiating processes.

1.6.1 Commitments

Several quantified CO_2 reduction targets have gained some prominence. At the 1988 meeting of scientists and policy makers in Toronto, Canada, the target of a 20% reduction in CO_2 emissions by the year 2005 was adopted as a near-term goal for all countries. Several scientists have proposed that the rate of warming should not exceed approximately 0.1 °C per decade, a number they base on their assessment of how rapidly some ecosystems can adapt to a changing climate. Those strategies probably require a steady emissions reduction by 75% between now and the end of the next century. Recently, the term "stabilization" has become a popular target for climate control. It now appears that many countries view the stabilization of *emissions* as a near-term goal (e.g., within the next 10–15 years). As a longer-term goal, the stabilization of *concentrations* has been proposed (e.g., INC, 1991). Harvey (1989) has calculated that to stabilize concentrations of CO_2 will initially require a reduction in emissions by about one-half from current levels.

An obvious criterion by which an effective international agreement to slow global warming must be evaluated is fairness. However, it is unclear how the burden would be shared in the fairest possible agreement, or how issues of fairness will be settled when they conflict with other demands such as economic efficiency and the desire to maintain the status quo. Several different criteria for a fair agreement are outlined below, and are discussed in more detail by Grubb (1989), Young (1991), Subak and Clark (1991), Burtraw and Toman (1991), Fujii (1990), and Grübler and Fujii (1991):

1. Future emissions should be allowed on a per-capita basis.
2. No emissions should be allowed.
3. Any person can pollute any amount, provide he or she pays a fine (the "polluter-pays" principle).
4. The required reduction should be proportional to past emissions.
5. The "natural sink" for greenhouse gases should be distributed on a per-capita basis.
6. The right to emit should be distributed equally between all (current, past, and future) generations.
7. Per-capita allocation should be done on the basis of the adult population.

At least in the short term, criteria such as these have given way to a status quo in the international debate on how much to slow global warming and how to share the burden.

Many of the arguments underlying the above fairness criteria can be extended to adaptation to climate change. However, enormous practical problems remain for implementing any system of compensation: how to identify which climate changes are natural, which are due to past and present greenhouse gas emissions, who bears the burden of responsibility, and how large a payment is needed?

1.6.2 Mechanisms

This study shows that there are many opportunities to control emissions. The critical policy question, however, is what are the appropriate instruments to achieve emission control? Two broad strategies have been widely discussed: first, rule-based or regulatory approaches, also known as "command-and-control"; and second, market-based approaches such as the use of tradable permits and emission fees. Here, we review both of those and also briefly consider some additional approaches.

The traditional way to control pollution has been to devise regulations for polluters. The main critique of regulation has come from economists, who have argued that the costs have been excessive in relation to what has been achieved. Some have also suggested that regulation, because it vests control with government bureaucrats rather than in the decentralized market, is not democratic and certainly not efficient.

The critique of regulation has led an increasing number of scholars (mostly but not entirely economists) to advocate the wider use of markets to control pollution. Here, we examine two broad classes of market-based approaches.

First, government can use the price signal directly through additional taxes (or subsidies) in order to penalize (or reward) behavior that produces (or reduces) greenhouse effects. The obvious proposal is a carbon tax, for which there is widespread (but not universal) theoretical support, at least among economists (e.g., see Dornbusch and Poterba, 1991). However, macroeconomic energy models have computed that tax levels of \$50–250 per tonne of carbon (and, in some cases, even higher) would be needed to freeze the growth in carbon emissions, with even higher taxes needed to achieve a reduction (for a review of the models, see Nordhaus, 1991). Second, governments can indirectly use the price mechanism by issuing tradable emission permits.

One of the main objections to market-based approaches is that in practice they rarely meet their theoretical goals. In some respects, market-based approaches are administratively more complex than simple regulation, although generalizations are difficult to fashion.

A third and possibly powerful mechanism for slowing global warming is the emergence of norms that discourage carbon-intensive behavior through general environmental education. For example, there is now a recycling norm in many countries. Peer pressure (and children who learn about recycling from the media and at school) helps to bring the population into compliance with the norm, with the result that recycling has increased markedly in OECD countries (OECD, 1989). Environmental awareness may provide a selection mechanism that favors dematerialization of society, including further decarbonization and also reduced emissions of other greenhouse gases.

1.6.3 Institutions

The particular set of institutions needed to implement international and domestic efforts to slow global warming will, of course, depend upon the mechanisms chosen for climate control. For example, a system of tradable permits will require an authority to monitor and enforce the trading rules and a system of technology transfer to developing countries will require local institutions (see Chapter 7).

However, there may also be some institutional functions that are generic and thus will be part of any effort to control greenhouse emissions (Victor *et al.*, 1992). For example, regardless of international mechanisms there will surely be a need for the exchange of technical data and emissions inventories. Indeed, this has been part of most international environmental treaties, such as the Montreal Protocol and the United Nations Framework Convention on Climate Change. There may also be a generic need for a system of review and assessment of policies. Regardless of the exact set of mechanisms each country employs to slow global warming, it will be important to have an international process to disseminate worldwide information on how different nations are adjusting their policies, and how effective those adjustments have been. There are many precedents for such reviews and assessments, including the International Labor Organization (ILO, 1991) the International Monetary Fund (Chayes, 1991), and the Organisation for Economic Cooperation and Development (e.g., see Nichols and Crawford, 1983).

1.6.4 Greenhouse Diplomacy: The State of Play

The above discussion reflects the many proposals on how best to structure domestic and international efforts to slow global warming. Meanwhile, a number of policy efforts are already under way. At the local level, several cities have adopted targets for controlling their CO_2 emissions. At the national level, nearly all OECD countries have committed to halt the growth in CO_2 emissions. However, few have actually implemented policies to achieve those emission controls, although several European countries are now in various stages of introducing carbon taxes (for a review of greenhouse tax policies in the Nordic countries, see Haugland *et al.*, 1992; for a review of the Swedish tax reform, which includes a carbon tax, see SEPA, 1991). At the regional level, the EC has adopted a target of freezing the growth of carbon emissions by the year 2000 and is studying a hybrid carbon tax as one of several means to meet that goal (FTBI, 1991; BNA, 1991).

At the global level, negotiations through the Intergovernmental Negotiating Committee (INC), which was established by the United Nations at the end of 1990 have resulted in the Framework Convention on Climate Change. It commits all parties to develop inventories of greenhouse sources and sinks, develop and implement mitigation and adaptation measures, promote transfer of technologies, practices, and processes to reduce greenhouse gas emissions that result from energy system and other anthropogenic activities, to consider climate change in all relevant policies with a view to minimize adverse economic effects and to exchange relevant information related to climate change and response policies (INC, 1992). However, the Framework Convention does not forsee any specific reduction commitments or targets.

Finally, it should be noted that these negotiations were taking place in parallel with a larger effort to link environmental and economic development issues through the UN Conference on Environment and Development (UNCED) held in Rio de Janeiro in June 1992. First is a series of principles related to environment and development that could guide future efforts, much the way the principles from the 1972 Stockholm meeting have helped to make salient and shape the means of environmental protection over the last 20 years. Second is an action plan – "Agenda 21" – on many topics, including the transfer of environmentally benign technologies, protection of the atmosphere, cooperation and promotion of scientific research, and the strengthening of environmental institutions (UNCED, 1992a). It is not clear which of the Agenda 21 goals will be met since these programs are expensive: UNCED has estimated the price at approximately $500 billion per year (UNCED, 1992b). Nonetheless, on the issue of energy technology, the combination of the INC negotiations and the UNCED process are sure to promote wider adoption of less polluting and more efficient innovations.

Energy Vol. 18, No. 5, pp. 421–435, 1993
Printed in Great Britain. All rights reserved

0360-5442/93 $6.00 + 0.00

Chapter 2

Energy Conversion, Conservation, and Efficiency†

2.1 Introduction

Modern societies depend on elaborate and complex systems for converting energy from less to more desirable forms. The overall effectiveness of these systems depends on the structure of energy supply and conversion and on the patterns of energy end uses. It is in this broader perspective of energy systems and services that we analyze current levels of efficiency and evaluate the potentials of efficiency improvements and conservation measures. We also analyze technical aspects of energy use with emphasis on assessing the prevailing efficiencies with a number of examples from developing and developed regions.

Much has been already written about the efficiency of single-step energy conversion and transformation processes, but little attention has been paid to the overall efficiency of energy use. The overall efficiency is the result of compounding the efficiencies of the whole chain of energy supply, conversion and distribution processes. The weakest link in the analysis of the overall efficiency of energy chains is in fact energy end use. This is due in part to the inaccessibility or lack of appropriate statistics concerning the vintage, and in part to the structure of end-use devices and to changing patterns of their use.

The efficient provision of energy services not only reduces the required amounts of primary energy but in general also reduces adverse environmental impacts. However, it should be mentioned that efficiency is an important but not the only determinant of energy systems performance. Other determinants include, for example, the availability of power, controllability of energy flows, capital and operating costs, etc.

Energy and available work can be used more or less efficiently; this sometimes depends on technical factors or the capacity utilization, but more often it is a question of economic and social choice, i.e., the question of lifestyles and consequently the kinds of energy services that are demanded and provided. We consider both ways of reducing primary energy requirements: efficiency improvements and conservation.

---

†Nebojša Nakićenović with contributions by Arnulf Grübler.

2.1.1 Energy Conversion

Primary energy is the energy that is recovered or gathered directly from natural sources. Typical examples are fossil energy forms such as mined coal or produced crude oil and natural gas, collected biomass or harnessed hydroelectric power, solar energy absorbed by collectors, and heat produced in a nuclear reactor. For the most part, primary energy is first converted into *secondary energy*, such as electricity, gasoline, jet fuel, heating oil, and charcoal.

Final energy forms are fuels, electricity and other energy carriers that are delivered to the point of consumption and subsequently used in various devices such as appliances, machines, and vehicles: gasoline at a service station, electricity in a home, or fuelwood in a barn.

The next energy transformation is the conversion of final energy in end-use devices to *useful energy* forms such as work and heat. Useful energy is measured at the shaft of an automobile engine or an industrial electric motor, the heat of household radiators or an industrial boiler, or the luminosity of a light bulb. The application of useful energy serves to provide *energy services* such as a moving vehicle, a warm room, or process heat. It is important to realize that in providing goods and services (say, a well-lit room or computer software), energy services are a factor input for the transformation and embodiment of other resources – capital, materials, labor skills and know-how.

2.1.2 Energy Conservation

In the past, most of the reductions in the specific energy needs and energy intensity have been achieved through improvements in technical efficiency, while today it is often claimed that it will be necessary to place higher emphasis on energy conservation in the future. Here, we refer to all reductions in specific energy needs for performing a given task as *efficiency* improvements, and all reductions in energy needs due to changes in the nature or level of the required energy services as *conservation*. For example, the use of a more fuel-efficient automobile for a particular trip would be a question of efficiency improvement, while any reductions in energy needs for this given trip that are related to the improved utilization of the automobile, improved traffic conditions, etc., would be a question of conservation measures. In addition, alternatives to undertaking the given trip would also be conservation measures, such as walking or making a telephone call.

This concept of conservation measures, however, can be used in different contexts; sometimes it could refer to what we call service efficiency and at others it could refer to actual changes in social behavior and lifestyles. The concept of service efficiency is analogous to energy efficiency, meaning the provision of a given task with less useful energy without loss of "service" quality. Other social behavioral and lifestyle measures that reduce actual provision of services and thus also reduce energy requirements imply a loss of "service", whether voluntary or not. This is obviously related to issues such as social norms and lifestyles. Austerity in some social and economic situations might actually be a virtue. In post-war Japan, the use of *Kotasy* was associated with having a "cool head and warm feet" and therefore also within a positive social context rather than with sacrifices (Yamaji, 1991). The same could happen with some energy conservation measures in the future. We consider conservation measures and their potential improvement only to the extent that they are related to energy services, but not those that imply a loss of service or austerity measures.

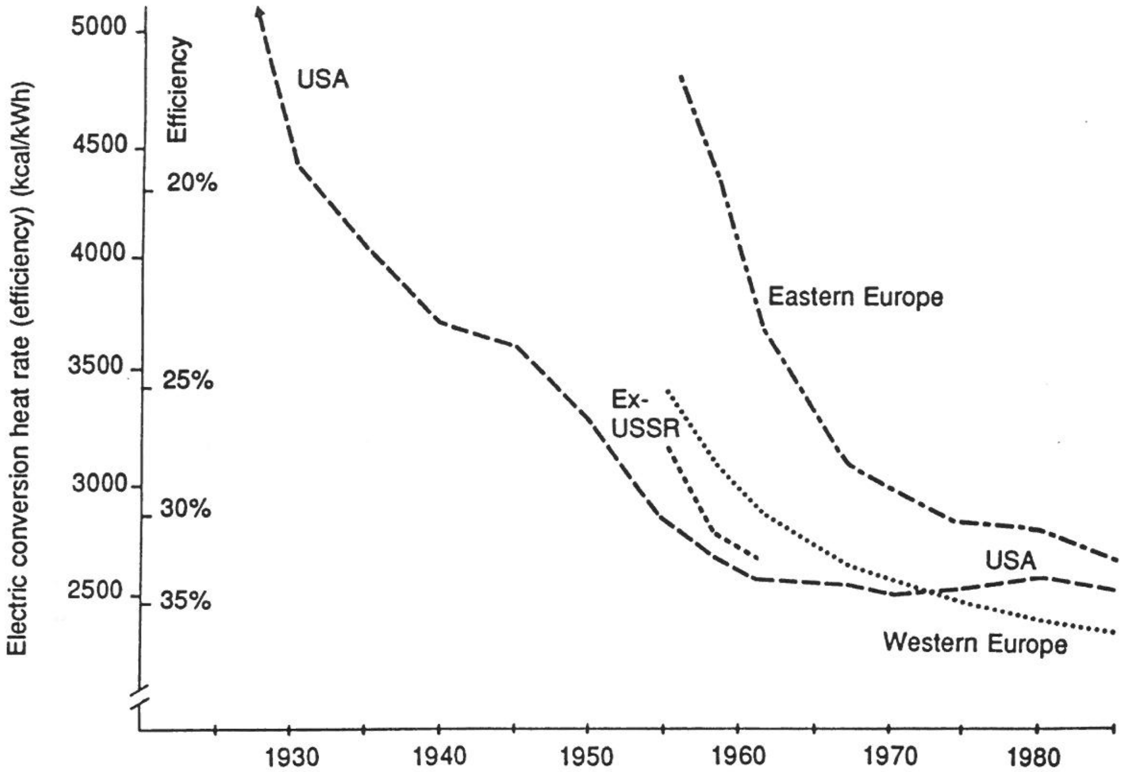


Figure 2-1. Improvements in electric conversion efficiency in the USA, Western Europe, and the former USSR and Eastern Europe (Source: Nakićenović *et al.*, 1990).

2.1.3 Energy Efficiency

Decarbonization through efficiency improvements is the fundamental option for achieving environmentally compatible energy development. Efficiency improvements reduce most of the adverse environmental impacts of energy, including greenhouse gas emissions, while they also lead to lower primary energy inputs and therefore to lower fuel costs. However, efficiency improvements are rarely a "free lunch". Investments in new equipment, and institutional and organizational changes are necessary to deliver energy services with lower primary energy inputs. Energy efficiency improvements also have to compete with other investments throughout the economy. This is a critical factor, especially for most of the developing economies.

Efficiency is usually measured as the ratio of energy output to input. Measured this way, energy efficiency improvements have already been achieved for almost all types of energy conversion facilities. For example, dramatic improvements in fuel conversion efficiencies were achieved in electricity generation during this century. The prevailing efficiency of electricity generation was about 5% around the turn of the century, whereas today, the average efficiency in OECD countries is about 36% and the best combined-cycle natural gas-fired power plants can achieve more than 50% efficiency.

Figure 2-1 illustrates the historical improvements in electric conversion efficiency in the USA and Western and the former Eastern Europe, showing that sevenfold efficiency increases have been achieved in recent decades.

Another way of measuring the overall efficiency of energy use is to determine the ratio of primary energy consumption divided by the gross domestic product (GDP), usually called the energy intensity. On the average, the energy intensity of most developed countries has declined by about 1% per year, indicating that during the last 70 years the energy requirements for producing a unit value added have been halved.

2.2 Efficiency and Conservation Potentials

Before we attempt to assess the energy efficiency and conservation potentials, it is useful to review the actual efficiencies of individual conversion and end-use devices and systems. Figure 2-2 shows various pathways of energy conversion from one form to another and gives approximate net efficiencies. There is a considerable difference between the best performance and average performance of most of the conversion devices listed; the bars in Figure 2-2 indicate the ranges of representative values. The conversion efficiencies cover a wide range of values from less than 5% for the ordinary incandescent lamp to 99% for large electric generators. This also illustrates the large potential for efficiency improvements. For example, the replacement of steam by diesel locomotives improves the efficiency fourfold and the replacement of open wood fires with stoves by the same amount.

To determine how large the improvement opportunities are if, for example, the most efficient devices and systems are used, we have to evaluate the overall efficiency of energy systems. This means that we first have to calculate the aggregate efficiency of different energy chains and then to determine the weighted average efficiency of the whole system. This can be done by taking the efficiencies given in Figure 2-2 and multiplying them to obtain representative primary to useful energy chains that provide, for example, low-temperature space heating, vehicles propulsion, and lighting.

2.2.1 Representative Energy Efficiencies

Space Heating: With a boiler efficiency of about 80% for oil and/or gas central heating systems, the overall primary to useful energy efficiency of central heating system might be on the order of about 60%. There are additional conversion losses in going from the boiler heat to radiators and eventually providing the service of a warm room. Resistance is less efficient because electricity generation is on average 36% efficient, so that the overall efficiency might be around 30% after accounting for electricity transport and distribution. A heat pump, on the other hand, can provide space heating with a slightly higher efficiency. Depending on the coefficient of performance (COP), the overall efficiency could reach 80%.

Cogeneration of Electricity and Heat: The cogeneration of electricity and district heating is a typical example of how the overall efficiency of providing both power and heat can be substantially increased. In the cases of combined use of heat and electricity, the overall conversion efficiency of a power plant is much higher, in the range of 60–80%. This kind of enhancement of overall energy efficiencies is often hampered by the lack of useful applications of large amounts of low-temperature heat.

Lighting: Incandescent lamp efficiencies are about 4% when converting electricity into visible radiant energy, while fluorescent lamps can reach higher efficiencies of up to 35% with a typical value of 20%. This leads to an average efficiency of an electric light bulb of about 10% (some US estimates give a lower value of about 7%; see Ayres, 1988).

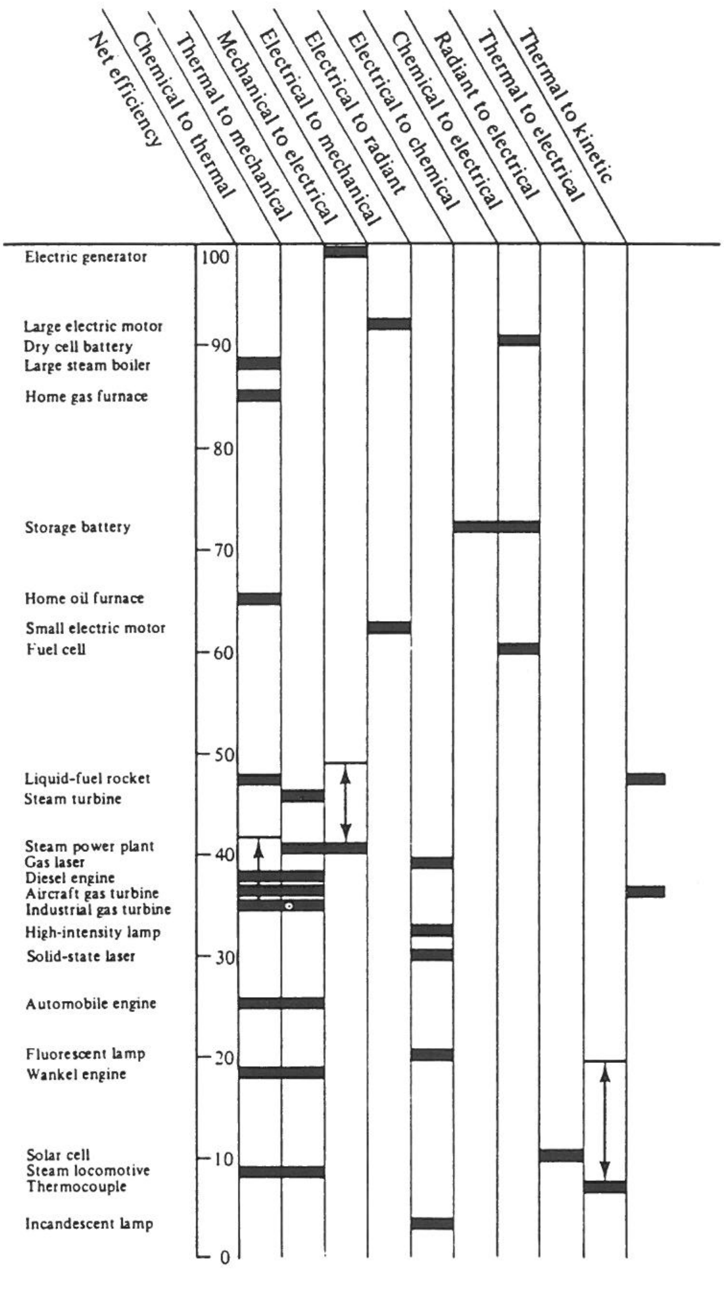


Figure 2-2. Efficiencies of various energy conversion pathways (Sources: Summers, 1971; Eden *et al.*, 1981).

Considering a 30% efficiency when converting primary energy into final electricity, the overall efficiency for lighting is about 3% or at most about 10% for fluorescent lamps.

Transportation: For illustrative purposes, we only briefly consider how the efficiency of a motor vehicle might be calculated. With an average efficiency for diesel engines of about 30% and for gasoline engines of about 20%, the overall primary to useful efficiency is probably closer to 15 and 20%, respectively. The transformation of mechanical to kinetic energy results in additional losses in the power train, rolling friction and aerodynamic drag. We estimate these losses at about 30% for automobiles and at 40% for trucks and buses. Parasitic loads such as refrigeration, hydraulic and compressed air drives, air conditioning, automatic transmission, power windows and power steering decrease the efficiencies as well. This results in an overall final to kinetic energy (or available vehicle-km) efficiency of 6–12%.

2.2.2 Energy Efficiency Balances

The above illustrative examples show that the overall efficiency of current energy systems in transforming primary to useful energy forms is somewhere between 3 and 30%. With the help of the energy balances for the market economies (OECD region), reforming economies (the former Eastern Europe) and developing economies given in Section 1.1, we now give more realistic estimates of the overall efficiencies from primary to useful energy.

Figures 2-3 to 2-5 show that the prevailing efficiencies of energy transformation from primary to useful forms range between 22 and 42%. The global average is about 34% as shown in Figure 2-6. The highest efficiencies prevail in the conversion of fuels from primary to secondary energy forms. Refinery efficiencies are about 90% and, on average, the conversion (incl. transport and distribution) of coal and gas also incurs rather low losses with efficiencies ranging from about 60 to almost 90%. The lowest fossil primary energy to final fuel efficiencies can be observed for natural gas in the developing economies (41%) and for natural gas and coal in the reforming economies (56 and 75%, respectively). Lower conversion efficiencies prevail for biomass transformation into final fuels; as low as 20% in the reforming economies. The generation of electricity is just as inefficient in comparison; about 36% in the market economies of the OECD countries, and often lower than 20% in both the reforming and developing economies. The global average is about 31%.

Overall, the primary to final energy conversion processes are quite efficient: the global average is about 74%; it is the highest in the developing economies with about 80% and lowest in economies in transition with 69%. It is perhaps counterintuitive that developing economies should have a *higher* efficiency than the economies in transition, although many individual energy chains such as electricity and natural gas are delivered with much *lower* efficiencies. The reason is that the shares of energy carriers with lower efficiency at present, electricity and natural gas, are much lower in the developing countries than in the former Soviet Union and Eastern Europe.

In comparison, the final to useful energy conversion efficiency is very low, with 46% at the global level and a range of only 30% in the economies in transition and almost 53% in the market economies. In general, natural gas and electricity have the highest end-use efficiencies compared with the lowest primary to final conversion rates. The lowest end-use efficiencies can be observed for biomass, with 17% at the global level and only 12% in the reforming and developing economies.

The resulting overall primary to useful energy efficiencies are well below 50%. It is 34% at the global level; lowest with 22% in the developing economies and the highest with 42% in the reforming economies. This is indeed a very surprising result. Generally, the energy systems of these economies are rather inefficient, especially when compared with the standards prevailing in the market economies of the OECD. Actually, this is exactly the case. All individual primary to useful energy chains are more efficient in the market than in the reforming economies. In some cases the differences are very large indeed. For example, electricity efficiency, with more than 22% is double of that

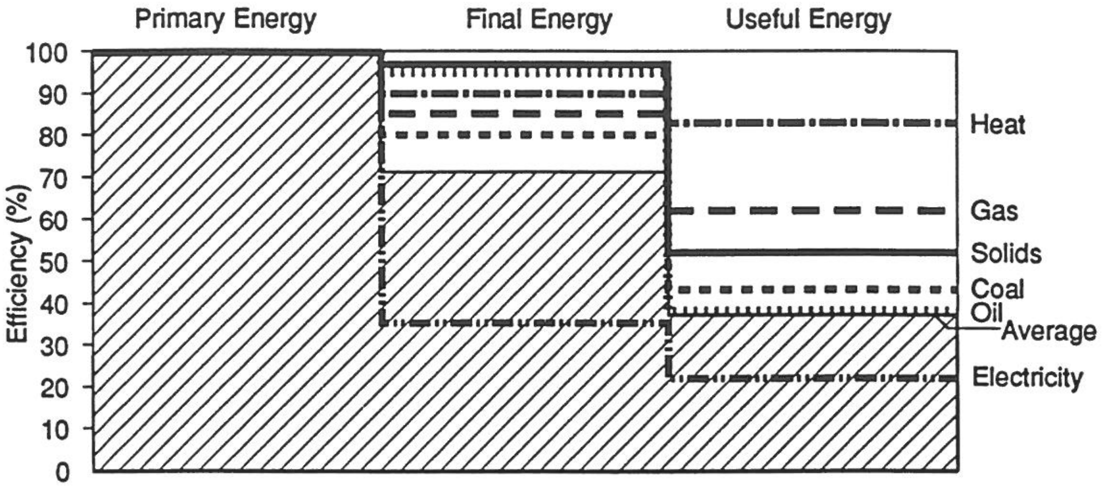


Figure 2-3. Energy efficiency in (industrialized) market economies, 1988; conversion efficiencies as percentages of primary energy. Vector-specific efficiencies exclude cogeneration; average includes district heating and cogeneration (also for Figures 2-4 to 2-8).

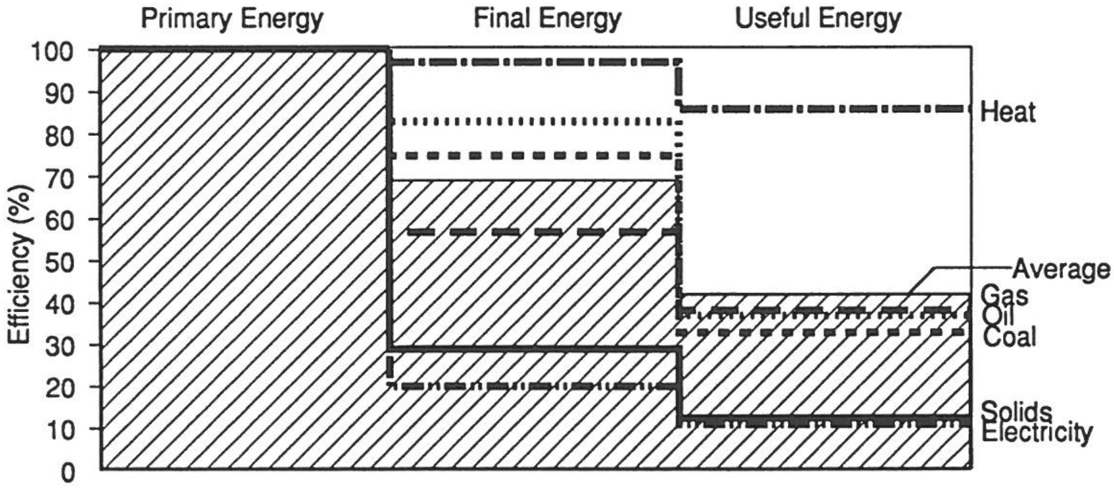


Figure 2-4. Energy efficiency in reforming economies, 1985; conversion efficiencies as percentages of primary energy.

in reforming economies (11%). The reason for the reverse situation with the overall aggregate efficiency is that the structure of the energy system in the reforming economies *favors* collective consumption and thus also *end-use efficiency.* People travel by public transport modes rather than private cars and they heat their homes using cogenerated heat rather than individual oil burners. Thus, while cars and buses are more fuel efficient in the market economies, traveling by bus in the reforming economies is more efficient than by car in the market economies.

The most important overall result is that energy end use is the least efficient part of all energy systems, and it is in this area that improvements would bring the greatest benefits. It also shows that even the most efficient technologies may not be sufficient to offset the energy-intensive lifestyles prevailing in very affluent market economies. Figure

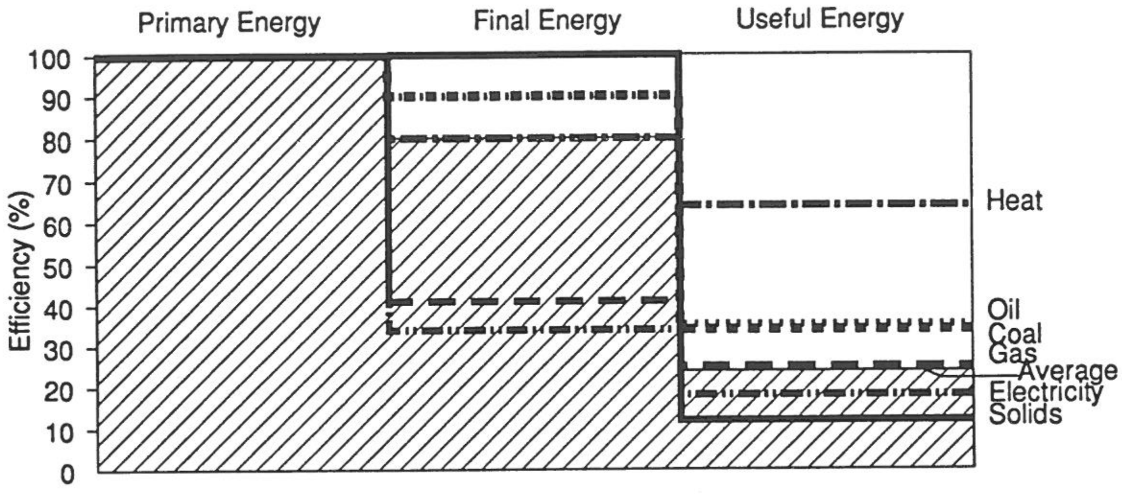


Figure 2-5. Energy efficiency in developing economies, 1988, conversion efficiencies as percentages of primary energy.

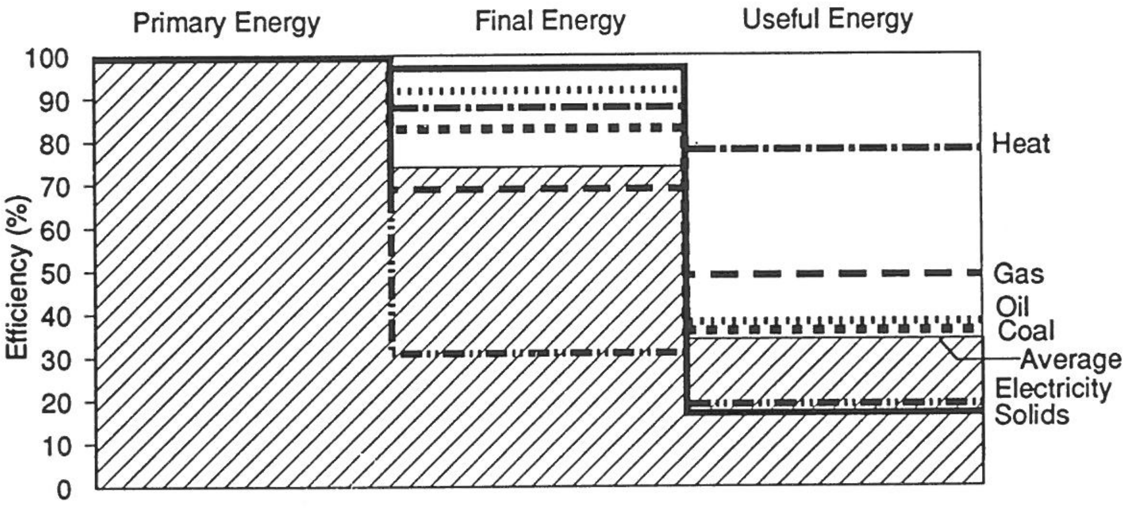


Figure 2-6. Global energy efficiency in the late 1980s; conversion efficiencies as percentages of primary energy.

2-7 shows the sectoral *useful energy* consumption in the three world regions, together with primary and useful energy consumption by fuel type. They are particularly low in residential and commercial applications, especially in the developing countries, where a large share of useful energy in the residential sector is used for cooking. Furthermore, the residential/commercial energy share is higher in developing countries. In the reforming economies of Eastern Europe and the former Soviet Union the largest share of industrial uses of useful energy have relatively low conversion efficiencies. These factors all lead to lower overall efficiencies.

2.2.3 Efficiency Improvements

The applications of efficiencies prevailing today in the market economies of the OECD to provide useful energy for the rest of the world would reduce the global primary energy

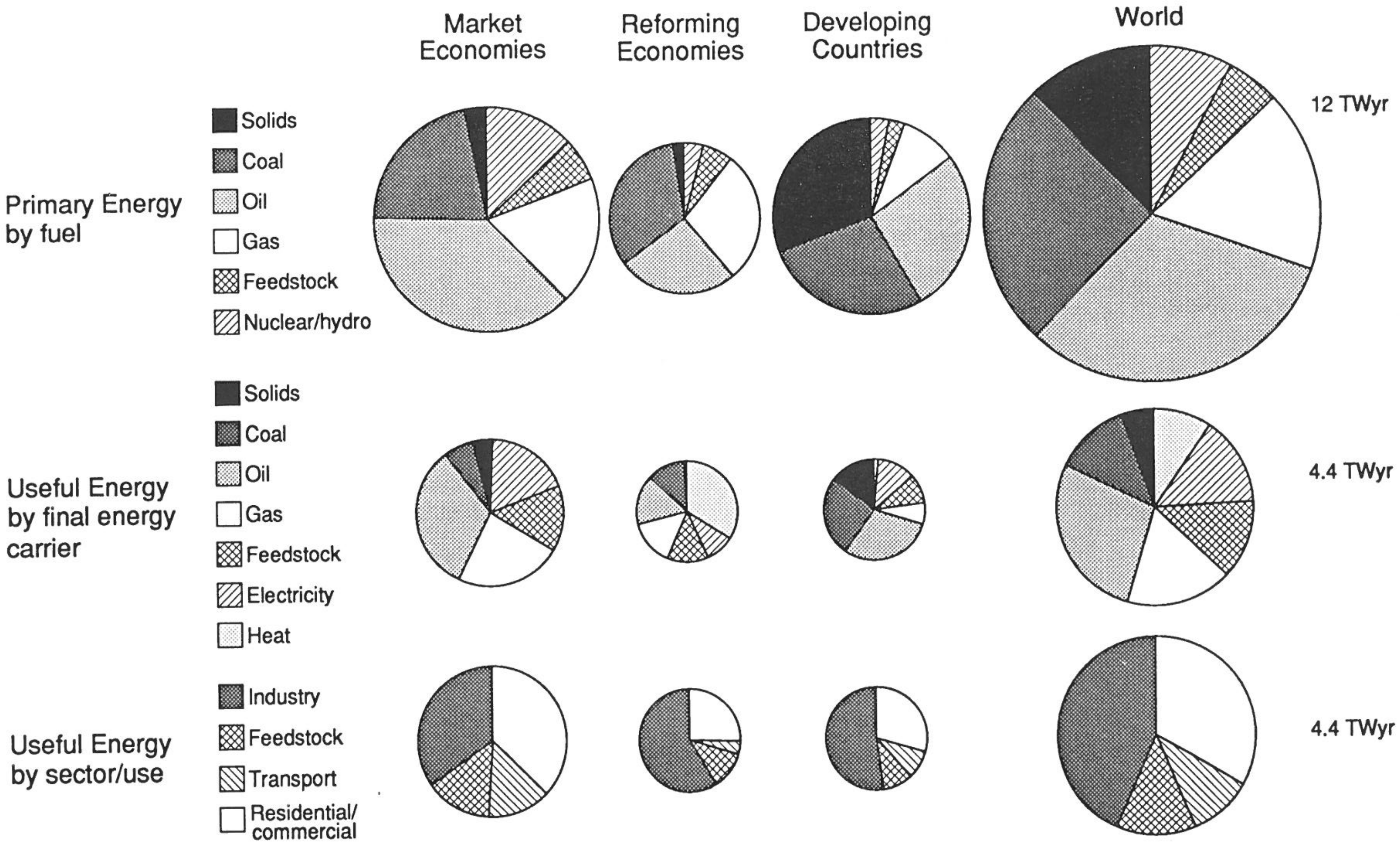


Figure 2-7. Sectoral useful and primary energy consumption in the three world regions.

requirements by 17% from 12 to 10 TWyr/yr, and would also lead to a similar reduction in CO_2. This is of course a very simplistic and static exercise.[1] It should be noted that the average useful to primary efficiency of 37% in the market economies is quite low compared with best current practice. This only illustrates the large opportunity for efficiency improvements if the current vintage structure of the OECD countries could be disseminated throughout the world. Technically speaking, the opportunities are clearly much larger even if we were to limit the analysis only to the currently practiced efficiencies. The difference within the market economies is large indeed if one compares the USA with Japan, France or the Netherlands. Since large efficiency opportunities exist within the market economies as well, we will next attempt to evaluate the efficiency improvement possibilities in the world by using the most efficient technologies currently available instead of the average vintage in actual use.

In the following hypothetical assessment of efficiency improvements, we assume a homeostatic development of the energy system by replacing current by the best possible efficiencies without changing the system structure. In other words, we estimate the energy reduction potential that would result from a worldwide diffusion of best available technologies without altering the structure of the energy system at any level, including energy end use. This is certainly unrealistic since the energy structure is dynamic and is also most likely to change in the future. However, this kind of static view of future energy demand allows comparison with the net effect on efficiency if the currently most advanced systems are employed throughout the global energy system. Here, we ignore the questions of costs, how long it might take before these new technologies can be introduced, as well as the institutional and social changes that will be necessary for their implementation.

A full account of all individual efficiency improvements would go beyond the scope of this study; here we summarize the major findings. An instantaneous replacement of the current energy system by the best available technologies would result in an overall efficiency increase of 60%. In other words, total primary energy requirements would decrease from about 12 TWyr actually consumed to about 7.2 TWyr in our hypothetical "high-efficiency" scenario. Figure 2-8 summarizes these results. Since the structure of the global energy system is unchanged, this also means that global CO_2 emissions would be reduced by the same percentage, from 5.5 to 3.3 Gt of carbon per year.

This result, however, illustrates the fact that technological change has been and will be in the future one of the most powerful determinants in reducing the energy requirements and improving the efficiency of many human activities. We have shown that reductions in specific energy needs have been an important feature of the evolution of energy-use patterns over the last two centuries. The average energy intensity (the energy–GDP ratio) has declined at a rate of about 1% per year. At this rate, it would take more than 70 years to reduce the average energy intensity to one-half. Using this analogy, it could take decades and almost half of the next century before our postulated energy efficiency improvements could be realized. In any case, the required time to double the efficiency of an energy system and end uses might be somewhere between 30 and 40 years if we assume that the relatively high improvement rates that have prevailed since the mid-1970s could be sustained.

---

[1] We assume the same structure of the energy system worldwide, but apply efficiencies prevailing in market economies everywhere. The only exception is district (co-generated) heat that we leave in the primary energy balances with actual current efficiencies.

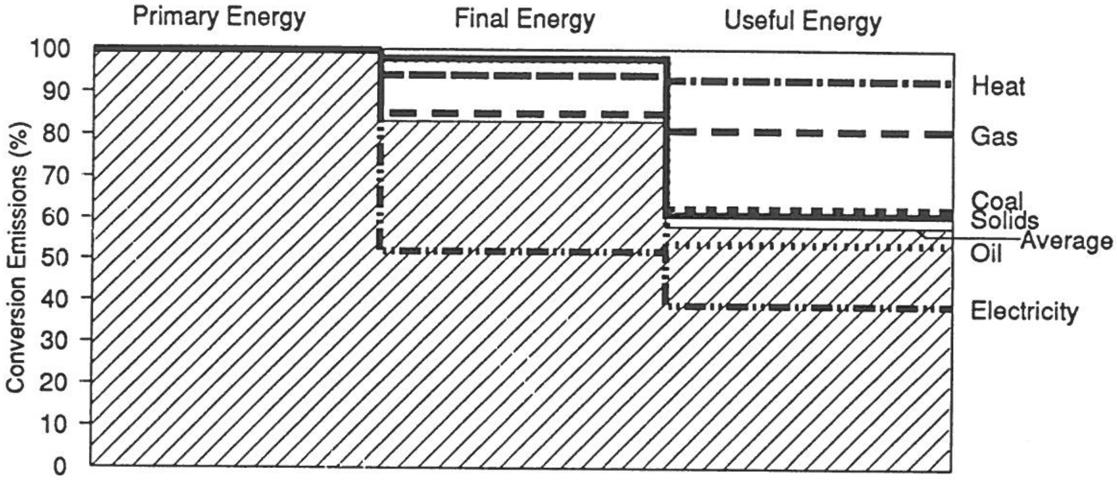


Figure 2-8. Global energy efficiencies using best available technologies; conversion efficiencies as percentages of primary energy.

2.3 Minimum Theoretical Energy Requirements

The illustrative examples above have shown that the global efficiency of transforming primary energy to useful energy forms is about 34%; that it is lowest in developing countries with an average of about 20% and that it is twice as high in the industrialized countries. The basic problem with this assessment, however, is that it is not clear how much these efficiencies could be improved. The key question is how to determine the ultimate efficiency improvement potential and by when it might be exploited.

2.3.1 Available Work or Exergy

An appropriate measure for a theoretical minimum energy requirement for a given task can be defined with the second law of thermodynamics. The distinction between energy and exergy efficiency is important theoretically because it allows to determine the ultimate potential of efficiency improvements.

The second law of thermodynamics defines a quantity called *available work* or *exergy*; it can be used instead of energy to define the alternative efficiency measure as the ratio of the *theoretical minimum amount of available work or exergy* needed to perform a particular function to *actual available work or exergy consumed* by a particular device or a system to perform the same function.[2] This efficiency measure can of course be applied to any energy device or facility, but its true value is that it is task-oriented *independent* of the employed device or conversion facility. The second-law efficiency, whose maximum is always one by definition, provides rapid insight into the performance

---

[2] The efficiency is calculated in terms of useful work or exergy. For example, the exergy of electricity and mechanical energy forms is very high, i.e., they can be transformed into other energy forms with efficiencies approaching 100%. The available work or exergy of fossil fuels is about equal to the heat of their combustion. For most fuels, exergy (or available work) is slightly higher than the heat of combustion, based on lower calorific value. This is illustrated in the following (approximate) ratios of exergy to heat of combustion. For coal (assuming an average of brown coal, anthracite and coke) 1.06; and for oil products 1.06; for natural gas (mostly methane) 1.04. In contrast, the exergy of low-temperature heat is very low, resulting in poor transformation efficiency to other energy forms (for many processes governed by Carnot's cycle for heat engines).

of a specific device executing a specified task in terms of how efficiently that task might be performed if an ideal device were available. It shows the maximal theoretical potential for the improvement of any given energy system.

Consequently, the second law imposes an upper limit for conversion of heat to work that can be achieved with any given conversion technology. In the case of modern steam turbines, the current net efficiencies of about 48% are still far from the maximum theoretical efficiency of about 62% for heat engines (working with a ΔT of about 500 °C). However, the efficiency need not be limited to the theoretical maximum given for the heat engines. The specified task is to convert the chemical energy of the fossil fuels into electricity. For this task, an ideal fuel cell (an electrochemical device) would be the more efficient alternative. This shows that the real merit of the second-law or exergy analysis is that it identifies a theoretical yardstick for determining potential improvement limits. The lowest efficiencies prevail in end use, in transformation from final to useful energy (and exergy) forms. It is in this area that the highest potential efficiency improvements are possible. The following three examples illustrate these possibilities.

2.3.2 Exergy Efficiency

The efficiencies of most conversion chains from primary to useful exergy are rather low compared with their energy efficiencies. Exergy efficiency therefore indicates a "waste" of fuels. For any specified energy task requiring work or heat, maximizing exergy efficiency is equivalent to minimizing fuel consumption. Let us briefly summarize the approximate range of calculated efficiencies for three examples: space heating, vehicle transportation, and lighting.

Space Heating: The idealized thermodynamic function could be conceived as the transfer of heat from an ambient heat reservoir, at the temperature of the outside air, assumed to be 1°C, to a reservoir at the temperature of the interior of the heated area, assumed to be 21 °C (AIP, 1975), meaning that ΔT is about 20 °C and resulting in the "second-law" or exergy efficiency of about 7%. Multiplying by the efficiency of the boiler, refinery and other components of the energy system would result in an overall efficiency of about 5%. Higher overall efficiencies of about 8% are possible by deploying heat pumps instead of conventional heaters. Other estimates of the heating efficiency lie in the same range, between 3 and 6% (see Schipper, 1976; Sorenson, 1982; AIP, 1975).

Transportation: The idealized function of transportation could be characterized as the provision of the energy for a vehicle to cover a certain distance at a given speed. In practice, there is usually little difference between the second-law and conventional efficiency measures for the conversion of fuels to transport services. Thus, the overall exergy efficiency is also in the range 6–12%. Other estimates are lower, ranging from 3% (Rossi, 1984), 8–9% (Ayres, 1988), 10% (Schipper, 1976), to 12–15% (Olivier and Miall, 1983). An automobile operating with a hydrogen fuel cell or a pure electric vehicle would both have higher exergy efficiencies. Maglev (magnetic levitation train) operating in an air-evacuated tube would achieve a substantially higher exergy efficiency.

Lighting: The function of artificial lighting could be characterized as the provision of light in order to maintain a certain illumination level throughout the day. We have already mentioned that the overall efficiency of the chain is about 3% (including the electricity

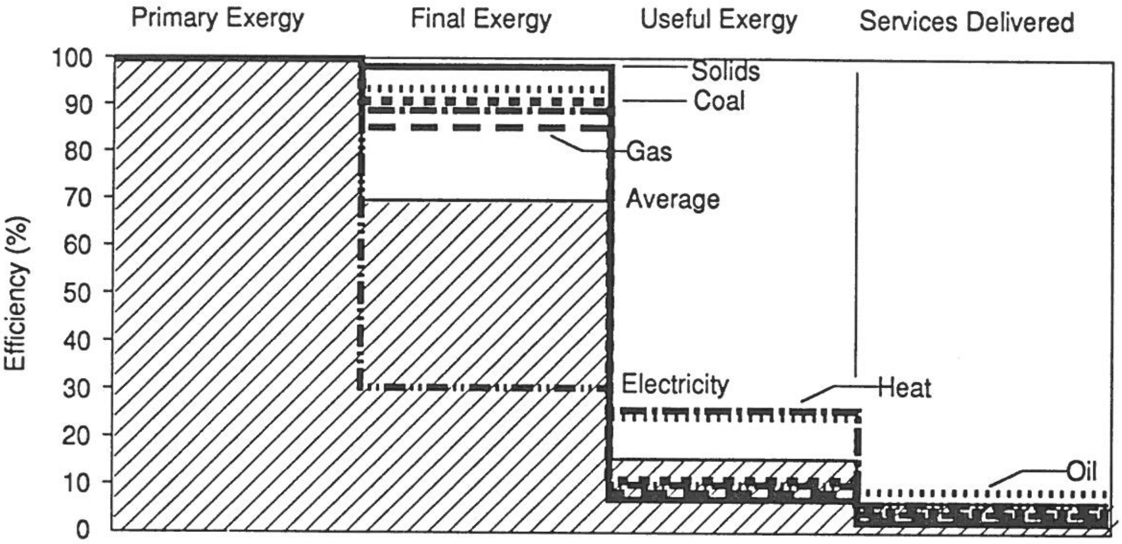


Figure 2-9. Exergy efficiency of primary inputs to the provision of services in the OECD countries, as percentages of primary exergy. Vector-specific efficiencies exclude cogeneration; average includes district heating and cogeneration.

generation efficiency). Again, the difference between exergy and energy efficiency is minimal. Ayres (1988) argues that an additional 25% of electricity should be added because radiant energy produces heat that must be removed, especially in hot weather, reducing the overall efficiency further to slightly more than 2%. However, in colder climates there would be a gain due to reduced heating. Sorensen (1982) and Olivier and Miall (1983) give even lower overall efficiency estimates of 2%. However, other conversion processes are also possible. For example, lighting is possible with hydrogen that is oxidized in the air with the help of a phosphor film inside a tube, very similar in appearance to a standard fluorescent lamp (Marchetti, 1973).

These three examples show a rather low range of conversion efficiencies for converting fuels into space heating, kinetic energy of vehicles and illumination. The overall average is somewhere between 3 and 15%. These are indicative numbers and not representative averages. Figure 2-9 shows the assessment of exergy efficiency in the market economies (Nakićenović *et al.*, 1990). Both energy and exergy analyses identify primary to final conversion processes resulting in average efficiencies of about 70%. However, they clearly indicate that the improvement potentials are very large and that they are the largest level of end-use applications. The analysis goes one step further and shows the overall efficiency from primary inputs to the provision of services. The resulting exergetic efficiency illustrated in Figure 2-9 is only a few percent. Figures for the reforming and developing economies would certainly be substantially lower. This indicates the large theoretical potential for efficiency improvements by a factor of between 20 and 50! Realization of this potential will depend on the implementation of many technological options and organizational innovations. It represents a theoretical potential that is not likely to be exploited for a long time well into the next century.

2.3.3 International Comparison of Efficiency Improvements

Exergy analysis shows that technical improvements and changes in consumption habits (increased service efficiency) are clear priorities for reducing CO_2 emissions through more efficient energy use. Consensus ends at this point, however, and widely diverging opinions appear as to how, when and where efficiency improvements should begin and to what extent they can be implemented (Nakićenović *et al.*, 1990).

The potential is large, even in those countries that have achieved high levels of efficiency. For example, one comprehensive technological analysis lists ways to improve the efficiency of over 300 single technologies in the Netherlands, broken down by industry and sector, ranging from greenhouse horticulture to production of aluminum to passenger transport (Blok *et al.*, 1991). The study concludes that if the energy conservation measures now economically viable were fully implemented by the year 2000, energy efficiency would be more than 30% higher than current levels. Similar studies have been conducted for other industrialized countries, (e.g., OTA, 1991a; COSEPUP, 1991; Kaya *et al.*, 1991), and for some developing countries. For example, a recent study for India identifies the overall cumulative CO_2 reduction potential during the next decade to be ten times larger than the current annual fossil energy emissions of about 160 Mt of carbon (Gupta and Khanna, 1991). The study illustrates three strategies that would lead to a reduction of CO_2 emissions without the loss of end-use services: an increase in energy utilization efficiency throughout all sectors of the economy, the wider deployment of renewable energy sources, and afforestation. In fact, there is increasing recognition in developing countries that improved energy efficiency and conservation (i.e., the "no regrets" policy) serves the dual purpose of saving the usually limited energy resources in these countries as well as reducing CO_2 emissions (AEI, 1991). Despite this large potential to reduce CO_2 emissions, the shortage of capital in most developing countries is a major obstacle to the implementation of mitigation measures.

In fact, Socolow (1991) defines conservation as the gap between technical promise and practical achievement. Thus, in general all of these reduction potentials implicitly assume that conditions for their implementation not currently in existence would be expected in the future. This not only involves the adoption of more efficient technologies and energy conservation measures but also a whole host of institutional and behavioral changes. In most mitigation studies, the first class of CO_2 reduction measures that are achievable either at low or almost no additional cost rely on efficiency improvement and conservation measures. For example, the cost curves for the former Soviet Union (e.g., Sinyak and Nagano, 1992) usually show that the elimination of large inefficiencies throughout the economy could facilitate emission reductions at practically no additional cost. Most of the other mitigation measures, such as changes in the structure of energy supply and the introduction of energy sources with low carbon contents, are in contrast associated with much higher costs than mitigation through efficiency improvements.

Unfortunately, there are a number of severe barriers that may delay or inhibit the achievement of efficiency potential in the near future. One of them is the cost of these measures and the associated capital requirements. The other class of barriers is related to the inherently long process of innovation diffusion and technology transfer. The introduction of new energy technologies takes anywhere from 10 to 50 years in the case of infrastructural investments. Thus the vintage structure of the capital stock and its replacement dynamics also determine the likely rates of future efficiency improvements. For example, the replacement of vehicles and rolling stock took between 10 and 20 years in most countries. At the other extreme, the replacement of housing stock is a much longer process lasting many decades and in some cases even centuries. For example, a study for the UK indicates that the replacement rate might be as low as 1% per year (Skea, 1990). The realization of some of the efficiency improvement potentials will therefore need to be associated with retrofitting some of the older vintages, and these may not be replaced in the near future. In most industrialized countries almost 80% of the capital stock is replaced over a period of 20 years, meaning that substantial efficiency gains could be achieved over the next two decades in most energy end uses.

2.3.4 Lifestyles and Social Behavior: Service Efficiency

The relatively low exergetic conversion values indicate that higher-quality energy forms are often applied to provide low-quality services. A good example is the use of work (electricity) to provide (low-temperature) heat: It is inefficient to use an energy form with an exergy of one to provide heat with a low temperature gradient. The overall efficiency can be improved by a better match between the thermodynamic quality of an energy carrier and the minimum quality required for the provision of a particular energy service. However, all of these inefficiencies are dwarfed by wasteful energy utilization in end-use applications. The energy services appear to be the least efficient and perhaps the weakest link in the efficiency of the whole energy system.

There are many vivid examples of the notorious inefficiency of energy services including the "control" of room temperature by opening windows while the radiators are on full, or an automobile occupied by one driver idling in bumper-to-bumper standing traffic. In both cases, the primary to useful energy conversion chains might be very efficient, but the low efficiency of the last link in the chain, namely the provision of energy services, drastically reduces the overall efficiency. Major improvements in oil refining, power plants, automobiles and domestic heating systems can be diluted to insignificance by wasteful services.

At face value, the low efficiency figures suggest that enormous improvements should be possible. Yet everyone knows from personal experience how difficult it has been to conserve energy and improve the end-use efficiencies even during the periods of very high energy prices in the 1970s. Nevertheless, it is clear that we are still very far from any physical or theoretical limits to improving efficiencies. The primary to final energy conversion is in comparison rather high, and the efficiency of industrial and commercial applications of final energy is generally much higher than in domestic and other individual end-use applications. At the same time, this fact also illustrates the difficulties embedded in the attempts to improve energy service efficiencies. The largest gain potentials are available at the point of consumption. They are associated with changes in social behavior and lifestyles, all of which are notoriously difficult to quantify. However, the patterns of energy use indicate that most of the potential efficiency improvements could, in principle, be technological and institutional in nature without directly affecting the consumer. This implies that much of the capital stock invested in machines, devices, appliances, buildings, and vehicles would have to be replaced by more energy-efficient ones, and this takes time. The improvement potential of energy, exergy and service efficiencies will depend on the likely timing of the replacement of existing capital stock with more efficient ones and will thus depend on the duration of these processes.

Energy Vol. 18, No. 5, pp. 437–459, 1993
Printed in Great Britain. All rights reserved

0360-5442/93 $6.00 + 0.00

Chapter 3

Renewable Energy Potentials†

3.1 Introduction

Biomass and other forms of renewable energy are the oldest energy sources harnessed by humanity. Today, they still constitute an important part of the total energy supply, particularly in the developing countries. Worldwide, biomass and hydropower supply about 1.5 and 0.3 TWyr/yr, respectively, and together, represent more than 15% of total primary energy consumed. In this chapter we review the current status of biomass and renewable energy technologies throughout the world and estimate their medium-term potential for providing carbon-free fuels and electricity. The time frame is until about 2030 and covers the second-generation renewable technologies. This is long enough for further development and market introduction of already known technologies, but before new technological breakthroughs are likely.

We consider all non-fossil, non-nuclear energy sources that are likely to provide significant quantities of commercial energy commodities. This definition does not include building energy technologies such as passive solar heating and daylighting, which are difficult to distinguish from energy-efficient technologies, but it includes electricity production from solar, wind, hydro, geothermal, ocean and biomass energy sources. We focus primarily on the decentralized technologies such as wind and solar photovoltaics (PV).

We also consider the potential for producing commercial fuels from biomass energy plantations, to the extent that such plantations can produce fuel sustainably, i.e., on a truly renewable basis. We exclude traditional biomass fuel use in developing countries because most countries' development strategies do not include growth in their use, and because it is unclear whether the use of such fuel is either renewable or low in greenhouse gas emissions.

The current level of use of noncommercial biomass energy is unsustainable in many areas of developing countries, and in some areas it is a significant cause of deforestation and potential desertification. Great improvements in energy efficiency and emission controls could be applied to the combustion of these fuels, possibly making their use sustainable, but it is still unclear whether they could support either greater populations or higher living standards in many areas. Moreover, the emission of greenhouse gases other than CO_2 (notably methane) from traditional biomass combustion makes these fuels questionable with regard to global warming mitigation strategies.

---

†Joel Swisher and Deborah Wilson with contributions by Leo Schrattenholzer (Section 3.6).

As a first step in our evaluation, in Section 3.2 we review the costs and performance of major classes of renewable energy technologies and the most promising biomass conversion technologies. This is not an exhaustive review; rather, we identify the important emerging technologies that have recently entered the market or are expected to do so during the 1990s. We emphasize decentralized sources of renewable electricity and biomass fuels, and we evaluate their potential costs, conversion efficiencies and land requirements.

Following the technology evaluation, in Section 3.3 we summarize three case studies of current biomass and renewable energy use: ethanol from sugar in Brazil, solar and wind power in the USA, and biomass and wind power in the Nordic countries. We also consider the important relationships between these newly exploited renewable energy sources and the existing hydropower resources in several of the countries studied. These case studies review the status of each country's biomass and renewable energy program, evaluate the future potential for its expanded implementation, and identify important limitations and opportunities related to each country's land, economy and energy system.

We then apply, in Section 3.4, the insights gained from the technology and country evaluations to estimate the global potential for biomass and renewable energy use, again in the medium-term until 2030. The analysis is based on our own calculations and a quantitative critique of several published estimates of biomass plantation area and renewable energy availability. We calculate the energy potential, by technology and by region, for both a "maximum potential" case and a more conservative, though still aggressive, "practical potential" case. We use this analysis to identify which biomass and renewable technologies are likely to be important globally, regionally, locally or not at all over the next 35–40 years.

Finally, in Section 3.5, we compare the projections of future use of solar energy and other renewables from the International Energy Workshop (IEW) with the potentials derived here.

3.2 Technology Review

3.2.1 Production of Feedstocks

Fuelwood

Trees grown in plantations on marginal crop land present a much lower risk of erosion than annual crops such as corn. High-production energy crops require less fertilizers and pesticides than corn (Lynd *et al.*, 1991). Yields of 4–8 dry tonnes/ha/yr in temperate climates and 10–12 tonnes/ha/yr in tropical regions are achievable with long-rotation forests. Short-rotation tree crops can be grown to produce 9–12 tonnes/ha/yr in temperate regions and 20–30 tonnes/ha/yr in the tropics (Hall *et al.*, 1991). The net biomass energy yields for short-rotation tree crops are typically 12 times the energy inputs (Hall, 1991). Eucalyptus can be grown with yields of up to 40 tonnes/ha/yr. Roughly 65% of the above-ground growth in trees is wood and 35% is foliage (Hall *et al.*, 1992). Nutrient availability is the most important limiting factor determining wood-crop yields. Optimizing nutrient availability can result in four- to sixfold increases in yield (Hall, 1991). In the USA, cellulosic biomass can be produced with costs of \$20–\$70 per dry tonne (\$35–\$117/kWyr or \$1.1–\$3.7/GJ; Wyman *et al.*, 1992).[1] In Sweden, wood chips from forest residues currently cost about \$107/kWyr (\$3.4/GJ) whereas wood chips from

---

[1] Throughout this chapter, all monetary values are in 1989/90 US dollars unless noted otherwise.

short-rotation energy crops are estimated to cost \$76–\$107/kWyr (\$2.4–\$3.4/GJ; Hall, 1991).

Herbaceous Crops

Herbaceous crops such as switchgrass and sweet sorghum can often be grown at relatively high productivity on crop and pasture lands that are not well suited to growing trees (Hall *et al.*, 1991). Herbaceous crops are well suited for biological conversion processes. In the USA, herbaceous crops yielded 17 dry tonnes/ha/yr in 1987 at a cost of \$90/kWyr (\$2.8/GJ; DOE, 1988).

Sugar Cane

The global average yield for sugar cane is about 58 tonnes/ha/yr (Ogden *et al.*, 1990),[2] although the yields in some locations are twice this figure (Hall, 1991). The limiting factor in sugar cane production is water rather than land. For high plant productivity, 112,000 liters/ha/day are required with ditch irrigation, and 73,000 liters/ha/day with drip irrigation. Cane production costs range from \$8/tonne in Brazil to over \$20/tonne in Louisiana, or about \$50–\$129/kWyr (\$1.6–\$4.1/GJ; Ogden *et al.*, 1990).

3.2.2 Commercial Feedstock Conversion Technologies

Hydroelectricity

After biomass, hydropower is the world's second largest renewable energy source, accounting for 2.5% of global primary energy. In 1990, almost 256 GWyr_e of electricity were generated by hydropower worldwide (about 20% of the global electricity production). Despite the fact that hydropower is unique as a mature, zero-carbon energy source, its growth has been slowing down in recent years due to numerous environmental, socioeconomic and economic constraints. Resistance to further hydropower projects is increasing throughout the world so that it now appears unlikely that it would make a substantial contribution to reductions in global warming much beyond its current relative share in primary energy. Most of the industrialized countries have already exploited much of their hydropower potential. Much of the future growth can be expected in the former Soviet Union, South America, Asia and to a lesser degree also in Africa since all of these regions still have substantial, unexploited hydro potentials. Table 3-1 gives the current hydropower installed capacities, electricity generation and total capacity under construction. When all new facilities come on line during the remainder of the decade, the global hydroelectric installed capacity should reach 650 GW_e (Fisher, 1990).

The costs of electricity produced by existing hydroelectric facilities are among the cheapest available: as low as \$0.01/kWh_e (\$87/kWyr_e), increasing to up six times that much for newer facilities (Fisher, 1990). Almost all of the generation costs are due to high capital costs in the range of \$500–\$2000/kW_e (Shea, 1988).

Solar Photovoltaics

Solar photovoltaic (PV) cells directly convert solar insolation to electricity. Land requirements for PV applications can be reduced by installing cells on multipurpose surfaces

---

[2] Unless noted otherwise, tonnes of cane refers to cane stalks only, of which 250 kg/tonne are solid matter (Larson, 1992).

Table 3-1. World hydro development by region (Source: Fisher, 1990).

Region	Total hydro installed capacity (GW_e)	Total hydro generation in 1988 (GWh_e)	Total hydro capacity under construction (GW_e)
USSR[a]	62.2	219,800	14.5
South America	75.975	330,558	27.458
Southern Asia and the Middle East[b]	45.438	170,937	>25
China[c]	32.69	109,177	16.735
Africa	15.84	35,775	1.573
Canada and USA	129.09	536,127	5.374
Western Europe	128.441	436,269	4.263
Central America[4]	10.71	32,242	1.6
Australasia[e]	12	36,945	1.259
Eastern Europe[f]	16.561	49,107	1.256
Japan	20.250	87,384	0.92
World Total	549.2	2,044,296	>100

[a] USSR includes the whole of the former USSR (European and Asian parts).

[b] Southern Asia and the Middle East excludes the former USSR, China, and Japan; includes Turkey and Taiwan.

[c] China excludes Taiwan.

[d] Central America includes Mexico and the Caribbean islands.

[e] Australasia includes Australia, New Zealand, Papua-New Guinea and Pacific islands close to Australia.

[f] Eastern Europe includes Albania, Bulgaria, Czecho-Slovakia, the former GDR, Hungary, Poland, Romania, and the former Yugoslavia.

with solar access, such as rooftops. Yields per unit area are determined by cell efficiencies and insolation availability. In the past, photovoltaic electricity generation has gone through periods of rapid technological advances followed by periods of stagnation. In particular, advances achieved in the laboratory took considerable times to translate into equivalent performance improvements in the field. Current thin-film amorphous silicon cells achieve efficiencies of 12–14% under laboratory conditions. Commercial silicon system *modules* achieve efficiencies of 8–9% in the field. This should be compared with the at best 1% efficiency of cells produced in the mid-1970s.

Photovoltaic technology development focuses on economic and technological optimization, and so far these have been conflicting objectives. High efficiencies tend to correlate with high costs and vice versa. Meanwhile, it appears that the balance has tilted toward economic optimization rather than high efficiencies. Consequently, thin-film amorphous single-junction cells have moved high on the list of promising technologies, leaving behind the more efficient but also more expensive monocrystal designs. Gallium arsenide cells are also based on crystals so that the costs are likely to remain prohibitive; however, other materials such as thin-film copper indium diselenide may be competitive. Despite significant reductions, high capital costs are a major barrier to further diffusion of photovoltaic systems. Current PV cells cost between \$5 and \$6 per peak Watt (W_p). A fully operational installation in the range of 1–10 kW capacity costs about \$10/W_p, including the support structure, power conditioning and other system components. System lifetimes are roughly 30 years. In 1990 the range of electricity production costs for typical PV systems was \$0.25–0.45/kWh_e (\$2200–3900/kWyr of produced electricity), and in some cases reach \$1/kWh$_e$. Due to these high costs, PV systems are currently limited to the highest-value end uses. For example, in regions with large air-conditioning loads, the value of PV-generated electricity is also high because power-output peaks closely match utility peak loads. Small-scale PV systems were traditionally used mostly for space applications and in remote locations.

Regarding technology optimization, photovoltaic development focuses on very efficient, multi-junction, high-concentration crystalline cells. The highest single-junction cell efficiencies are projected at 25%, while two- and multi-junction designs are expected to reach efficiencies as high as 34%. Operating efficiencies are typically 80% of those achieved in laboratory tests. The energy available to concentrating tracking modules is 50% greater than that for fixed-plate modules in desert areas and 20% greater in cloudy regions. In highly humid regions where sunlight is diffused, fixed-plates receive about 25% more energy than concentrating tracking systems.

Solar Thermal

In the only large-scale commercial application of solar energy, sunlight is focused on a linear receiver by parabolic trough-shaped mirrors. A heat transfer fluid circulates through the receiver at 370°C and drives a steam turbine cycle, backed up by a gas-fired boiler, to generate electricity. In a more sophisticated but presently more expensive technology, heliostats or large fields of sun-tracking mirrors focus sunlight onto panels mounted on top of central towers. Water circulating through these panels is superheated and sent to a conventional steam turbine for electricity generation. Steam temperatures are about 500 °C and the resulting thermal efficiencies can reach 35%.

Alternatively, the superheated water enters a heat exchanger where it heats oil that is then sent to a thermal storage tank. The tank contains crushed granite and sand through which the oil circulates. The heat from the tank can be removed through heat exchangers to produce 279 °C steam, again for electricity generation. This thermal storage system not only allows load shifting but also creates a buffer for changing weather conditions such as passing clouds. Cost estimates for complete systems are in the order of \$4500/kW, which puts the cost of heliostat electricity in the vicinity of \$0.25–0.30/kWh$_e$ (\$2200–2600/kWyr$_e$).

Wind Electricity

Wind turbines are typically designed for optimal performance under wind speeds in the range 7–5 meters/second with a shut down at speeds exceeding 25 meters/second to avoid damaging the blades. Turbines can be placed on land used for other purposes (such as cattle grazing) and would require at most only 5% of the swept area for their foundations. Because air must be able to move away from behind the blades, maximum theoretical wind converter efficiency is capped at 60% of the wind's kinetic energy. Mechanical conversion losses further reduce system efficiency. High-speed two-blade type wind converters are projected to achieve efficiencies in the 40% range.

The majority of wind turbines in use today are designed with a horizontal axis and three blades. Optimal machine sizes are currently 0.2–0.5 MW. For such turbines, rotor diameters range from 17 to 39 meters. The average capacity factor for turbines operating in 1990 was 24% (Cavallo *et al.*, 1992). Annual capacity factors of at least 30% appear possible.

In Californian mountain passes, where wind patterns are unidirectional, turbines are typically spaced 2.5 rotor diameters apart in rows set 8 rotor diameters apart. For a variety of turbines in the 0.225–0.5 MW range, as described above, the electric capacity range would be 270–330 kW_{inst}/ha. Assuming a capacity factor of 24%, this gives a total output range of 570–700 MWh/ha/yr (65–80 $kWyr_e$ha/yr).

The current investment costs for wind power plants in the 50–200 kW size range are about \$1200–\$1800/kW_{inst}. The future second-generation wind technology based on variable-speed generators is expected to lower specific investment costs to less than \$1000/kW_{inst}. At this cost level, wind power plants would require a minimum load factor of 30% to achieve electricity production costs of \$0.05/kWh (\$440/$kWyr_e$), approximately the current world average. Coastal areas in California, Denmark or Hawaii allow for capacity factors on the order of 30–35%. Furthermore, California has only 2% of the total US wind power potential at high-quality sites (550 W/m^2 at 50 m). Electricity generation costs in California and Denmark in 1990 were on the order of \$0.07/kWh (\$610/$kWyr_e$; Cavallo *et al.*, 1992). However, for locations with moderate wind availability capacity factors would be in the 10–15% range and production costs would vary around \$0.10/kWh. Costs for back-up capacity and other continuous supply-related costs are not included.

Ethanol Production from the Fermentation of Sugar Cane

Although many sugar and starch crops (cassava, sugar beet, etc.), can be fermented to produce ethanol fuel, the important crops currently in use are corn (used in the USA) and sugar cane (used in Brazil, etc.). In the United States, approximately 3 billion liters of ethanol from corn are produced annually, selling for approximately \$1.20 per gallon (\$0.32/liter) (Lynd *et al.*, 1991).[3] In Brazil, the world's largest producer of fuel ethanol, the existing industrial capacity for ethanol production from sugar cane is 16,3 billion liters per year. In 1989, 12 billion liters were produced and production is expected to exhaust current capacity in the mid-1990s (Goldemberg *et al.*, 1992).

Ethanol, used primarily as an automotive fuel, has a lower energy-to-volume ratio than gasoline. The energy content of 1 liter of ethanol is equivalent to that of 0.7 liters of gasoline (Goldemberg *et al.*, 1992). The octane values and latent heats of vaporization of ethanol, however, are higher than those of gasoline. These characteristics make it possible to achieve higher engine efficiencies in dedicated ethanol vehicles than in gasoline vehicles. Approximately 1.25 liters of ethanol combusted in a dedicated ethanol vehicle are required to travel the same distance as an equivalent vehicle burning 1 liter of gasoline (Lynd *et al.*, 1991).

Sugar cane yields 70 liters of ethanol (53 kWyr hhv)[4] per tonne of cane. The two most important determinants of ethanol production costs are feedstock and capital costs. Large distilleries which process 4000 tonnes of cane to produce 280,000 liters of ethanol per day have a capital cost of \$18 million (Ogden *et al.*, 1990). In Brazil, the average ethanol production cost in 1990 was \$0.21/liter.

In 1990, as a by-product of ethanol production in Brazil, 283 kg (wet – 67 Wyr or 2.1 GJ) of bagasse was produced on average per tonne of cane processed (Goldemberg

---

[3] Because the total fossil energy input requirements to produce ethanol from corn is approximately equal to the energy content of the ethanol produced, we do not consider corn as a renewable energy source and exclude it from the subsequent discussion.

[4] Unless noted with hhv (higher heating value), as shown here, lower heating values are used for fuels in this report.

et al., 1992). Bagasse is the residue left after extracting the sugar juice from cane (in both ethanol and sugar production), which is used as a fuel for producing steam and electricity for the ethanol production process. The overall viability of ethanol industries can be greatly improved by increasing the efficiency of the industry's own use of bagasse[5] and commercially producing excess electricity (and/or steam) with the remaining bagasse resource. For each tonne of processed cane, 50–100 $\mathrm{kWh_e}$ (5.7 to 11.4 $\mathrm{Wyr_e}$) of excess electricity can be produced with the cogenerating condensing-extraction steam turbines (CEST) currently in use. Biomass gasifiers coupled to steam-injected gas turbines (BIG/STIG) are expected to double the output of excess electricity per tonne of cane processed (see below and Ogden *et al.*, 1990).

In addition to bagasse, the tops and leaves of sugar cane plants (*barbojo*), if harvestable, could supply about 150 kg of dry mass residue per tonne of cane per year, with an energy content of 89 Wyr (2.8 GJ; Goldemberg *et al.*, 1992).

3.2.3 Demonstrated Feedstock Conversion Technologies

Ethanol from Enzymatic Hydrolysis of Cellulosic Feedstocks

Forestry residues and agricultural residues, municipal solid waste (MSW), as well as annual and perennial crops are all potential feedstocks for ethanol production through hydrolysis using acids or cellulase enzymes. The potential ethanol yields per mass of feedstock are slightly lower for MSW than for wood production. The energy inputs required to produce these feedstocks differ considerably; zero for MSW and 13–18% for wood (fraction of ethanol combustion energy). One dry tonne of wood yields roughly 330 liters of ethanol. As with ethanol production from sugar cane, ethanol production from cellulose results in unfermentable raw material by-products (primarily lignin) that can be used to produce electricity and steam to fuel the ethanol production process, and excess electricity or steam that can be sold. Lignin outputs range from 0.27 to 0.35 Wyr (8–11 MJ) per liter of ethanol produced. The costs of producing ethanol from cellulosic biomass have fallen from \$1420 to \$410/kWyr (\$45 to \$13/GJ or \$275 to \$80/boe) and opportunities have been identified to reduce them further to about \$220/kWyr (\$7/GJ; Lynd *et al.*, 1991).

Biomass Gasification for Use in Gas Turbines

Research into solid-fuel gasification for use in gas turbines began with the aim of improving potentials for utilizing vast coal resources. Coal-integrated gasifiers coupled to aero-derivative gas turbines (CIG/GT) have been demonstrated, but are not likely to be used commercially because their economic performance is no better than that of steam-electric power-generating technology. The main reason for this is the high cost of required sulfur removal. Because most biomass contains negligible amounts of sulfur, this costly step in the gasification process can be eliminated for coal-gasification technologies adapted for biomass feedstocks, making the technology easier to commercialize (Ogden *et al.*, 1990).

Although no gas-turbine cycle is commercially available for biomass applications, several applications that are available for high-quality fluid fuels are of interest for future biomass applications (Williams and Larson, 1992). The small scale of aero-derivative turbine technologies (5–100 $\mathrm{MW_e}$) such as steam-injected gas turbines (STIGs) makes

---

[5] Bagasse is currently burned inefficiently as a waste-disposal tactic.

them a promising technology for gasified-biomass applications because of the wide distribution of biomass resources. STIG technologies for burning high-quality fluid fuels are commercially available. Coal-fired STIG plants with capacities of 100 MW and operating at 34.5% efficiency are estimated to cost \$1290/kW. The capital cost of a biomass integrated gasification (BIG)/STIG system for central-station power generation with the capacity to produce 53 MW_e with an operating efficiency of 24.4% (assuming a feedstock moisture content of 50%) has been estimated at \$1100/kW based on cost estimates for the General Electric LM-5000 gas turbine (Larson *et al.*, 1989). Potential busbar costs for electricity generated with BIG/STIG systems have been estimated at about \$0.05/kWh_e (\$440/Wyr_e; Williams and Larson, 1992).

The first commercial-scale combined-cycle cogeneration plant using pressurized gasification of biomass is now (1992) under construction in southern Sweden. The purpose of developing this technology is to produce electricity at high efficiency, together with district heating and useful organic by-products, on a scale small enough to operate in ecological balance with a nearby biomass energy plantation.

A Swedish utility is building the facility in cooperation with a Finnish firm that is providing the gasifier technology. The overall thermal design efficiency of the plant is 83%, including district heating output. The capital costs of the project are about \$2500/kW and are expected to decrease considerably as the technology becomes fully commercialized (Svensk Energi Utveckling, 1991).

Methanol Production from Biomass

Methanol is produced thermochemically in a two-stage process in which the biomass feedstock is converted to a synthesis gas (gasified) which in turn is converted to methanol through a shift reaction. Biomass-derived methanol is not yet produced commercially, but recent advances in gasification technologies increase the possibility of utilizing the biomass/methanol potential (Wyman *et al.*, 1992).

Biomass feedstocks must first be dried to reduce their moisture content of 50% to 5–15% before they can be converted to synthesis gas (syngas). Approximately 63 kWyr (2 GJ) of heat are required to produce 1 Mt of dry biomass. Waste heat from reformer furnace flue gases is used for this purpose. Oxygen-blown gasifiers designed specifically for wood feedstocks have been successfully demonstrated at scales of 5–100 tonnes of wood per day. Biomass conversion to syngas has also been demonstrated in indirectly heated gasifiers that eliminate the expense of using a separate facility to provide purified oxygen. This process requires a reforming step before methanol synthesis, however, because it results in higher methane concentrations in the syngas, which must be reduced before methanol synthesis.

The final step in methanol production would be to catalytically recombine the carbon monoxide and hydrogen in the syngas that has been cleaned to remove particulates and acid gas. This could be done using systems very similar to those used to produce methanol from natural gas. Overall process energy ratios (energy in product – energy inputs/energy in feedstock) for systems in converting biomass to methanol range from 40 to 53%.

Methanol production from biomass has not yet been commercialized, so that the economics of the processes involved can only be estimated. Economic estimates of the gasification step are based on costs for commercial coal gasification technologies adapted for biomass. The capital costs for plants with capacities of 790–5550 tonnes per stream day of methanol produced range from \$321 to \$544 million, respectively. Methanol production costs for the same plants lie in the range 470–850\$/kWyr (15–27\$/GJ or 92–165\$/boe).

Biogas from Biomass

Biogas is a mixture of methane and CO_2 produced from the anaerobic digestion of organic compounds.[6] Anaerobic digestion has traditionally been used to reduce the volume of municipal sewage sludge before disposal and has been flared rather than recovered as an energy source. Biogas can be produced from a variety of waste and energy crops. Municipal solid waste must be sorted into organic and inorganic compounds before use. US Department of Energy research facilities were producing biogas at a conversion efficiency of 55% in 1987, for a biogas cost of \$23/kWyr (\$0.74/GJ or \$4.5/boe; DOE, 1988). Biogas production and use is particularly widespread in China (Cheng Chun and Wei Du, 1991).

3.3 The Role of Renewables Today

In this section we present three case studies to illustrate the potentials of renewable energy sources: ethanol in Brazil, wind and solar electricity in the USA, and wind and biomass in the Nordic countries.

3.3.1 Biomass Energy in Brazil

Brazilian ethanol consumption climbed from 0.44 GWyr in 1976, (equivalent to 6200 barrels per day, bbl/day), to 8.8 GWyr (124000 bbl/day) of gasoline replacement in 1989. In 1989, this corresponded to avoided emissions of 7 Mt of carbon. Ethanol production in the mid-1990s is expected to be around 12 GWyr, but for it to compete economically with gasoline, crude oil prices must be more than \$20/bbl.

Today, 10–20 kWh of electricity per tonne of sugar cane processed are generated by burning bagasse. With a combined-cycle gas turbine (CC/GT) converting gasified biomass at an efficiency of about 40%, the estimated potential output of electricity is 200 kWh per tonne of cane processed (Zylberstajn, 1992). For Brazil, the annual potential using such systems is roughly 5.5 GWyr/yr. If the leaves and tops from the cane crop could be harvested economically, this potential would be doubled. In terms of land use, CC/GT systems compare favorably with hydro power. They could produce, on average, 1890 MWh (electric or thermal) per hectare per year, whereas current hydropower plans would flood one hectare for each 274 MWh_e.

3.3.2 Wind and Solar Electricity in the USA

A large amount of renewable electricity was developed in one American state, California, in the 1980s. This activity was stimulated by Federal and state-level energy policies, such that renewable energy developers received a 10-year guaranteed price (over \$0.08/kWh_e) for their product, together with generous tax credits at both the Federal and state levels. The most significant results were that approximately 1500 MW_e of wind capacity and

---

[6] Small- and community-scale conversion of organic materials to biogas has been in existence for many years. They are not discussed here.

350 MW_e of solar thermal electric capacity have been installed in California since 1982. As a result of technical refinement and economies of both increased size and number of units produced, solar thermal power costs fell from \$0.27 to 0.09/kWh_e (\$0.35 to 0.12/kWh_e for solar only), and wind power costs fell from \$0.20 to 0.07/kWh_e (Kearney *et al.*, 1992).

The wind capacity construction peaked in 1985 with 400 MW_e connected in a single year, mostly in one of three "wind farms," which concentrated large numbers of 60–100 kW_e turbines (Gipe, 1991). Many of the developers had inadequate technology and/or financing, and they produced little more than tax shelters for their sponsors. At the end of 1985, the removal of both the tax credits and the most attractive utility price offers led to an immediate collapse of much of the industry. However, the strongest manufacturers, which included several Danish firms and one American firm, survived the shake-out that followed and have continued to develop their technology.

The story was similar but less intense with regard to solar thermal power. An American-Israeli firm, Luz International, entered the market with a parabolic trough line-focus system, using natural gas back-up to the extent allowed by the existing regulations (Kearney *et al.*, 1991). Luz was able to survive the first round of subsidy cut-backs and had 354 MW_e of capacity on-line (producing almost 1 TWh_e/yr) and 80 MW_e under construction in 1991 when the expiration of the last Federal tax credits, combined with the unexpected removal of state-level property tax exemption, prevented the firm from securing needed financing and forced them into bankruptcy. The lesson here is not that subsidies must be provided indefinitely to a renewable energy technology, but that their removal as the technology matures should be orderly and predictable, as in the case of the Danish wind program discussed below.

Depending on the projected level of the future energy demand, it appears that the USA could generate up to 2600 TWh per year of electricity from renewable sources, including over 1000 TWh from solar and wind power. This total is enough to meet 37–76% of projected total demand in 2030. At this level, the electricity supply from wind and solar technologies does not appear to be limited by the available resource. Instead, the major limitation is the fraction of the electricity supply system that can be reliably provided by intermittent energy sources. The conventional assumption is that 10–20% is acceptable, although some have argued that up to 40% of total electricity supplies could be provided by wind and/or solar (Grubb and Meyer, 1992). Significant advancements in electricity storage technology, however, could overcome this limitation.

It is less clear whether renewable energy will be able to penetrate the market for transportation fuels. In a relatively ambitious scenario, perhaps stimulated by policy responses to environmental concerns and/or increasing oil prices, the USA could produce about 2500 TWh of alcohol fuel from biomass. Additional renewable transportation fuel could be provided from stored electricity via batteries or hydrogen-fuel cells, such that 25–60% of non-electric energy or 30–65% of primary energy, could be supplied by renewable sources. The transition to this kind of energy system could be facilitated first by the introduction of alcohol and hybrid electric vehicles, and later by fuel-cell vehicles.

3.3.3 Wind Energy in the Nordic Countries

Although Denmark's electric system is presently dominated by coal-fired generation, since the 1980s Denmark has become the world's leader in wind turbine exports. About half of the 1500 MW_e of wind capacity installed to date in California is Danish technology, and many of the best performing systems there have been Danish. This capability developed from a long tradition of wind energy in agriculture and in the technical education, as well as public and government support for environmental protection. In contrast to the erratic energy policy in the USA, Danish manufacturers received modest but consistent government incentives starting in 1979. The subsidy was gradually reduced as the industry matured, and in 1990 it was removed (Gipe, 1991). Similar to the USA, however, Danish regulations require utilities to buy wind power from privately-owned turbines at about \$0.09/kWh$_e$, about 60% of the residential electricity price.

Wind power presently provides a small but significant contribution (about 2%) to the Danish electric grid. The national wind resource, including offshore sites, is estimated to be about 20 TWh$_e$, about 100 times today's annual output, or about 50–60% of projected demand. The primary limitation at present is the fraction of the national electric supply that can be provided by an intermittent wind resource without disrupting the system. Because the current system is dominated by large coal-fired power stations, it has a limited ability for load-following, i.e., quickly adjusting its output to accommodate fluctuations in demand or in other supplies such as wind. The current limit of wind capacity is estimated at 10% of the national electric demand, increasing to 30% in the future as the system shifts to a greater share of gas turbine and combined-cycle generating capacity.

An additional possibility, however, is greater inter-connection with the hydro-rich Norwegian system, such that Denmark could sell all available wind energy, and buy hydroelectricity in times of low wind. The storage capacity and load-following ability of hydropower would make it possible to use all available wind resources in Denmark, as well as Sweden and Finland, if the Nordic countries' electric systems become more interconnected. In this case, about 20 TWh$_e$ of wind energy could be generated in each of the four countries, with further output constrained by the need for enough thermal generation of electricity to provide energy for the countries' district heating systems.

3.4 World Potential for Biomass and Renewable Energy

Renewable technologies are often praised as the best solution for the problems caused by reliance on fossil fuels. The extensive use of renewable energy sources would help reduce CO_2 emissions provided they are used in a sustainable manner. This means that especially those renewable energy forms that contain carbon, such as biomass, would have to fix the carbon released into the atmosphere in new feedstocks. Such sustainable use would lead to effective carbon recycling and thus to only negligible additional atmospheric loading. The main barriers to this mitigation strategy are the physical limitations to the potential availability of some renewable energy sources (such as biomass and hydro) and the relatively high costs of others (such as solar and wind). In this section we assess both the potential contribution of renewables over the time horizon of second-generation technologies (up to the 2030s) and the associated energy costs.

Table 3-2 gives a brief summary of the maximum technical potentials and Table 3-3 the more practical potentials for harnessing biomass and renewable energy resources using second-generation technologies worldwide. Again, the scope of the analysis is the medium term, until 2030. In this brief assessment we ignore both direct building and heating technologies, as well as non-commercial biomass use. However, we include the sustainable development of tropical forest land, including changes in land-use practices

Table 3-2. Estimates of maximum technical potentials of renewable energy sources in 2030 (TWh_e/yr).

Region	Hydro	Geothermal	Wind	Solar	Oceans	Biomass[a]	Energy crops and plantations	Forests
Canada	590	0	2165	0	20	319	800	0
USA	600	370	1082	1800	0	1347	2433	0
Mexico/Central America	327	159	148	252	0	458	167	575
Andean Countries	1270	0	148	162	0	333	389	3833
Brazil	751	0	148	324	0	1028	667	5175
Southern Cone	325	0	492	162	30	250	211	0
Nordic Countries	320	0	116	0	0	181	333	0
Western Europe	561	267	232	144	30	694	211	0
Eastern Europe	170	0	23	0	0	375	144	0
Former USSR	3830	328	1293	432	150	1111	1933	0
Japan	132	194	0	49	54	0	83	0
Australia/New Zealand	84	190	541	288	0	236	267	0
China	2170	222	492	846	0	1278	444	0
India	205	0	295	1368	17	1403	211	196
Four Tigers	14	0	8	36	0	28	0	0
ASEAN	820	285	49	306	0	569	189	1679
Other Asia/Pacific	570	0	148	882	0	1014	489	924
Middle East	70	11	20	342	0	0	0	0
North Africa	18	11	30	216	0	83	44	0
Sub-Saharan Africa	700	32	148	756	0	1333	1333	3672
Total	13527	2068	7625	8370	247	12125	10333	16055

[a] Data from Hall (1991), assuming a conversion efficiency of 50%.

Table 3-3. Estimates of practical potentials of renewable energy sources in 2030 (TWh_e/yr).

Region	Hydro	Geothermal	Wind	Solar	Oceans	Biomass[a]	Energy crops and plantations	Forests
Canada	354	0	1400	0	20	211	233	0
USA	360	370	700	300	0	889	734	0
Mexico/Central America	196	86	95	42	0	303	84	178
Andean Countries	762	0	95	27	0	220	100	1187
Brazil	451	0	95	54	0	678	536	1603
Southern Cone	195	0	318	27	30	165	105	0
Nordic Countries	192	0	75	0	0	119	103	0
Western Europe	437	267	150	24	30	458	211	0
Eastern Europe	102	0	15	0	0	248	59	0
Former USSR	1149	177	836	72	150	733	354	0
Japan	89	194	32	9	0	0	55	0
Australia/New Zealand	50	103	350	48	0	156	81	0
China	1302	120	318	141	0	843	60	0
India	123	0	191	228	17	926	62	196
Four Tigers	8	0	5	6	0	18	0	0
ASEAN	492	154	32	51	0	376	103	1679
Other Asia/Pacific	342	0	95	147	0	669	17	924
Middle East	42	6	13	57	0	0	0	0
North Africa	11	6	19	36	0	55	40	0
Sub-Saharan Africa	420	17	95	126	0	880	720	1101
Total	7077	1499	4931	1395	247	8003	3603	6868

[a] Data from Hall (1991), assuming a conversion efficiency of 33%.

meant to relieve deforestation pressure, and we estimate the carbon savings from these measures and their fossil energy equivalent.

The purpose of this exercise is to evaluate qualitatively which classes of technologies could be significant globally, regionally, locally or not at all. We attempt to distinguish between the maximum theoretical potentials of energy resources and a more practical definition of accessible resources in the medium-term time horizon. For example, resource potentials are limited by competition for land, conversion efficiency is limited by capital cost constraints, and market penetration is limited by both industrial expansion and market absorption.

Much of this analysis consists of a quantitative critique of estimates published elsewhere, but we also try to put these estimates and our own in a logically consistent framework. For example, a recent analysis of renewable potential by Dessus *et al.* (1992), focuses on the 1990s but also includes global and regional estimates for 2020. We adopt some of the Dessus results, but for other energy resources we rely on a variety of information sources and try to explain or reconcile the differences between them.

3.4.1 Hydroelectricity

Hydropower is presently the most fully developed renewable resource worldwide. As mentioned above, about 256 $\mathrm{GWyr_e}$ (2240 $\mathrm{TWh_e}$) of electricity were generated worldwide by hydropower plants in 1990. Table 3-2 shows that the maximum potential is almost seven times this value, with some 1.5 TWyr/yr of electricity (13500 $\mathrm{TWh_e/yr}$) according to estimates from the World Energy Council and the World Bank (WRI, 1990). Fisher (1990) gives a slightly higher global estimate of about 1.7 TWyr/yr of electricity. However, many industrialized countries are already finding it difficult to expand their hydropower capacity because of environmental restrictions and competing uses for rivers and water. For example, Canada has huge untapped potential for hydroelectricity in the James Bay region of Quebec, but the development of this resource has already created unexpected environmental problems and its expansion is opposed by many environmental and indigenous peoples' organizations. Also, large dam projects in developing countries such as Brazil and India are facing increasing opposition because of the large land areas that are planned to be inundated.

Several countries that have almost stopped increasing hydro development, including Japan, Australia and New Zealand, most of northern Europe, and perhaps the USA, appear to have developed about 60% of their total potential. Thus, we estimate the practical hydro potential to be 60% of the maximum potential for other regions, except for the former Soviet Union, where we use 30% of the maximum potential due to the extreme remoteness of many Siberian rivers. As shown in Table 3-3, the resulting global practical potential is about 7000 TWh per year. Other estimates include 5500 TWh in 2020 (Dessus *et al.*, 1992) and 4500 in 2025 and 6300 in 2050 (Johansson *et al.*, 1992). Both of these estimates start with a maximum potential value and apply a correction factor that varies by region, without explaining the method behind the variations.

3.4.2 Geothermal Electricity

The technology for extracting electricity from hydrothermal resources is mature, and its use is expanding in both industrialized and developing countries. Its current use is less than 5 GWyr/yr, and an approximately equal amount is used directly for thermal uses not considered here. Geothermal sources all originate from thermal energy trapped beneath and within the solid crust of the Earth. In part, this energy originates from primordial thermal heating of the Earth when it was formed and, in part, from nuclear reactions (the decay of heavy radioisotopes). Theoretically, the total accessible resource base of geothermal energy to a depth of 5 km is over 1 million TWyr, but only an infinitesimal fraction of this total could ever be captured even with advanced technology including hot dry rock (HDR) concepts under development in the USA and elsewhere. There are vast occurrences of thermal energy trapped beneath the Earth's crust that are well beyond the reach of current and foreseeable drilling technology. Geothermal energy is naturally released via hot springs, geysers or volcanic activity, i.e., usually in the vicinity of geological faults.

There are four types of geo-thermal sources, including hydrothermal sources (hot water and steam), hot dry rock (HDR), magma (molten rock reservoirs either very deep or in the vicinity of volcanoes) and geopressurized sources (hot brine usually associated with methane in pressurized water aquifers). Such occurrences within easily accessible layers of the crust are limited. This translates into an estimated global potential of about 1500 $\mathrm{TWh_e}$/yr (or about 200 $\mathrm{GW_e}$/yr; see Table 3-3) due to relatively low efficiency of converting medium-temperature steam into electricity. This estimate is based on the assumption that the US geothermal potential is ten times today's level and represents at most one-sixth of the global total, which gives a global potential of about 1200 $\mathrm{TWh_e}$/yr (140 $\mathrm{GWyr_e}$/yr; see Table 3-2). The distribution of regional estimates is similar to the present development pattern. In addition, HDR potential is estimated at 170 $\mathrm{TWh_e}$/yr in the USA and at 800 $\mathrm{TWh_e}$/yr worldwide, while a more realistic estimate is that 300 $\mathrm{TWh_e}$/yr of HDR resources will only be developed in the most advanced countries such as Japan, the USA, and Europe. Costs are very site-specific and difficult to estimate. Moreover, geothermal is not necessarily a non-polluting energy source; hydrogen sulfide, mercury and CO_2 are often released from existing geothermal electricity-generating plants.

3.4.3 Wind Energy

The kinetic energy of the atmosphere is, at any one time, about one day's worth of solar radiation. This corresponds to about 500 TWyr/yr of wind energy. Of that total only a small fraction could possibly be tapped for power generation. The height limitations of wind converters restrict wind utilization to less than 200 meters above ground. Sites with wind velocities of more than 5 meters/second are considered satisfactory; sites with velocities higher than 7 meters/second at a height of 25 meters are prime wind energy resource locations. Without all these limitations, the ultimate potential of wind-generated electricity worldwide could indeed be very large, some estimates place it at 20 times current global electricity generation, i.e., at about 25 TWyr/yr. The maximum potential that could be harnessed by wind turbines to generate electricity is smaller by a large factor.

As regards the prospects of wind energy utilization for the early twenty-first century, efficiency is not the real barrier to the successful operation of large-scale wind-powered electricity generators. The technological challenge is that wind velocity is rarely constant in magnitude and direction, nor is it constant across the blades. This results in stressful fluctuating load changes on the rotor system creating fatigue problems. Because wind loads and strengths are several times higher offshore than onshore, one option is to install floating offshore windmills and to transport the electricity generated directly to the location of consumption, or to use it for onboard hydrogen production by electrolysis.

Wind turbines in use today operate at constant rotation frequencies, relying on continuous feedback between the generator and rotor system by means of changes in the gear ratios and/or changes in blade orientation. Although this design makes the generation of ac electricity easier, the need for a constant angular velocity reduces the usable wind range for any given wind power plant design. Variable-speed turbines are also commercially available, which could increase annual electricity output while supplying higher-quality output to grids and reducing structural loads. Converters stabilize the generator's variable output frequency and produce a constant frequency electrical output. This would increase the load factor substantially and yield better overall economic performance. Although power-handling electronics in variable-speed turbines tend to increase capital costs, power-generating costs from variable-speed turbines are expected to be less than \$0.06/kWh (\$525/kWyr$_e$). Large-scale research turbines are also under development, ranging from 0.65 MW in Germany to 3 MW in Sweden.

Wind power economics hinge upon the average annual duration and strength of wind availability. Once more, the need for energy storage or back-up may link wind energy to hydrogen production. As the wind power market develops, it is likely that good wind resource assessments will be made for many parts of the world. Unfortunately, there is currently little such information for regions outside North America, Scandinavia, the UK, and New Zealand, and even the assessments for these areas are rather coarse.

Table 3-3 gives more practical wind power potentials. The estimates for the USA and the Nordic countries are based on SERI (1990) and Brinck *et al.* (1991). These estimates are based on high wind thresholds (500 W/m^2 at 50 m) and rather strict land-use exclusions, so they are considerably less than the maximum potentials. Comparable estimates are available for Canada, the UK and New Zealand, but for other regions the most consistent data available are only estimates from the US wind atlas of land areas with various wind speed categories (Grubb and Meyer, 1992). The estimates given in Table 3-3 are based on the ratios between these area estimates and the ratios between the wind resources of various regions compared to North America and the Nordic countries. In addition, we have further reduced the estimates for Western Europe and Japan by 50% to reflect the greater land exclusions that result from the high population densities in these countries.

This procedure gives a global total of almost 5000 TWh$_e$/yr of wind power (Table 3-3). As a more ambitious maximum estimate, we apply these same ratios to the estimated wind resource at a lower wind speed threshold (400 W/m^2 at 50 m) and a fourfold stricter land exclusion rate, reflecting the ability of better technology to exploit lighter winds and the increased difficulty of siting a larger number of wind power facilities. This approach gives a global total of about 7600 TWh$_e$/yr (Table 3-2). We can compare these values with the much lower values estimated by Dessus of about 650 TWh in 2020 (Dessus *et al.*, 1992). This estimate, which is less than the DOE laboratories estimate for the USA alone in 2030, is based on wind resource data that seem to account only for coastal areas (SERI, 1990). However, the North American wind resources and those of several other regions are concentrated in continental rather than coastal areas (Elliot *et al.*, 1991).

The major limitation on wind power development in the medium term is likely to be the fraction of the electricity supply that can be met by intermittent sources such as wind and solar without reducing overall system reliability. This restriction could limit the penetration of wind power to 10–20% of the regional electricity supply market. Alternatively, wind electricity could be used for available independent services such as sea water desalination. However, the availability of cost-effective electric storage, superconducting cables for long-distance electricity transmission, or the conversion to hydrogen as an intermediary vector, could dramatically increase the usable fraction of the wind potential.

3.4.4 Solar Energy

The Earth intercepts about 180,000 TWyr/yr of solar energy. Diverting a small fraction of this energy to replace the current supply of fossil energy sources would eliminate all energy-related CO_2 emissions. The major practical obstacle is that the solar energy is quite "dilute"; the power densities per unit area are low compared with the density of energy consumption and generation by fossil energy sources. In practical terms this means that the areas required for harnessing solar energy tend to be large and the capital costs high. In Section 3.4 we have discussed the current use of solar energy, and described photovoltaic systems as one of the most promising technologies for the next century. Although silicon-cell systems are currently the best developed PV technology, several other technologies are in various stages of development and it is unclear which of these will prove least expensive under what conditions in the future. Polycrystalline thin films, for example, are expected to reduce PV module costs to $0.50–1.00 per peak Watt, in which case flat-plate thin-film systems may be capable of producing electricity for $350–700/kWyr$_e$ ($0.04–0.08/kWh$_e$).

For the purpose of a resource estimate, we combine solar thermal and PV, since they rely on the same solar energy resource and in many situations may be equally suitable, depending on local economics. There are differences in the attributes of these technologies, however. PV may ultimately become more widely applicable because it is relatively well suited to decentralized applications, to rooftop siting, and to less sunny climates (since flat-plate PV technology makes better use of diffuse radiation) compared with solar thermal concentrators. However, at present, the most promising PV technologies such as thin-film cells are less well developed and much less efficient than solar thermal technologies, especially the line-focus parabolic troughs. The total output of commercial PV electricity is only a small fraction of wind or solar thermal power. Thus, while the ultimate PV market may be extremely large, it will probably take a relatively long time for PV technology to gain a significant market share.

As a conservative estimate of the accessible solar resource, we take the Dessus *et al.* (1992) results for remote and grid-connected PV solar energy in 2020, which gives a moderate global potential of about 1400 TWh$_e$/yr; (160 GWyr$_e$/yr; Table 3-3). These results are based on a regional set of solar energy resource data. For a maximum potential estimate, we assume a maximum sustainable annual growth rate of 20% from 2020 to 2030. Thus, the total solar potential in 2030 could be six times the 2020 photovoltaic potential estimated by Dessus *et al.* (1992). This is consistent with the DOE laboratories' estimate that the solar energy conversion in 2030 could increase threefold from 2020 for both photovoltaic and solar thermal energy. Applying this ratio to the Dessus 2020 result gives a maximum solar potential in 2030 of over 8000 TWh$_e$/yr (1 TWyr$_e$/yr; Table 3-2). This would be equivalent to replacing 2–3 TWyr/yr of fossil energy or almost the same number of gigatons of carbon in the form of CO_2 emissions. Thus, even over the time-scale of second-generation technologies, solar energy could at least in principle reduce CO_2 emissions by half the current energy-related CO_2 emissions.

The same market penetration limitations and opportunities with regard to wind also apply to solar electric technologies. Solar thermal generation may be more flexible, however, because it is not so difficult nor expensive to store thermal energy, which can be used to fit generator output to the electric load profile.

Considering a more open-ended time horizon of the whole of the next century, the actual potential of solar energy becomes much larger. In principle, all of the conceivable human energy needs could be provided for by diverting only a small fraction of the solar influx to energy use. Photovoltaics and solar thermal plants could do the job provided that a large enough area could be devoted to the scheme and that costs can be sufficiently reduced. Other proposals have also been made, including, for instance, the idea of solar power satellites. In fact, solar cells have always been competitive as a power source for satellites. In the context of energy generation, the basic idea is to place large photovoltaic panels in geostationary orbit around the Earth and beam the collected energy to Earth. Although such satellites would generate electricity from solar energy, they really belong to the category of other orbital "geoengineering" options that we will discuss in Chapter 5.

3.4.5 Ocean Energy

The oceans offer a number of energy flows that could be tapped as sources of energy. They include ocean thermal energy, waves and tidal power, and the sea-freshwater interface as rivers flow into oceans.

Ocean thermal conversion (OTEC) systems utilize the relatively low temperature gradient in the oceans for electricity generation. The warm surface water of the oceans is used to boil a working fluid in a Rankine-cycle power plant. Temperature gradients of at most 20 °C can be achieved, leading to very low efficiencies. This means that the systems would need to be large and associated with high capital costs estimated at about $\$2500/\mathrm{kW_e}$ resulting in production costs of about $\$0.04/\mathrm{kWh_e}$ ($\$350/\mathrm{kWyr_e}$). The temperature gradients are lower in coastal regions and the potential is very limited, so that this option does not appear to be attractive in the context of second-generation technologies.

Tidal power utilizes the oscillatory flow of water in and out of partly enclosed basins along coastlines with sufficient tidal flow. Water then flows back and forth through a number of reversible hydro turbines located in dams across the entrances of the tidal basins. The total resource is very limited. Assuming that tidal flows of more than 5 meters are required for a practical plant, the realizable global potential is some $64\,\mathrm{GW_e}$. In view of the relatively low potential, tidal power is not a globally important resource, but it has regional potential that has been reasonably well evaluated. Our estimate of a realistic global potential by the year 2030 is about $250\,\mathrm{TWh_e/yr}$ ($30\,\mathrm{GWyr_e/yr}$). Even this reduced potential might be too high, the large resource in the former Soviet Union being the most uncertain contribution to this estimate (Baker, 1991). Several concepts to harness wave energy have been proposed, ranging from turbines that utilize oscillating water columns, combined water and air arrangements, to a design known as the Salter's duck. The latter consists of a series of wing-like, interconnected objects. It is not clear whether any of them will lead to a practical design. Cost estimates for both wave and tidal energy are difficult to obtain. It appears, however, that chances are low for costs less than \$0.10/kWh$_e$ (\$876/TWyr$_e$).

The mixing of salt and fresh water in estuaries is another way to tap solar energy. Membranes separating the two fluids create different partial pressures that could be used for power generation. The low efficiency of the process may in part be offset by the large resource potential. Differences in the salinity of water are an integral part of solar ponds. The salt gradient creates zones of different heat trapping potentials that can be utilized in analogy to the OTEC process.

3.4.6 Biomass Energy

We consider two general categories of biomass energy resources: wastes and energy plantations. We exclude traditional uses of non-commercial biomass energy for fuelwood in developing countries. Biomass wastes include farm crops and animal wastes, forestry and wood processing by-products, and municipal waste and sewage. To the extent that these waste flows can be collected, they can be converted to commercial fuels and electricity. For the sake of simplicity and to reflect the potential of the decentralized use of new electric technologies, we assume that wastes are converted to electricity. We assume an efficiency of 33% for our practical energy potential and 50% for our maximum potential estimate.

We take estimates of the energy potential in accessible biomass wastes from Hall (1991), who gives a country-by-country accounting of the energy content of residues, assuming the collectible fractions range from 25% for animal wastes to 80% for forestry wastes. The global result is 8000 TWh at a 33% conversion efficiency and 12,000 TWh at 50% (Tables 3-2 and 3-3). Other estimates include 7000 TWh from waste in 2020 (Dessus *et al.*, 1992) and 8000 TWh at a 50% conversion efficiency or 5500 TWh at 33% (Johansson *et al.* (1992).

The energy potential of biomass energy crops and plantations is especially difficult to estimate. The energy quantity depends on the land area available, the harvestable yield, its energy content, and the conversion efficiency. All of these parameters are rather speculative at present, except for a few cases such as Brazil's ethanol program. For the industrialized countries, we take Hall's estimate of biomass energy potential, which is based on a yield of 150 GJ/ha/yr on 10% of the total crop land, forest and woodlands (Hall, 1991). When we increase the land area values for the USA and the Nordic countries to be consistent with the results of our case studies for those countries, the resulting total is 6000 TWh or 480 Mtoe per year (0.7 TWyr thermal), assuming conversion to alcohol fuel at a 40% efficiency.

Hall (1991) also gives an estimate of biomass energy potential in developing countries based on a yield of 75 GJ/ha/year on 10% of the total crop, pasture and forest lands. The resulting land area is 500 million hectares. Based on land-use capacity studies, similar estimates of the land available for tropical plantations range from 580 to 620 million hectares (Houghton *et al.*, 1991; Grainger, 1990). Although the biological productivity of land in most tropical climates should be higher than in temperate climates, the lower assumed value is reasonable because of the many biological and economic barriers to successful agriculture in the tropics, and because of the marginal quality of much of the land that might be used for energy feedstock purposes.

We assume that this type of marginal land would most likely be converted to growing energy feedstocks to meet the demand for transportation fuels, of which ethanol is the most versatile. These assumptions give an energy value of 4500 TWh or 320 Mtoe per year (0.45 TWyr thermal) from biomass, if the biomass is converted to ethanol at a net efficiency of 40%, for a global total of about 10000 TWh or 800 Mtoe per year (1.1 TWyr thermal) of fuel energy (Wyman *et al.*, 1992). We use this value as our maximum energy potential estimate (Table 3-2). As a more conservative value, we take Dessus estimate for biomass energy crops, excluding wood fuels, which gives a total of 3600 TWh or 290 Mtoe per year (400 GWyr thermal) (Table 3-3).

3.4.7 Carbon Storage

There are many places where the production of biomass energy feedstocks through annual or short-rotation perennial crops is unlikely to be sustainable. In such places, less intensive land uses such as agroforestry or perhaps forest protection are more appropriate. To avoid an over-emphasis on energy-related land uses, we try to measure the ecological value of non-energy land uses. A simple measure of this value is the energy equivalent (as petroleum) of the carbon that can be stored in non-energy forest projects. This value is a one-time increment of carbon removed or saved from entering the atmosphere, as compared to the annual energy flows we are evaluating here. For the sake of comparison, we provide these energy-equivalent estimates as annual quantities, assuming that they take effect over a 35-year period (1995–2030).

A realistic analysis of sustainable forestry requires a true bottom-up, national-level analysis, rather than the global application of parameters based on a limited number of observations. However, for a rough global estimate, a methodologically consistent estimate is given by Houghton, based on land-use capacity analysis on a very coarse scale using satellite data (Houghton *et al.*, 1991). This method categorizes land areas according to their current use and suitability for forest protection, agroforestry, plantations, or non-forest uses. The estimated global area suitable for protection forestry is 860 million hectares, and the agroforestry area is 490 million hectares. Based on net carbon storage rates of 30–60 tonnes of carbon per hectare for agroforestry and 10–60 tonnes of carbon per hectare for forest protection, these areas can store almost 40000 million tonnes of carbon. Note that this value is considerably lower than earlier estimates by Houghton, which include carbon storage in forest plantations and assume higher rates of carbon storage per hectare.

The carbon-storage value is the equivalent of 560,000 TWh, or 16,000 TWh for 35 years (Table 3-2). We take this as a maximum potential estimate and use the protection area only to give a more conservative estimate of 7000 TWh (Table 3-3). This is a one-time carbon store, as compared to an infinitely renewable one. However, its magnitude shows that in the coming decades sustainable forestry development and the reversal of tropical deforestation are essential components of global ecological management and carbon emission reductions.

3.4.8 The Costs of Renewable Energy Technologies

Some of the renewable energy production costs estimated above are summarized in Table 3-4. The present costs are based on the best performing systems now in operation. The ranges are given to indicate the site-dependence of solar and wind costs. The future costs are based on the technology assessments cited above, some of which are relatively speculative in projecting costs substantially lower than those of the present technologies.

Table 3-4. Summary of renewable energy technology costs.

Energy technology	Present cost	Future cost	Density
Electric:	(\$/kWh)	(\$/kWh)	(kW_{av}/ha)
Hydro	0.05	0.05–0.10	50–1000
Wind	0.07	0.03–0.06	1000–2000[a]
Solar thermal (line-focus)	0.12	0.05–0.10	300–600
Solar thermal (point-focus)	0.25	0.04–0.08	300–600
Photovoltaic	0.30	0.04–0.08	200–400
Biomass/STIG		0.05	5–10
Tidal		0.08–0.10	
Fuel:	(\$/GJ)	(\$/GJ)	
Ethanol from sugar	8	6	
Ethanol from wood	13	7	
Methanol from wood	15	10	
Biogas		1	

[a] Refers to net density; the gross density range is 70–140 kW/ha.

An additional issue with regard to the performance of renewable energy conversion technologies is the energy density, i.e., that amount of energy produced from a given area of land. The general estimates of the land area density of several renewable electricity sources are also given in Table 3-4. Wind energy densities are given for both the gross land area occupied and the net land actually removed from other uses.

It appears that the land area itself is likely to be a real constraint only with regard to biomass technologies because of their relatively low overall solar energy conversion efficiencies. Conventional energy conversion technologies, including coal and nuclear fuel cycles and centralized high-head[7] electricity, have energy densities on the order of 1000 kW/ha. Some large low-head hydro projects have energy densities of as low as those given in Table 3-4 for biomass conversion.

3.5 Projections of the International Energy Workshop

The IEW poll includes two items concerning the prospective development of renewable energy sources, i.e., hydroelectric and geothermal (poll item 14) and solar and other renewables (poll item 16).

Figure 3-1 shows the histogram of IEW poll responses for the global supply of hydro and geothermal energy. They are given in their original units, i.e., Mtoe of primary energy equivalent. Converting these into TWh (thermal) and dividing the result by 3 to achieve the electric equivalent, we get 2280, 2700, 3550, and 4320 TWh as median responses for the years 1990, 2000, 2010, and 2020, respectively. Disregarding for the time being one constant global projection (which surely indicates that studying hydro and geothermal was not the focus of that study), the projections for the year 2020 range from 3500 to almost 5000 TWh. For comparison, the estimated practical potential in 2030 was 7000 TWh (1690 Mtoe primary energy equivalent) for hydro and 1500 TWh (360 Mtoe primary energy equivalent) for geothermal energy. The median of the IEW

---

[7] Head refers to the vertical distance between hydro-electric turbines and their water intake. To achieve a given quantity of water (and therefore energy) storage in a low-head project, a larger land area must be flooded than in a high-head project.

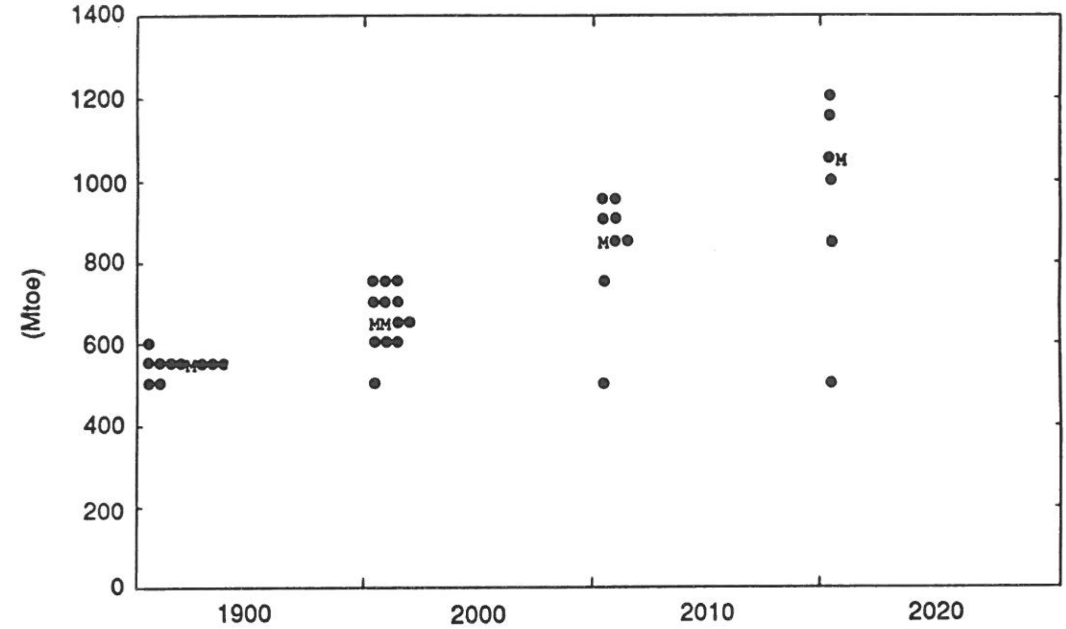


Figure 3-1. Global potential for energy supplied by hydroelectric and geothermal sources (IEW poll, January 1992).

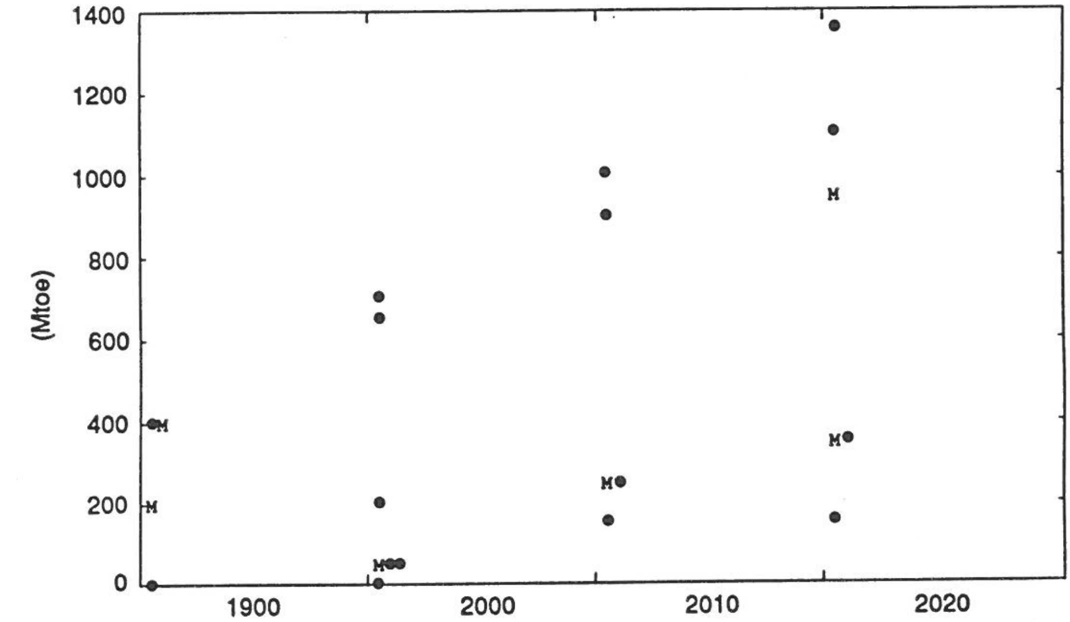


Figure 3-2. Global potential for energy supplied by solar and other renewable sources by the year 2020 (IEW poll, January 1992).

response thus exhausts in 2020 about 50% of what we gave as the practical potential in 2030 in Section 3.5.

The situation with the "other renewables" in the IEW poll is less clear-cut. Ever since the inception of the IEW poll, the responses to that item showed great variability. The January 1992 poll is no exception as Figure 3-2 shows. The ratio between the highest and lowest projections for the global use of commercial "other" renewables approaches 30 for the year 2000. The factor 7.9 for 2020 is "lower" but it still covers the interval 170–1350 Mtoe. Some conversion is necessary before the IEW responses can be compared with the numbers given as the practical potential in Section 3.5, because the summary table mixes electric and thermal units. Counting biofuels as thermal energy and the rest as electric, we arrive at a total potential of some 16,000 TWh electrical energy. Using the same conversion procedure as for hydro and geothermal, the range of IEW responses for the year 2020 translates into the usage of between 5% and 35% of the practical potential in the year 2030.

Energy Vol. 18, No. 5, pp. 461–484, 1993
Printed in Great Britain. All rights reserved

0360-5442/93 $6.00 + 0.00

Chapter 4

Second- and Third-Generation Energy Technologies†

4.1 Introduction

Fossil fuels provide today most of the global energy supply. Although the geological potential of fossil resources is vast, they are nevertheless finite. What is perhaps even more important is that the available resources are sufficiently large to threaten the assimilative capacity of the global biosphere. Therefore, in the long run, there is a clear need to shift to energy sources with low carbon content, such as natural gas, and ultimately to those with no carbon whatsoever, such as solar, nuclear and possibly in the far future to fundamentally new energy sources such as fusion. Currently, technologies hold the promise of substantially lower CO_2 (and other pollutant) emissions. Such technologies not only include zero-carbon options but also systems for eliminating carbon from energy carriers prior to end use. Thus, in addition to the zero-carbon energy sources such as nuclear, we will also discuss the technological possibilities, costs, and mitigation potentials of clean fossil energy sources.

The clean fossil energy technologies could in principle rely on a very large resource base to provide energy for decades. Thus, in this chapter, we first summarize the current perceptions of the global energy resource base and then return to the assessment of the second- and third-generation clean fossil and nuclear energy technologies.

4.2 Fossil Energy Reserves and Resources

Before we venture into an attempt to assess the CO_2 mitigation potentials of new "clean" fossil energy technologies, we first give an account of the global coal, oil and natural gas reserves and resource estimates. This is very important since the prospects of possible resource scarcities have been perceived in the past as the most important reasons for developing alternative energy sources.

In reality, energy resources have become even larger with each new assessment. They have also been much more dynamic than most resource depletion models predicted, and static geological appraisals of ultimately recoverable resources suggested. Therefore it is necessary to start with some definitions of energy reserves and resources. This will help answer the question of how large might be the quantity of fossil energy that may

---

†Holger Rogner, Nebojša Nakićenović, and Arnulf Grübler.

ultimately be available. Today, environmental issues and the potential danger of climate change have emerged as important driving forces in the development of alternative energy forms with lower greenhouse gas and other emissions. From this standpoint, some emission reductions are also possible by switching among fossil energy sources. For example, coal emits substantially more CO_2, particulates, and sulfur dioxide than does natural gas. Assuming that natural gas resources throughout the world are abundant and pervasive, a shift away from coal would be possible and would lead to a reduction in CO_2 emissions per unit of energy consumed. As an alternative one could also rely on "clean" coal technologies. The basic idea of clean energy conversion systems is that they can contain the carbon and deliver energy to the end user in a carbon-free form such as electricity or perhaps even hydrogen in the more distant future.

4.2.1 Distinguishing Reserves and Resources

Fossil energy resources and their future potential recoverability cannot be characterized by simple measures or single numbers. They comprise quantities all along a continuum in at least three dimensions: *geological knowledge, economics*, and *technology.* Most reserve and resource classifications include two dimensions. McKelvey (1972) proposed a diagram with a matrix structure for the classification along two dimensions: decreasing geological certainty of occurrence and decreasing economic recoverability. For example, identified occurrences have the highest certainty along the geological dimension, followed (with decreasing degrees of certainty) by inferred and speculative ones. In a similar fashion, some occurrences are known to be economically recoverable, while others are only marginally economic or perhaps even uneconomic. *Reserves* are those occurrences that are identified, measured and at the same time known to be economically and and technically recoverable. Thus, reserves are recoverable using current technologies and prices. *Resources* comprise the remainder of occurrences with less certain geological and economic characteristics. The so-called *resource base* includes both categories.[1] Additional quantities with unknown certainty of occurrence or with unknown or no economic significance at present are referred to here simply as "*occurrences.*" For example, such occurrences might include methane clathrates, known to exist in large quantities, but with unknown certainty of occurrence and unknown economics of extraction.

Improved geological knowledge, both scientific and experimental (e.g., reservoir theories and exploration), has continuously served to increase the fossil energy resource base and has also led to numerous large discoveries. In fact, the additions to the resource base have generally outpaced consumption since the beginning of the fossil era. Other factors that have influenced additions to the resource base are prices and technology. Increasing prices can render previously marginal or even uneconomic resources profitable. Improved technology can have even more dramatic effects; it can help to identify and assess quantities that were previously only inferred, and sometimes also results in reclassification of resources into reserves. In addition, improved technology can increase the technical recoverability of known and even of depleted deposits. Typically, only 30% (oil) to 50% (coal) of identified economic reserves *in situ* are actually recoverable using conventional methods. For example, enhanced oil recovery can double the recovery rate

---

[1] The resource base estimates include (ultimately) recoverable reserves, and potentially recoverable resources of coal, conventional oil and natural gas, and also of unconventional oil (oil shale, tar sands, and heavy crude) and natural gas resources (gas in Devonian shales, tight sand formations, geopressured aquifers, and coal seams).

from some reservoirs. Finally, technology improvements can reduce the costs of recovery or even make quantities recoverable, which were previously classified as not recoverable. The history of deep offshore oil and gas exploration and production provides a good illustration of such resource dynamics.

4.2.2 Conventional Fossil Energy Reserves

The quantities of identified fossil energy reserves that are economically and technically recoverable are particularly important for short- to medium-term planning. Generally, the data are assembled by industry and the accuracy is frequently so high that some reservoirs are accepted as collateral for credit to finance subsequent field development expenditures. At present, the global fossil energy reserves are estimated to reach 1,280 TWyr. This quantity is so large that it could last almost 130 years at the 1990 level total global energy consumption (10 TWyr). It is four times larger than the cumulative fossil energy consumption since the beginning of coal era in the mid-nineteenth century. Table 4-1 summarizes past and current consumption levels, and the estimates of global fossil energy reserves, resources and additional occurrences. Coal accounts for more than half of all fossil reserves. Consequently, its reserve to production ratio is the highest (almost 230 years at 1990 consumption levels), while this ratio is the smallest for oil (less than 50 years). This is an indication of the greater geological abundance of coal, especially compared with those of (conventional) oil and gas, and constitutes an important reason to develop clean technologies. Despite or perhaps because of its relative abundance, coal reserves have not changed for decades. In contrast, oil and natural gas reserves have increased dramatically during the last 50 years as crude oil has become the world's dominant primary energy source.

The total reserves of fossil energy described above correspond to a carbon endowment of 690 Gt, nearly equaling the current carbon content of the Earth's atmosphere (about 760 Gt of carbon, corresponding to an atmospheric concentration of 353 ppm).

4.2.3 Fossil Energy Resources and Additional Occurrences

Compared to the currently identified recoverable reserves, estimates of additional resources and occurrences of fossil energy are much larger (but also more uncertain). Table 4-1 shows the global fossil resource base estimate to be about 5,600 TWyr and additional occurrences up to 30,000 TWyr. At face value, these numbers are so vast that the availability of fossil energy appears basically "unlimited". Furthermore, some of the current resources might become actual reserves even before the year 2000, and certainly by 2030. Thus, it is very likely that the reserves will increase during the time period of diffusion of second-generation fossil energy technologies. Because of the relative abundance of coal reserves, only additional quantities of oil and natural gas are examined here.

For a number of years, a group of geologists at the USGS (Masters *et al.*, 1987) have been using a probabilistic approach to assess the ultimately recoverable reserves of conventional oil and gas to be discovered in the future at 95, 50 and 5% probability levels. Their estimates range from 40 to 190 TWyr for oil and 80 to 300 TWyr for gas (see Table 4-2); their 50% probability estimates were given in Table 4-1 under the category of "reserves remaining to be discovered".

However, the probabilistic assessments of ultimate future discoveries of recoverable fossil resources (i.e., of ultimate *reserves*) are highly time-specific and, in retrospect,

Table 4-1. Global fossil energy reserves, resources, and occurrences: the broader spectrum, in TWyr (Sources: BGR, 1989; BP, 1991; Grübler, 1991; Rogner, 1990; WEC, 1989).

	Consumption		Reserves		Resources		Resource base (reserves plus resources)	Additional occurrences
	1860–1990	1990	Identified	Remaining to be discovered[a]	Currently recoverable	Recoverable with foreseeable technological progress		
Oil								
Conventional	106	4.4	194	79			273	> 320
Unconventional	–	–	240			285	525	> 4600
Gas								
Conventional	54	2.5	144	136			280	> 320
Unconventional	–	–			70	565	635	> 700
Clathrates	–	–						20000
Coal	165	3.1	701		440	2740	3880	> 4100
Total[b]	325	10.0	1279	>215	>510	>3590	>5590	>30000

[a] Masters *et al.* (1987), 50% probability estimates.

[b] All totals have been rounded.

– negligible amounts; blanks, data not available.

Table 4.2. Estimates of unconventional oil reserves and probabilistic estimates of undiscovered conventional oil and gas, in TWyr (Source: Masters *et al.*, 1987; BGR, 1989; Enquête-Kommission, 1990).

	Undiscovered conventional oil at probability			Identified reserves of unconventional oil[a]	Undiscovered conventional gas at probability		
	95%	50%	5%		95%	50%	5%
North America	6.2	12.5	24.7	12.9	14.2	19.4	37.5
Western Europe	1.7	4.1	8.8	9.6	2.4	5.8	9.9
Former USSR and Eastern Europe	9.1	15.3	37.0	3.8	24.7	41.0	95.8
Oceania	0.4	0.7	1.9	120.7	1.1	2.1	6.3
Asia	6.3	10.8	27.8		9.7	16.8	38.5
Middle East	9.9	19.2	40.3	22.0	20.1	31.5	64.7
Africa	3.5	6.1	18.6	10.0	5.9	10.9	28.7
Latin America	5.4	10.1	29.8	59.6	4.3	8.9	24.1
World	42.7	78.8	188.9	240.5	82.3	136.4	305.6

[a] Heavy crude, tar sands and oil shales (BGR, 1989).

have been rather conservative. Frequently, the ultimate future potential of resources remaining to be discovered is surpassed within a short time period by upward revisions of *reserves*. For instance, the quantities estimated as ultimately recoverable (at the low probability level of 5%) for the Middle East in 1987 (Masters *et al.*, 1987) were surpassed within seven years by net additions to oil reserves (240 billion barrels between 1985 and 1992).

The availability of methane resources is of particular interest because methane has the lowest specific carbon emissions per unit energy of all fossil fuels. Its lower emissions could eventually lead to a "methane economy" (Ausubel *et al.*, 1988; Lee *et al.*, 1988). The figures presented in Table 4-1 indicate a resource base of conventional and unconventional gas of at least a similar order of magnitude as that for oil. Additionally, there are large gas occurrences in form of clathrates in permafrost areas and offshore continental shelf sediments. The order of magnitude of these natural gas occurrences (in the range of 20,000 TWyr, or 140 times the identified gas reserves; see MacDonald, 1990) suggests that methane might be the most abundant form of hydrocarbons in the Earth's crust. This has led a number of researchers to reopen the question of the appropriate theories of the origin of hydrocarbons (see Gold, 1967).

As technology and production economics improve, it will be possible to tap even larger fractions of the total resource base and part of already known occurrences, which implies that fossil fuels are likely to be available for centuries rather than for just decades.

4.2.4 Fossil Fuels as "Carbon Wealth"

The fossil resource base and additional occurrences represent the ultimate global "carbon wealth" that will be available to future generations. This kind of estimating the ultimate carbon stock was proposed more than ten years ago (Ausubel, 1980). The result of this hypothetical calculation, converting from energy units into the corresponding carbon content[2], is given in Table 4-3.

---

[2] For specific emission factors see Ausubel *et al.* (1988).

Table 4-3. "Carbon wealth" expressed as the carbon content of past and present energy consumption and of fossil reserves, resource base and occurrences (in Gt carbon).

	Coal	Oil	Gas	Total	As a % of current atmospheric carbon loading (760 Gt)
1860–1990 consumption	121.9	65.6	27.7	215.2	28
1990 consumption	2.3	2.5	1.1	5.9	<1
Reserves (conventional)	515.5	108.6	63.7	687.8	90
Total resource base	2853	447	405	3705	490
Additional occurrences	>3000	>2700	>450	>6150	810
Methane clathrates			>8850	>8850	1160
Total				>18700	2460

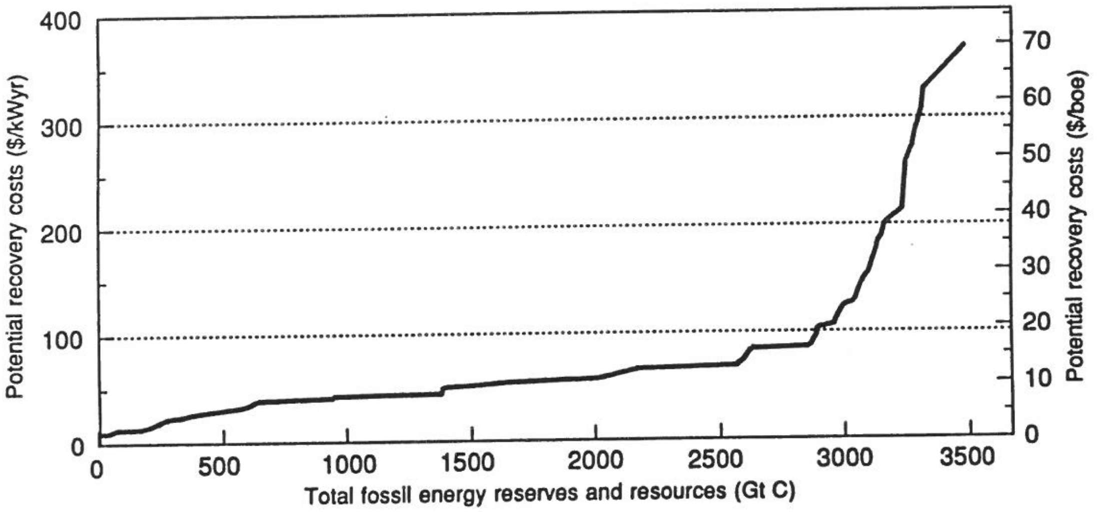


Figure 4-1. Global carbon supply curve of fossil reserves and resources (in Gt carbon, cumulative), versus estimated recovery costs (in 1990 dollars) (Source: Rogner and Grübler, 1992).

Global fossil reserves contain more than three times as much carbon as was released by the burning of fossil fuels over the entire period from 1860 to 1990. If all fossil fuel reserves were burned (assuming that 50% of CO_2 emissions remained airborne), this would result in an increase in the current atmospheric carbon concentration (353 ppm) by some 160 ppm to 513 ppm.

The resource base, with some 3700 Gt carbon, is about five times as large as the current atmospheric carbon (content) loading. This represents the currently estimated "carbon wealth" available to humanity. We have plotted the global resource base (carbon wealth) against the estimated recovery costs[3] and have in that way derived a global "carbon supply curve" as shown in Figure 4-1.

The supply curve indicates that some 3,500 Gt of carbon are estimated to be potentially recoverable worldwide. The majority (some 2650 Gt) of this "carbon wealth" consists of coal, and the largest part would be recoverable at production costs (not energy

---

[3] Costs include exploration, development, and extraction costs. Modest technological improvements were also considered in estimating future recovery costs.

prices) of less than \$20/boe. Even at production costs below \$10/boe, more than 1500 Gt of carbon in the form of fossil fuels are recoverable. This range of production costs corresponds to a cost range of \$90–180 per tonne of carbon. This is to be contrasted with the similar cost range of \$100–200 per tonne of carbon for removal technologies (see Chapter 5). The above range is also of the same magnitude as the levels suggested for a "carbon tax" in a number of countries (see, for example, CEC, 1992).

This result shows that the real problem lies in the fact that perhaps as much as 3000 Gt of carbon in fossil fuel resources could be recovered at relatively modest costs (of less than \$20/boe) which could double[4] the current atmospheric CO_2 concentration if actually mined and used as fuel. This clearly points to the urgent need to identify clean fossil energy technologies that could mitigate CO_2 emissions if larger shares of the carbon wealth are ever consumed.

4.3 Clean Fossil Energy Conversion Technologies

The past 30 years have witnessed steady improvements in steam and combustion turbine efficiencies as well as in the overall system reliability, availability and maintainability. These performance improvements are the compounded result of autonomous technical progress, price-induced technology change and technology responses to reduce the discharge of fossil fuel combustion products that are harmful to the environment.

The environmental factor has often been considered as a road block to efficiency improvements in the field of fossil-based electricity and heat generation. Indeed, a drop in efficiencies has been observed when technology responses consisted of add-on abatement measures only. Recent innovative plant design and integration, however, have succeeded in both efficiency improvements and emission reductions (over and above those directly linked to the efficiency factor). In particular, concepts such as integrated gasification combined-cycle or pressurized fluidized bed combustion technologies all reduce, by design and without environmental add-ons, most of the emissions significantly. Furthermore, advanced fossil fuel electricity-generating technology reduces carbon emissions through higher conversion efficiencies. In the longer run, what may be more important than pure efficiency considerations is the principal shift to combined-cycle technologies for all fossil fuels including coal.

Combined-cycle technology harnesses the exhaust gases of a gas turbine to raise steam to turn a steam turbine. This is not a new concept. Meanwhile, advances in material technology permit baseload operation of combustion turbines adding economic attractiveness to the already high efficiencies associated with combined-cycle technology. The latest natural gas-fueled combined cycle installations have achieved an availability of 95% and net baseload conversion efficiencies in excess of 53% (e.g., the Siemens plant in Ambarli, Turkey). Premixing of fuel and air in a hybrid burner avoids temperature peaks during combustion and thus reduces NO_x emissions significantly (Valenti, 1991).

Combined-cycle technology represents a hedge against the uncertainty of future environmental policy constraints, and it also represents an effective least-regret cost investment strategy. This is to say, economics of combined-cycle technology do not hinge either on the availability of low-cost natural gas or diesel oil, or on the possibility of restrictive environmental policies. The crucial element in this strategy is the use of coal, which, at first glance, is the least likely fossil fuel for clean electricity generation. In

---

[4] Assuming that 50% of emissions would remain airborne.

essence, most "clean coal technologies" involves the marriage of gas turbines and coal or coal-based fuels (Bajura and Webb, 1991).

Clean coal technologies fall into several categories including clean combustion processes like pressurized fluidized bed (PFB); coal gasification, and combustion of the synthesis gas in combined-cycle gas turbines; direct and indirect coal-fired turbines; fuel and pure oxygen gas turbines; magneto-hydrodynamic generators; carboniferous fuel cells; and the separation of hydrogen from coal and the storage of elemental carbon (hydrocarb process). PFB and indirect concepts like the integrated gasification combined cycle (IGCC) are either already operational or rapidly approaching the stage of commercial availability. Direct coal-fired systems are in the prototype development stage, while magnetohydrodynamic generator development is in the proof-of-concept stage. The same is true of fuel cells and the hydrocarb process.

4.3.1 Pressurized Fluidized Bed Combustion (PFBC)

Fluidized bed combustion occurs in a vessel equipped with a base plate with a large number of nozzles. Combustion air is blown through these nozzles into a bed of fine-grained, inert material which above a certain level of air velocity behaves like a violently boiling liquid. Pulverized coal is blown into this floating bed from below through another set of nozzles. In the fluidized bed, every particle of coal is surrounded by hot inert bed material, thus providing ideal combustion conditions. The bed material also contains limestone or dolomite which effectively means that flue gas desulfurization occurs simultaneously with combustion. Likewise, the design keeps nitrogen oxidation at favorably low levels.

Fluidized bed technology can be used in a variety of configuration concepts, including atmospheric or pressurized combustion, heat transfer by water/steam or by means of air, and various output combinations (electricity, process steam and/or district heat). Because of its inherently higher efficiency and modular design, pressurized fluidized bed combustion appears as the most promising fluidized bed technology. An important benefit of pressurization is an increase in the power density and the option to add a gas turbine or combined-cycle system in addition to the basic steam cycle. The net electricity generating efficiency amounts to 42% (ABB, 1982).

4.3.2 Integrated Gasification Combined Cycle (IGCC)

The IGCC integrates coal and combined cycle technology. Coal is gasified by partial combustion in a pressurized furnace. In an advanced IGCC system, an air-blown rather than oxygen-blown gasification is used, thus eliminating the capital cost of an oxygen plant. The gasification stage involves the burning of a mixture of coal, water and air to produce a synthesis gas (mainly hydrogen and carbon monoxide). The hot gas cleaning unit (employing zinc alloy-based desulfurization sorbents) strips the sulfur from both hydrogen and carbon monoxide to less than 10 ppm (Culp, 1991). The waste heat from the gasification step can be used either for steam generation, together with the bottom cycle of the combined cycle unit, or for regenerative heating of feed water.

The remaining part of the IGCC system corresponds to a standard combined cycle with turbine exhaust heat raising steam for the bottoming steam cycle. Overall efficiencies for plant and equipment currently under construction are expected to be in the range of 42–46% (SBS, 1991).

4.3.3 Direct Coal-Fueled Turbines (DCFT)

A joint effort of Westinghouse and a subsidiary of General Motors aims at developing direct coal-fired turbines. Coal is fed into the combustor either in dry pulverized form or as a coal-water slurry. After initial combustion, one stream containing the fully oxidized carbon is directed to the expansion turbine via slag separators, cyclones, ceramic filters, etc., while the other stream containing the bulk of unburned carbon is returned after ash removal to the combustor (Bajura and Webb, 1991).

Direct coal-fired turbine technology has yet to pass beyond the test bench scale of application. A 4.6 MW full-scale integrated coal-water slurry system is being tested in Indianapolis. Conversion efficiencies are expected to fall into the lower 40% range.

4.3.4 Indirect Coal-Fired Turbines (ICFT)

Indirect coal-fired systems avoid several technical barriers that are encountered when the combustion products pass through the turbine directly. Instead, the air from the compressor is heated by the combustion gases in a ceramic heat exchanger. Thus, clean air is the only mass flow entering the expansion turbine. This means that the combustion process associated with the indirect coal-fired system may range from conventional atmospheric combustion (with flue gas abatement technologies) to fluidized bed combustion.

High cycle efficiencies require high turbine inlet temperatures as well as complete recuperative operation. Therefore, high-temperature heat exchangers have to be based on ceramic materials that can withstand the hostility of a hot coal flue gas environment. Combined cycle efficiencies of up to 52% can be achieved by water injection into the compressor discharge air.

Current indirect coal-fired projects are hybrid systems in which, after compression, air is heated to the temperature limit of conventional metallic heat exchangers, resulting in efficiencies on the order of 47%. Pressurized high-temperature ceramic heat exchangers for use with indirect coal-fired gas turbines are about to enter the demonstration phase (Bajura and Webb, 1991).

4.3.5 Fuel and Pure Oxygen Gas Turbines

One promising scheme to reduce carbon emissions with gas turbines is the combustion of methane or synthesis gas from coal (the carbon monoxide stream) in a mixture of oxygen and recycled CO_2. The amount of oxygen has to be controlled since combustion in pure oxygen would lead to excessive temperatures.

However, there is an efficiency penalty of combustion in pure oxygen of about 10 percentage points. This is due to the energy requirements for air separation in an oxygen plant. The overall plant efficiency is about 30% (Abele *et al.*, 1987). A 650 kW pilot plant has been built by the Black Hills Corporation in the USA for combustion of pulverized coal in a gas turbine with pure oxygen. Pulverized coal is added to inlet gas mixture of 70% CO_2 and 30% oxygen. After combustion, flue gases consist of about 95% CO_2. Water vapor, residual oxygen, and SO_x and NO_x are removed before about 70% of the CO_2 is recycled.

4.3.6 Magnetohydrodynamic Generators (MHD)

The magnetohydrodynamic (MHD) generator operates in a manner similar to a conventional mechanical-electrical generator. Instead of a rotating metallic conductor, MHD forces an electrically conducting fluid through a perpendicular magnetic field at high velocity. The fluid passing through the magnetic field generates an electric field. Electrodes constituting the wall draw the current.

The conducting fluid is either an ionized gas or a liquid metal. In the case of coal, the MHD generator forms an ionized conducting gas from the combustion gas, which then serves as the working fluid (Chapman and Johanson, 1991). In a combined cycle configuration, MHD would assume the role of a topping cycle where hot gas from the generator generates steam for the bottoming cycle. The steam boiler associated with a MHD generator, however, is distinctly different from a standard boiler and rather resembles a black liquor paper mill boiler. Most significantly, the gases exiting the generator are fuel-rich. The utilization of the exhaust fuel contents requires a secondary combustor. Because of the secondary combustor, the bottoming cycle must be equipped with an exhaust gas clean-up system. The efficiency of the MHD topping cycle is about 28–30%. Because of the high exit temperatures, the overall efficiency of a combined-cycle arrangement amounts to approximately 55%.

4.3.7 Carboniferous Fuel Cells

In addition to the carbon-free fuel cells that we will return to again in Section 4.5, there are two fuel cell designs which fall into the categories of clean fossil fuel technologies. In many respects, fuel cells resemble batteries. The battery and fuel cell are systems in which stored chemical energy is converted directly into direct current (dc) electricity. The main difference between the two is the fuel storage. Batteries contain a fixed quantity of fuel or chemical energy (that can be recharged or restored through a reversible process of applying the reversed dc), whereas a fuel cell operates with a continuous external supply of fuel.

The fuel cells that are suitable for fossil fuel use operate typically at high temperatures so that they are less sensitive to carbon impurities. Indeed, they utilize carbon for providing, in part, the operating temperature. It is unlikely that these cells would be able to accommodate coal directly within a 20–30 year time frame; they belong to the class of the third-generation technologies that might diffuse later in the next century. In the meantime, the dominant hydrocarbon fuels for these cells will be natural gas, methanol or synthesis gas produced from coal.

Molten Carbonate Fuel Cells (MCFCs)

The electrolyte of a molten carbonate fuel cell consists of molten salts operating at 650 °C, opening the possibility of using carbonaceous fuels and internal reforming. Internal reforming of the synthesis gas results in hydrogen and CO_2. Hydrogen is immediately oxidized electrochemically to water vapor which, in turn, drives the shift process. If natural gas is used as fuel feed, the internal reforming requires the presence of a reforming catalyst eliminating the cost of an external steam methane reformer. The high-grade steam facilitates easy integration of the fuel cell with an external coal gasifier. Moreover, sufficient steam is available to run steam turbines in a bottoming cycle with overall efficiencies as high as 60 and 65% for synthesis gas and natural gas, respectively.

The experience initially gained so far with MCFCs (in the 10–100 kW range) has given rise to some doubts as to their durability due to the high operating temperatures. Moreover, the MCFCs have shown extreme sensitivity to impurities such as sulfur, halogens, etc., in the fuel stream (Cameron, 1990). Current test programs are set to demonstrate 40,000 hours of reliable electricity production.

Solid Oxide Fuel Cells (SOFCs)

Operating at temperatures in the vicinity of 1000 °C, certain solid oxide materials become sufficiently conductive to oxygen ions (while remaining insulators for electrons). Unlike internally reforming MCFCs, solid oxide fuel cells fueled directly with natural gas do not require the presence of a catalyst. The higher operating temperature and some excess steam suffice to stimulate instant reforming.

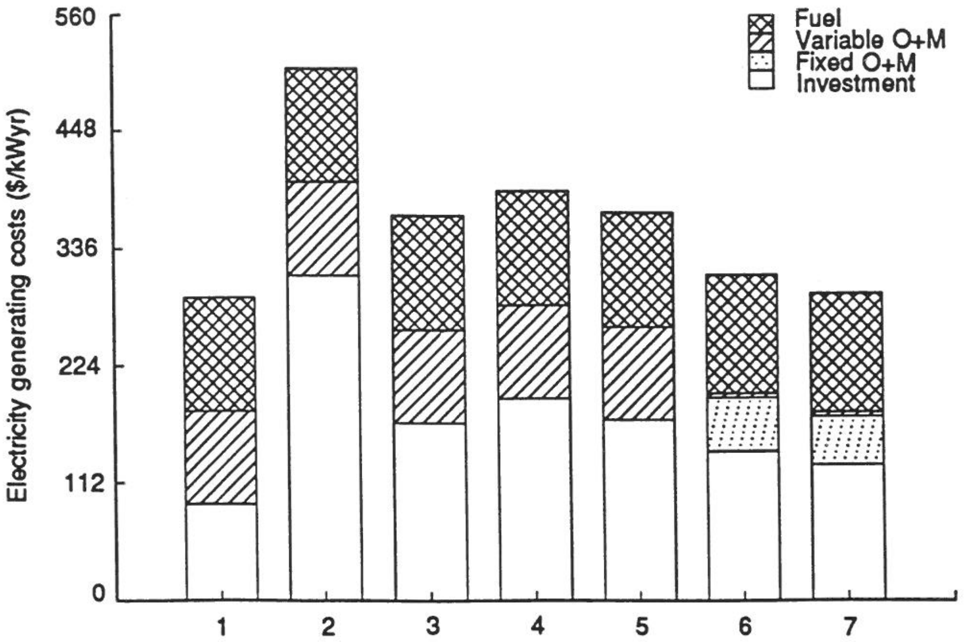
SOFCs operate equally well on hydrogen and on carbon monoxide, individually and jointly. Hence, synthesis gas from methanol reforming or coal gasification can easily be used. Generally, the presence of carbon monoxide lowers the cell's performance by about 10%. Seemingly, SOFCs have a relatively high tolerance to impurities such as sulfur, allowing the use of untreated coal-based synthesis gas.

Estimates of obtainable overall conversion efficiencies vary around the 55% level. Advanced designs target a power density of 1 MW/m^3 by packing tubular solid oxide cells into a honeycomb structure. Like MCFCs, the next threshold to commercialization will be to provide proof of reliable operation over 40,000 hours.

4.3.8 The Hydrocarb Process

The basic idea behind the hydrocarb process is to separate hydrogen from carbon in coal, store the carbon generated, and to use the hydrogen as a clean fuel (Steinberg and Grohse, 1989). There are two basic coal conversion steps in the hydrocarb process. First, coal is hydrogenated into methane, and the methane is then thermally decomposed into carbon black and hydrogen. Together, the two conversion steps are thermally balanced and require no additional energy inputs. The advantage of the process is that the removed elementary carbon (black) has low oxygen affinity so that it can be retained in permanent storage for practically indefinite periods. This renders the scheme very attractive as a means of removing carbon from fossil fuels.

The overall efficiency of the hydrocarb process for producing hydrogen from coal is at most 16% because most of the coal energy is retained in the elementary carbon that is left unused (Seifritz, 1991). For this reason, the hydrocarb process is more efficient if applied to coals with higher hydrogen to carbon ratios. Of all fossil energy forms, methane has the highest ratio (of four) resulting in a maximal efficiency of 51% for hydrogen production with the process. The hydrocarb process has been also suggested for conversion of biomass into hydrogen or hydrogen-rich fuels such as methanol (Steinberg, 1990) or for strategies combining biomass and fossil fuels for methanol production and carbon sequestering. Another refinement of the process is the application to underground coal gasification (Steinberg, 1991). Methane and hydrogen-rich gases would be used for energy purposes after coal gasification, while elementary carbon would be stored either for later use or final disposal.



1 LWR in USA ordered 1970.
2 LWR in USA, present licensing, ordered now.
3 LWR in USA target value for "reborn" nuclear industry, ordered now (EPRI estimate).
4 LWR in Europe, start-up 1990, 10 year construction.
5 LWR in Europe, start-up 1990, 6 year construction.
6 LWR in Europe (Germany) cost estimate for 2000.
7 LWR in Europe (Germany) cost estimate for 2020.

Figure 4-4. Electricity generating costs of current and advanced light water reactors (1990 dollars).

4.4.1 "Once-Through" Nuclear Technologies

The current nuclear fuel cycle reactors are of the "once-through" kind, meaning that fuel is produced, "burned" in converter reactors and the resulting fissile products are discarded. The inherent disadvantages are that the reactors consume fissile uranium and that spent fuel disposal is required. This relatively large fuel requirement of the currently practiced open nuclear fuel cycle "dilutes" many of the potential advantages of nuclear energy compared with fossil fuels, such that one gram of material handled (e.g., natural uranium mined, overburden and uranium tailings handled, etc.) results in not much more energy than one gram of carbon mined as coal, especially for lower-grade uranium ores (Häfele *et al.*, 1981). Thus, the promise of the advantage of minimal material handling requirements of nuclear compared with coal is ultimately diluted from one million to one down to unity so that the open, once-through fuel cycle may in practice be equivalent to mining "yellow coal". Most reactors in use today operate in this mode, the most widespread type being the light water reactor (LWR). Despite this inefficiency, nuclear electricity production could continue for decades if not a century with current uranium reserves.

4.4.2 Nuclear Energy by Breeders and Burners

In the converter-breeder scheme the nuclear fuel cycle is closed with low additional natural uranium inputs and low streams of fissile product wastes requiring final disposal. There are numerous variants of this strategy. The basic scheme involves breeder reactors to convert natural uranium (mostly non-fissile U_{238}) into fissile plutonium that can be used to fuel converter reactors. There are alternative proposals (using a thorium fuel cycle, for example), which are no doubt technically elegant, but their high costs, unresolved safety issues and perhaps most important the lack of actual need in the foreseeable future present serious problems. Most fast breeder programs have either been halted or scaled down, with the exception of the Super-Phénix fast breeder reactor (FBR) in France, although this too has been plagued with difficulties. The technical complexity of such schemes extends throughout the fuel cycle, including reprocessing, fuel fabrication, etc. Despite the many potential advantages of a closed fuel cycle, most of the components associated with such integrated fast reactors (IFR), including mixed oxide fuel, are likely to be much more expensive than the conventional once-through systems in operation today. These integrated or closed fuel cycle schemes might become more attractive should natural uranium resources start to limit the future expansion of nuclear energy.

4.4.3 High-Temperature Nuclear Energy

Should nuclear energy be able to make a significant contribution to the future energy supply, then it will undoubtedly also have to expand its niche beyond electricity generation. In particular, advanced high-temperature gas-cooled reactors (HTGRs) could provide process heat for industrial processes and other services along the temperature cascade. The difficulty lies in the co-location of nuclear plants with industry and commercial areas. To resolve such issues, it is required to transport nuclear energy (heat) over longer distances with a minimum of losses and in a carbon-free form. Along these lines, the so-called "Adam and Eva" system has been developed in Germany, in which a high-temperature reactor is used to reform methane into carbon monoxide and hydrogen in a closed cycle that, when combined with the help of catalysts, provides high-temperature heat for end-use applications at any desired distance from the power plant itself, returning methane and water to the plant. Alternatively, this cycle can be opened whereby an HTGR provides heat for "refining" natural gas into hydrogen and CO_2 by steam reforming (Marchetti, 1991; 1992a). CO_2 could be used for enhanced oil recovery or diverted directly to permanent storage (see Chapter 5) and hydrogen provided directly to consumers. The most important feature of this scheme is that the final fuel is decarbonized while the system is only a quarter nuclear, the rest of energy and hydrogen originating from natural gas.

4.4.4 Advanced Safe and Multipurpose Reactors

Based on the 6000 years of mixed operating experience with commercial nuclear reactors, new "inherently safe" modular designs could resolve some of the open problems such as safety and poor economics. The basic idea behind most of the inherently safe reactors is that all of the heat generated after emergency shutdown should be able to dissipate from the reactor vessel through passive measures such as thermal conduction. Such designs are now being evaluated in a number of countries. Asea Brown Boveri (ABB) has advanced the process-inherent ultimate safety (PIUS) reactor with "walkaway safety features", meaning that in an emergency the reactor can be left alone. PIUS relies on thermohydraulics and gravity to prevent the reactor core from overheating. The core sits in a pool of borated water that will shut down the reaction in an emergency, without human intervention. In the United Kingdom, reactor designs with passive safety features are also being investigated, including a safe integral reactor (SIR). There are a number of programs in the United States such as the semi-passive safety LWRs and the advanced passive (AP600) reactor (IAEA, 1991; COSEPUP, 1991).

In addition to the development of modular and smaller advanced reactors, most of the other efforts are devoted to improvements in the economic performance of converter reactors and the development of advanced fast and high-temperature reactor designs. France is continuing the development of FBRs jointly with Germany, and the United Kingdom and is also planning to build several advanced large pressurized water reactors (PWRs). Japan is developing an experimental HTGR and a demonstration fast reactor. All of these developments will help establish a technological base for the next generation of nuclear systems provided that public acceptance and safety barriers can be overcome.

An alternative nuclear option to the fission of larger atoms is the fusion of smaller ones. In contrast to the experience gained with the fission reactors in operation, the feasibility of power generation by fusion has yet to be demonstrated. Despite enormous progress in achieving both high deuterium-tritium plasma confinement and temperatures, the actual plasma "ignition" and controlled fusion is still at least a decade away. "Cold fusion" briefly attracted attention in the media, but it is now clear that there are no easy short-cuts to a demonstration fusion facility. Thus, fusion remains a third-generation technology: only after the middle of the next century some electricity might be produced by fusion reactors (COSEPUP, 1991).

4.4.5 Integrated Energy Systems

A number of advanced energy systems that would result in either low or zero-carbon emissions rely on the integration of the technologies discussed above. For example, the combustion of natural gas in oxygen could integrate an air separation facility with a gas turbine, or a high-temperature reactor could be used to "refine" natural gas into hydrogen and CO_2 by steam reforming. All of these technologies can be thought of as elements of a "novel integrated energy system" (NIES). The basic idea of a NIES is to decompose and purify the primary fossil fuel *before* combustion, to integrate these decomposed (clean) products *horizontally*, and to allocate them *stoichiometrically* to the synthesis of zero-carbon and clean final energy forms (Häfele and Nakićenović, 1984). Figure 4-5 gives a schematic diagram of a novel integrated energy system (Häfele *et al.*, 1986), incorporating a number of individual energy conversion technologies in order to provide a high degree of flexibility in separating CO_2 and other sidestream emission products (such as sulfur dioxide, nitrogen oxides and certain heavy metals) from the final energy delivered to consumers. This means that supply and demand are treated holistically in a NIES. The NIES first decomposes primary fossil energy sources such as coal, oil and natural gas mostly into carbon monoxide and hydrogen. Other inputs are also processed, including, for example, air separation for the production of oxygen, so that most of the potential pollutants are removed from the input stream. The next step is to "horizontally" integrate carbon monoxide, hydrogen and oxygen (using nuclear, solar, or other sources of heat) into an output stream of clean and also carbon-free final

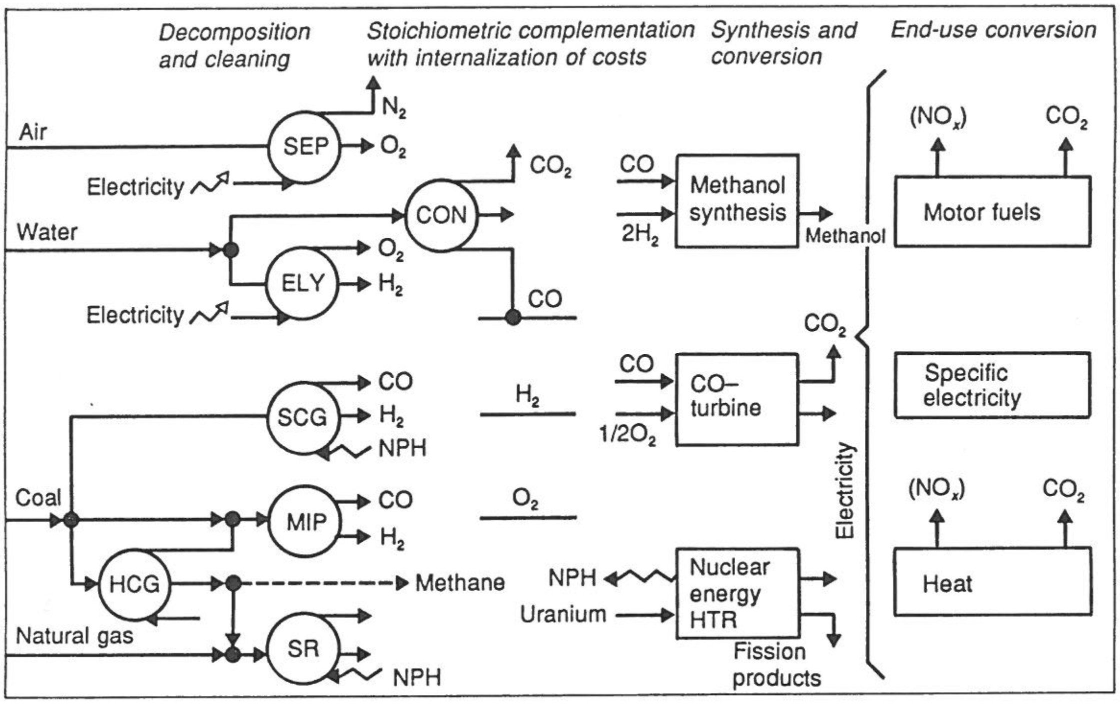


Figure 4-5. Schematic overview of a zero-emission novel integrated energy system (NIES) (Source: Häfele *et al.*, 1986).

energy carriers such as hydrogen and electricity. Other alternatives include the synthesis of methanol, possibly using biomass as a feedstock to close the carbon cycle (Lee *et al.*, 1990).

There are a number of barriers that are likely to block the diffusion and implementation of integrated energy systems, however, most of which are institutional in nature. Should pressure increase in the future to limit or even eliminate CO_2 emissions, the NIES concept would certainly gain economic attractiveness so that it is very likely that at least some second-generation technologies might operate within a larger integrated conversion and distribution system.

4.5 Carbon-Free End-Use Technologies

In 1990, more than half of global carbon emissions originated from end-use technologies and less than half from the preceding conversion processes, including fossil-fired electricity generation. Primary energy conversion processes have been the prime target for technological response measures. Conversely, energy end use has been principally discussed for conservation and efficiency improvements (see Chapter 2). Although essential for any greenhouse gas reduction strategy, efficiency improvements alone will fail to curb significantly CO_2 emissions from energy end use.

Obviously, end-use technologies such as motor vehicles or light bulbs are intimately linked to particular fuels. More often than not, these technologies limit the flexibility for switching between carbon and zero-carbon fuels. The question is, therefore, which combination of end-use technologies and associated carbon-free fuels could provide the full range of energy services necessary for the future. Electricity is a carbon-free energy carrier which, at the point of use, also has the highest efficiency and versatility, but there are a number of energy end uses in which the nature of electricity poses a problem. In particular, electricity applications for vehicles will be restricted by the low onboard storage capacity (low power density of batteries).

4.5.1 Electricity and Hydrogen for End Use

Hydrogen and electricity are the only manufactured fuels that together could meet all energy service requirements, do not contain carbon, and are truly renewable. Electricity, which may be viewed as an electrical charge separation, returns to a neutral charge when it is used. Hydrogen – by analogy water separation – returns to water when it is used. Electricity makes use of the electron, hydrogen uses the proton, resulting in a perfect complementarity of the two fuels. Both can be produced through any of a considerable number of energy technologies and primary sources, including coal, natural gas, biomass, nuclear, hydro, solar, etc. To a large extent, both fuels are "blind" to their sources and thus constitute ideal final energy carriers.

The source flexibility of hydrogen and electricity on the one hand, and the storability of hydrogen and the synergism between the electron and proton carriers on the other, make hydrogen the ideal load-balancing fuel for primary energy sources with intermittent availability. It appears that the development of a hydrogen supply infrastructure will be an inevitable prerequisite for the large-scale utilization of many renewable forms of electricity. In other words, the prospects for a rapid market penetration of photovoltaic electricity beyond the level of local or incremental importance hinge on the removal of the electricity storage barrier. Hydrogen presents an immediate solution to electricity storage.

The world hydrogen market currently amounts to some 550 billion m^3 per year. In terms of its energy content, this amounts to about 210 GWyr (150 million toe). The bulk of hydrogen (about 80%) is used as a chemical feedstock either because of its easy reactivity in chemical reactions (hydrogenation) or because of its reduction potential. The remaining 20% of non-feedstock hydrogen are largely burnt as an under-boiler fuel (usually on-site where H_2 is a by-product). About 95% of hydrogen is produced directly or indirectly from fossil fuels, and the remaining 5% is electrolytic hydrogen.

4.5.2 Electricity End-Use Technologies

Electricity use is increasing worldwide. Close to one third of all primary energy reaches final use in the form of electricity. In the industrialized countries, almost 36% of primary energy is converted into electricity. There are numerous technology improvements that will increase the efficiency of electricity end use, probably leading to even higher shares. However, one large relative disadvantage of electricity is the losses inherent in transmission lines. For this reason, superconducting technologies for electricity transmission and other applications are of great interest. Studies have been made on the feasibility of achieving superconductivity at liquid-helium temperatures, but for electricity transmission such superconducting cables would have to be capable of transporting tens of gigawatts of electricity (COSEPUP, 1991). Other potentially attractive applications of superconductivity include the magnetic levitation trains (Maglev), advanced computer applications, and a host of other electricity end uses. The successful development of high-temperature superconducting materials may significantly alter the economics of electrical power generation, transmission and particularly end use.

4.5.3 Hydrogen End-Use Technologies

The use of hydrogen in adapted internal combustion engines has been investigated for quite some time. Although technically feasible and probably economically viable in a situation of strict carbon emission constraints, internal combustion does not represent the most efficient utilization of hydrogen. Instead, hydrogen in the transportation market will be closely associated with fuel cells, and could make major inroads in electricity generation, industrial cogeneration, commercial and residential space and water heating as well as in the chemical feedstock markets.

The use of hydrogen represents a large potential for reducing carbon emissions, regardless of whether the end-use technology is an internal combustion engine or a fuel cell. The common technological barrier to both end uses of hydrogen is that of storage, and this to a large extent will determine the rate of introduction of new applications of hydrogen as a fuel in the future.

In the following we discuss the future prospects of key hydrogen end-use technologies. Since an impact assessment in terms of carbon emission reductions of individual technologies in isolation from the upstream part of the energy system would be of limited significance, full source-to-service hydrogen chains are analyzed with respect to their carbon reduction cost-effectiveness. The analysis of source-to-service chains identifies several technoeconomic and socioeconomic barriers to large-scale hydrogen penetration. Within the time frame foreseen for the second-generation technologies to mature, most of the present technological issues are, however, unlikely to pose serious problems.

Fuel Cells and Hydrogen

Fuel cells have long offered an efficient method of converting hydrogen directly into electricity via electrochemical reactions. In addition to the more recent development of high-temperature fuel cells that are capable of using fossil fuels such as the molten carbonate fuel cells (MCFCs) and solid oxide fuel cells (SOFCs), most work has concentrated on developing just three types: alkaline fuel cells (AFCs), solid polymer fuel cells (SPFCs), and phosphoric acid fuel cells (PAFCs). Due to the lower operating temperatures of these cells, their efficiencies are also somewhat lower than the 55% efficiency of the high-temperature variants. SPFCs are the most suitable for vehicle applications. They have low operating temperatures, high power densities and relatively simple electrolyte design.

The major impediment to wider use of fuel cell technologies, however, has been their high cost. A phosphoric acid fuel cell system today costs about $2500/kW installed capacity, a significant part of which is the cost of the reformer to produce hydrogen (COSEPUP, 1991). Clearly, in a combination with a reformer, the fuel cell results in carbon emissions unless the carbon is removed in some manner and permanently stored, or hydrogen can be produced without CO_2 emissions. Mobile SPFCs are even more expensive today, at more than $5000/kW. "Clean" fossil fuel cells such as MCFCs and SOFCs fueled by natural gas are expected to achieve costs as low as $1000/kW.

Transportation

The efficiency of a gasoline engine ranges between 5 and 25% depending on the duty cycle performed, and the overall efficiency of the gasoline-powered vehicle drops to somewhere between 3 and 10% (see Chapter 2). In adapted internal combustion engines, hydrogen could boost their efficiencies by some 10–50%. Fuel cell efficiencies are on the order of 60% which, combined with an electric motor efficiency of 90% and other parasitic loads, leads to an overall fuel efficiency of up to 50%, at least double that of an internal combustion engine. Moreover, fuel cell efficiencies are highest under partial loads, adding to their overall performance edge, given realistic duty cycles.

The critical component in all vehicular hydrogen applications is onboard storage. Compressed hydrogen gas, liquid hydrogen (LH_2), metal hydrides and hydrogen absorption are the most likely onboard storage options. Each option has attractive features as well as drawbacks.

Within the time horizon of a second-generation technology assessment, onboard storage is not unlikely to be a limiting factor in the deployment of hydrogen technologies. First of all, they are considerably more efficient than existing internal combustion engines which will reduce the necessary amount of fuel stored onboard without compromising energy services in any significant manner. Second, the data characterizing the storage options exclude the energy inputs expended to get the fuel into an onboard storage tank. This issue will be taken up in the discussion of full hydrogen delivery chains below.

Hydrogen for Residential and Commercial Heating

Residential space and water heating account for more than 75% of residential energy consumption. Two major trends are expected to extend well into the time frame of second-generation technologies. First, natural gas, the fossil fuel with the lowest carbon content, will continue to substitute for oil products and coal. Second, the overall energy intensity of the housing stock and the efficiencies of end-use technologies will improve steadily. Individually and combined, these trends are important prerequisites for the introduction of zero-carbon heating technologies.

Some infrastructural adaptations will be required to account for the differences in the physical properties of natural gas and hydrogen, although the handling, distribution, and storage of hydrogen-rich gases should not present principal problems. Town gas, typically 50% hydrogen and 50% carbon monoxide, was widely used earlier in this century. Hydrogen flame burners are likely to resemble those used in today's natural gas heating systems and will thus require minimum technology adaptation. The efficiency, cost and performance would also be comparable. Although a zero-carbon supply option, hydrogen burners as in the case of natural gas furnaces would have to be vented to dissipate NO_x emissions.

Second-generation heating systems offer considerably higher efficiencies. Catalytic heaters release the internal energy of hydrogen by means of flameless combustion. In the presence of a catalyst (such as magnesium oxide, platinum, or stainless steel), hydrogen combines with oxygen in the air in a reaction that produces a radiant glow in the infrared range. Like electric heaters, catalytic space heaters could be installed in homes and would thus fully utilize radiant heating. The only reaction product is water vapor and a catalytic heater can thus act as an humidifier. Technoeconomic data on second-generation residential heating systems are summarized in Table 4-5.

Likewise, catalytic water heaters would operate with efficiencies close to 100%. Yet another pathway for hydrogen into the thermal heat market are metal hydrides for use in thermochemical machines such as heat pumps, refrigerators, air conditioners or heat transformers.

Table 4-5. Technoeconomic parameters for second-generation residential heating systems combined with insulation measure.

	Units	Natural gas furnaces	Natural gas recuperative furnaces	Natural gas catalytic burners[a]	Hydrogen furnaces	Hydrogen recuperative furnaces	Hydrogen catalytic burners[a]
Power	kW	12.6	8.5	3.4	12.6	8.5	3.4
Capital cost[b]	\$/kW	392	906	3,747	421	929	3,518
Fix O&M cost[b]	\$/kWyr	2.0	9.4	2.95	2.0	9.4	2.95
Useful heat demand	GJ/yr	128	90	30	128	90	30
Efficiency	%	69	95	95	65	95	99
Lifetime	years	18	20	20	18	20	20
Carbon emissions[c]	tons C/yr	2.78	1.42	0.47	0	0	0

[a] Includes additional investments for insulation.

[b] 1990 dollars.

[c] Emissions caused by the heating system only.

The principle is that of thermodynamic cycles within a closed system. For example, a renewable heat source such as solar radiation or waste heat would decompose hydrogen from a low-temperature ferro-titanium (FeTi) hydride. The hydrogen is then stored within the closed system. During periods of heat demand, the process would be reversed, i.e., the hydrogen would be re-absorbed and heat released. The entire process operates within a closed loop, effectively excluding the risk of hydride contamination.

Hydrogen for Industry

Industrial space heating and low- to medium-temperature process heat generation could also be based on second-generation catalytic conversion technologies. In addition, the use of phosphoric acid fuel cells offers an efficient combined heat and power cogeneration alternative.

Industrial energy use, however, is often determined by the actual production process and less by economic and environmental considerations. Product quality, flexibility, etc., have made electricity the preferred industrial fuel. A carbon-sensitive sociopolitical environment is therefore likely to accelerate the penetration of electricity.

A number of production processes, such as cutting and autogenous welding in the metal industry and the production of synthetic crystals or quartz glass, require temperatures in excess of 1700 °C. The stoichiometric combustion of hydrogen-oxygen mixtures yields flame temperatures on the order of 2000 °C. Likewise, hydrogen plasma processes could achieve better product quality than ordinary electric arc pyrolysis due to lower carbon formation.

Hydrogen could substitute as a chemical feedstock for hydrocarbon fuels in the production of industrial organic and inorganic chemicals. Likewise, in the metallurgical sector, the reduction of iron ore and the use of hydrogen as a reducing agent in the production of nonferrous metals could partially replace but not totally dominate carbon use.

By the nature of many industrial processes, the use of hydrogen would have indirect rather than direct carbon replacement effects, such as a substitute for fossil-based electricity.

Energy Vol. 18, No. 5, pp. 485–497, 1993
Printed in Great Britain. All rights reserved

0360-5442/93 $6.00 + 0.00

Chapter 5

Other Environmental Technologies†

5.1 Introduction

Carbon-free energy sources, such as nuclear and solar, make important but so far relatively small contributions toward the reduction of global CO_2 emissions. Decades will probably pass before they could replace fossil fuels as dominant energy sources. In the meantime, therefore, carbon removal from energy carriers and scrubbing after combustion might become important interim priorities. Strictly speaking, these are "add-on" environmental strategies and occur outside the energy conversion system *per se*. The principal route is removal of CO_2 from flue gases from power plants or other (large) boilers.

The disposal and storage of collected CO_2 pose additional challenges. In the ideal case, the collected CO_2 would be utilized in productive activities such as enhanced oil recovery or in processes that utilize carbon as a basic input material. The other alternative is to permanently store the collected CO_2 in the deep ocean, for example, or in natural underground reservoirs such as depleted natural gas fields, aquifers and salt domes. Should all of these measures fail to reduce the atmospheric carbon loading (concentrations), there are very few other easily available mitigation options except to increase the absorption of atmospheric CO_2 by afforestation or by enhancing terrestrial and marine photosynthesis (we investigate the possibility of enhancing carbon sinks in Chapter 6), or to compensate for a rise in global temperatures by reflecting a fraction of incoming solar radiation.

5.2 CO_2 Removal by Scrubbing

The advantages of removing CO_2 from a large, concentrated source such as the flue gas of a power plant, rather than direct removal from the atmosphere, are obvious. CO_2 is about 500 times more concentrated in flue gases compared to its dilution in the ambient atmosphere to about 350 ppm. For (near) stoichiometric combustion of fossil fuels in power plants, the concentration of CO_2 varies from about 15% by volume for coal to 8% for natural gas (Blok *et al.*, 1991). In the case of gas turbines, the concentrations are lower due to the high air-to-fuel ratios. At these concentrations, a wide range of

---

†Nebojša Nakićenović with contributions by Sabine Messner.

techniques can in principle be applied to recover the CO_2. Such schemes were first suggested by Marchetti (1976) and explored further by Baes *et al.* (1980), but in these early proposals, high power plant efficiency losses would be incurred. Subsequently, Steinberg *et al.* (1984) elaborated a more attractive solution of employing a chemical absorption process to recover CO_2 from flue gases and then to use steam extracted from the power plant as a heat source for separating CO_2 from the absorber.

All the systems originally proposed by Steinberg (1983) for CO_2 removal from flue gases are still being studied and some have been used in a number of facilities now in operation. Worldwide there are six plants with carbon scrubbing. The removed carbon is generally used in the food industry, as raw material, and in one case for enhanced oil recovery.

5.2.1 Scrubbing Processes

There are three main CO_2 scrubbing processes: chemical and physical absorption, cryogenic distillation, and membrane separation (see Figure 5-1).

Chemical Absorption Process

Chemical absorption is widely used to remove SO_x and NO_x from flue gases and there are a few (pilot) plants with CO_2 removal by the same process. The various absorbents include potassium carbonate and amines. Sea water can also be used as an absorber but at the cost of relatively high energy requirements and a substantial loss of efficiency. The consensus so far is that a regenerable amine scrubber is the best candidate for such removal schemes. In particular, the mono-ethanol-amine (MEA) process is the most widely used because of its high absorption capacity.

Blok *et al.* (1989, 1991) have estimated the process costs and energy requirements in detail and conclude that "starting with a coal-to-busbar efficiency of 41% in the original plant, its efficiency decreases to 29.7% if CO_2 emission is reduced from 0.23 kg/kWh in the original plant to 0.03 kg/kWh with scrubbing (all emissions expressed as kg C). The electricity costs would increase by about 80% resulting in CO_2 mitigation costs of about $140 per tonne of carbon removed.

Cryogenic Separation

Cryogenic separation involves cooling the flue gases to very low temperatures so that frozen (solidified) CO_2 can be separated. The potential advantages of the process include the possibility of direct disposal of CO_2 ice (e.g., in the deep ocean) and the high purity of the separated gas of almost 100%. The disadvantages include the high energy requirements for reaching cryogenic temperatures.

Schüßler and Kümmel (1989) have estimated that starting from a coal-to-busbar efficiency of 38%, the cryogenic CO_2 separation would decrease the power plant efficiency to 26% if the emissions were reduced from 0.26 to 0.04 kg/kWh with scrubbing. The major energy requirements are incurred during the compression stages so that improvements in this area would greatly reduce the overall power plant efficiency loss.

Membrane Separation

In the membrane separation process an appropriate membrane is used to separate the flue gases into CO_2-rich and lean gas streams (Blok *et al.*, 1991). A number of process

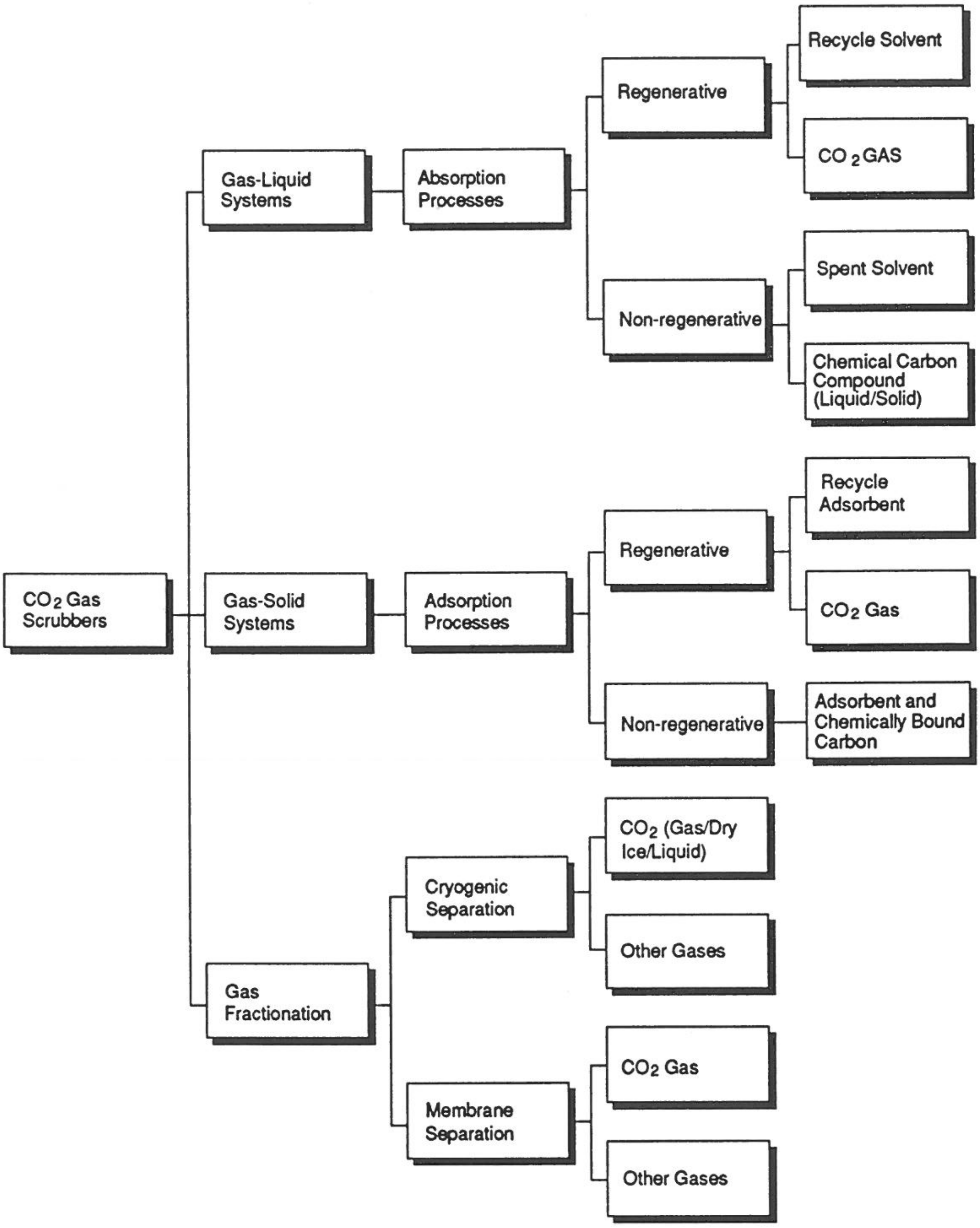


Figure 5-1. The three principal routes for recovering CO_2 from flue gases (Source: Blok *et al.*, 1991).

variations have been proposed, including liquid membranes (Saha and Chakma, 1992). The frequent choice for the membrane material is a nonporous polymer. Feron *et al.* (1992) suggested an alternative approach whereby a membrane without any selectivity would be used with an absorbent (such as MEA) used on the ambient side. This would drastically reduce costs.

For a two-stage cascade, Golomb *et al.* (1989) have estimated that the overall efficiency of a coal-fired power plant would decrease from 35% to 9–18% if about 80% of the CO_2 were removed from the flue gases with purity of 95%. With the same assumptions, they estimate the mitigation costs at $270 per tonne of carbon removed and about half of this sum as the lowest cost estimate but with lower carbon removal rate and purity of product gas.

5.2.2 CO_2 Recovery From Flue Gases

The major problems associated with scrubbing are to reduce the costs and minimize losses in plant efficiency due to the energy spent in separating CO_2 from flue gases. In the best case, using the absorption process, the efficiency reductions of power plants amount to about 10 percentage points. Typically a power plant with an efficiency of 40% might operate at a total net efficiency of 30% with scrubbing. Mitigation costs are typically in the region of $150 per tonne of carbon removed. Figure 5-2 summarizes the relative energy requirements, costs and (remaining) carbon emissions of alternative carbon removal processes from flue gases of coal-, oil-, and natural gas-fired power plants (compared with a "reference" coal plant without scrubbing). The base case power plant is assumed to be about 42% efficient which implies that it requires 2.4 kWyr/kWyr_e. In comparison, the energy requirements of plants with scrubbing vary between 3.2 and 7.9 kWyr/kWyr_e. This translates to a cost range of $90–$530 per tonne of carbon removed. Electricity production costs can be up to 2.5 times higher with scrubbing but lead in all cases to negligible CO_2 emissions compared with the base case plant without scrubbing.

It is likely that the costs and efficiency loss associated with carbon scrubbing will decrease, but the question remains how much and as to how long might it take for the technology to diffuse in the case of competitive economics compared with other mitigation options. Scrubbers are basically an add-on system for existing power plants and thus do not require an entirely new infrastructure. Retrofitting could certainly accelerate their diffusion. Diffusion based only on the introduction of new plant types would clearly retard the process. The time constant for achieving penetration of about half of the installed capacity of fossil-fired power plants would in all likelihood be longer than two to three decades. Although sulfur and nitrogen scrubbers are a factor four to five cheaper than carbon scrubbers, it took more than two decades to achieve the global installed capacities of less than 100 GW_e for NO_x removal and more than 200 GW_e for SO_2 removal. This should be compared with more than 1.6 TW_e of global installed capacity of coal, oil and natural gas power plants (UN, 1991a). This illustrates that the diffusion of CO_2 scrubbing can be expected to take quite some time, and would start to make a significant contribution to overall mitigation only in a few decades from now.

5.3 Recovery by Conversion Process Modification

In Chapter 4 we discussed a number of energy conversion schemes that allow for removal of CO_2 from energy carriers and sources prior to their final use. These include coal

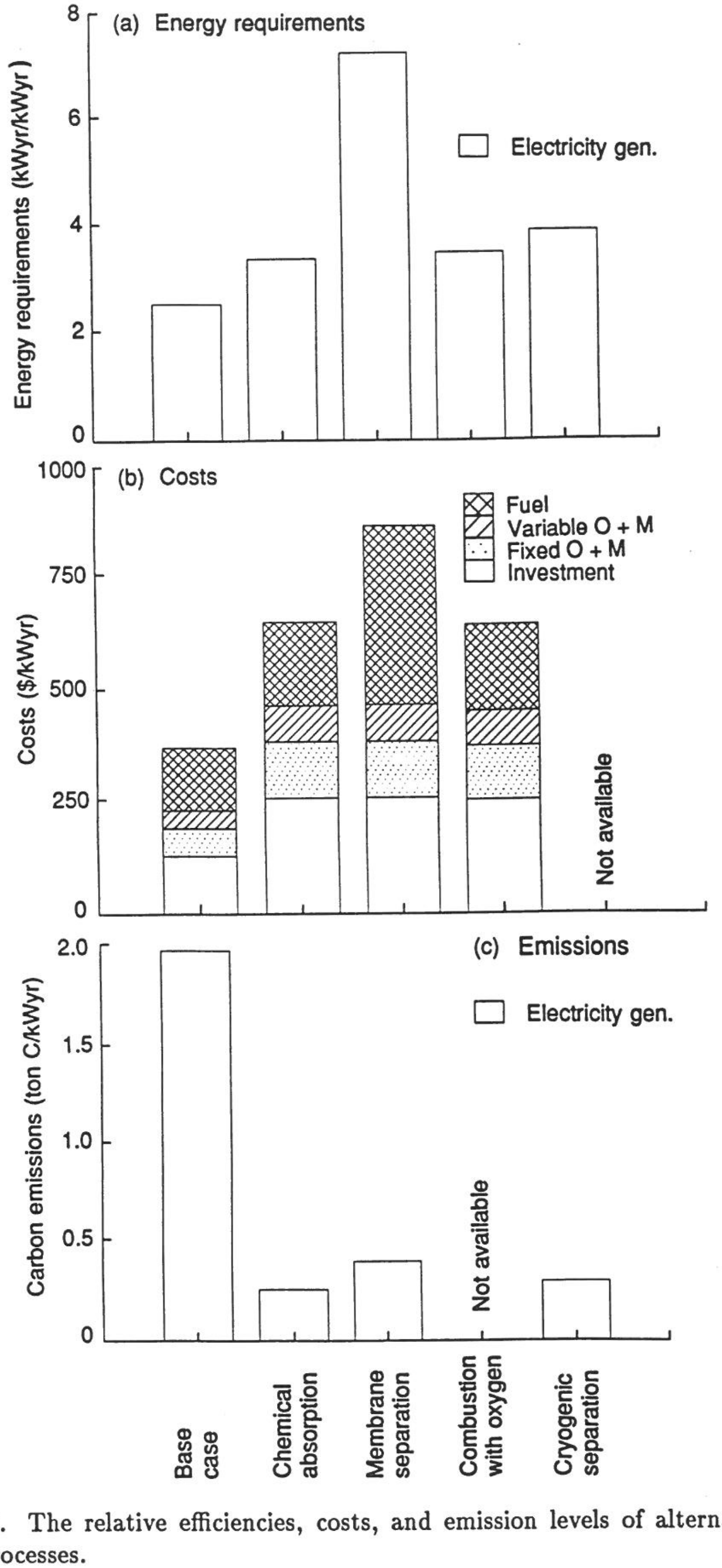


Figure 5-2. The relative efficiencies, costs, and emission levels of alternative carbon removal processes.

gasification or methane reforming followed by a shift reaction and the physical absorption of CO_2. Another possible technology is the combustion of methane or synthesis gas from coal in a mixture of oxygen and CO_2. This scheme allows for easier CO_2 removal after combustion and thus constitutes an alternative process for the recovery of carbon from flue gases. Golomb *et al.* (1989) have concluded that it is the least energy-intensive alternative compared with other post-combustion removal processes. Combustion in pure oxygen, on the other hand, produces high concentrations of CO_2. It relies on air separation so that combustion takes place in an oxygen-enriched gas stream. The amount of oxygen has to be controlled since combustion of fossil fuels in pure oxygen would lead to excessive temperatures. The resulting full emission stream can be carried to disposal.

Based on the work of Abele *et al.* (1987) and Golomb *et al.* (1989), Blok *et al.* (1991) concluded that starting from a coal-to-busbar efficiency of 40%, oxygen combustion would decrease this efficiency to about 29% with almost complete elimination of carbon emissions from the original level of 0.23 kg/kWh. This would result in cost increases of about 73% leading to mitigation costs of about $120 per tonne of carbon.

5.4 CO_2 Utilization, Disposal, and Storage

The amount of carbon generated by scrubbing alone would be truly enormous. Global emissions from energy use amount to close to 6 Gt per year and electricity's share is about 2 Gt of carbon or about 7 Gt of CO_2 per year. The amount of CO_2 generated in electric plants alone will thus dwarf 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 of CO_2 removed from energy plants 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 possible commercial uses of removed CO_2 only the first three provide permanent means of disposal. Additionally, CO_2 may also be permanently stored in natural underground reservoirs, such as aquifers or depleted natural gas fields, or alternatively in the deep ocean.

5.4.1 Enhanced Oil Recovery

The injection of CO_2 into oil fields is a well-known technique for improving the oil recovery rate. The advantage of the process is that CO_2 mixes readily with crude oil and thus displaces oil in the reservoir, i.e., enhancing its recovery rate. Ideally the crude oil should be light, with gravities above 25° API and the temperature should be low (see Dafter, 1980; van der Harst and van Nieuwland, 1989; Blok *et al.*, 1991). In general, the pressure required to achieve miscible displacement is less than 100 bar. The oil industry's interest in using CO_2 as a miscible agent has grown considerably in recent years. During the 1980s, more than 4% of all enhanced oil recovery worldwide was produced by the CO_2 miscible flooding process (about 2 million tonnes out of a total of about 44 million tonnes per year enhanced recovery production), most of it in the United States. Natural CO_2 supplies from underground reservoirs were priced in the United States at between

Table 5-1. Recovery rates and costs of different methods of enhanced oil recovery (Source: Masseron, 1990).

Method	Recovery rate (%) Before	Recovery rate (%) After	Costs (1981 \$/bbl)
Water and gas flooding	30	40	1–15
Steam drive	10	60	10–35
In situ combustion	40	70	10–35
Miscible CO_2	45	70	15–35
Miscible hydrocarbons	45	75	20–35
Water and surfactants	45	75	15–35
Water and polymers	30	40	15–35

\$30 and \$90 per tonne of carbon (in 1990 US dollars, based on 1979 prices given in Dafter, 1980).

As a rule of thumb, it takes several barrels of liquid CO_2 (equivalent) to displace each reservoir barrel of oil. The actual volume of CO_2 required varies greatly, depending on temperatures and pressures. In the following, we assume that about 1.4 tonnes of carbon (more than 5 tonnes of CO_2) are required to extract 1 tonne of crude oil (about 1 tonne of carbon per kWyr of oil).

Table 5-1 compares a number of selected methods of enhanced recovery, indicating that CO_2 is indeed competitive and that it could improve oil recovery rates from about 45 to 70%, roughly double the current average recovery rate of about 35%. This additional output could in principle be achieved from both past and future reservoirs with crude grades lighter than 25° API. About 85% of the original oil reserves in place (cumulative past production and current identified reserves) are lighter than 25° API (Masters *et al.*, 1991). The absolute magnitude of the original oil reserves in this category is estimated to amount to 960 TWyr (690 Gt) of crude oil, 35% of which or about 340 TWyr (240 Gt) could in principle be produced by enhanced recovery. Thus, about 340 Gt of carbon could be stored, corresponding to a storage capacity of about 60 years' worth of current global energy-related CO_2 emissions. Thus, at least in principle, enhanced recovery could provide storage for most of the CO_2 emissions until the middle of the next century.

Table 5-2 gives the global CO_2 storage by future enhanced recovery of original reserves plus undiscovered conventional oil (based on Masters *et al.*, 1987; 1991). The total represents a carbon storage capacity of more than 400 Gt of carbon assuming a 50% probability of discovery, most of it located in the Middle East, followed by North America and the former Soviet Union. It is clear, however, that this is a theoretical maximum and not a practical storage capacity for future carbon emissions. For many reasons, the practical capacities are likely to be substantially lower, but the estimates in Table 5-2 show that they could accommodate current levels of carbon emissions for at least a few decades. Assuming that the current global oil consumption of about 2.5 TWyr (in 1990) would all be produced by CO_2 enhanced oil recovery, this would provide a storage capability of about 2.5 Gt of carbon per year. Thus, the storage potential is indeed large by any standards.

The production costs of enhanced oil recovery are difficult to estimate and they depend to a large degree on the distance of the oil well from the source of CO_2. We estimate the costs at about \$130 per tonne of oil produced, or about \$90 per tonne of carbon stored (and kWyr of oil extracted). The transportation of CO_2 from the source to the wellhead might add another \$5 per tonne of carbon stored (for intercontinental

Table 5-2. Amounts of CO_2 that could be stored as a result of enhanced oil recovery in original and undiscovered conventional oil reservoirs (Reserve estimates: Masters *et al.*, 1987; 1991), in Gt of carbon.

	Original[a] oil reserves (Gt C)	Undiscovered conventional oil at probability		
		95%	50%	5%
North America	58	6	13	25
Western Europe	11	2	4	9
Former USSR and Eastern Europe	40	9	15	37
Oceania	1	–	1	2
Asia	18	6	11	28
Middle East	171	10	19	40
Africa	11	4	6	9
Latin America	27	5	10	30
World	337	42	79	190

[a] Cumulative past production plus current identified oil reserves.

distances, the transportation costs would be higher). Since the total costs are also roughly equivalent to the price of crude oil, enhanced oil recovery offers the promise of one of the cheapest CO_2 storage options.

5.4.2 Storage in Depleted Natural Gas and Other Underground Reservoirs

Many kinds of underground cavities could in principle be used for the storage of CO_2 including depleted natural gas reservoirs, aquifers, salt domes and excavated rock caverns (Blok *et al.*, 1991). Most of the estimates indicate that depleted natural gas wells represent the largest of these storage potentials, followed by aquifers.

The amount of CO_2 that could be stored, volume for volume, as a replacement for extracted natural gas depends of course on the storage density, which is a function of pressure (deposit depth). The density of CO_2 stored at representative natural gas reservoir temperatures and pressures would be about 3.5 times that of natural gas, and the carbon content of the stored gas would also be about 1.4 times higher than that of the natural gas originally in place (Hendriks *et al.*, 1991).

Further research is necessary to determine whether the introduction of CO_2 into a natural gas reservoir would lead to adverse environmental effects. It is almost certain, however, that the leakage of CO_2 back to the atmosphere is highly unlikely due to the fact that the reservoir had contained natural gas for millions of years. It is important that the reservoir is not exposed to pressures above its original level, and the integrity of the cap rock is preserved during the gas extraction phase and reinjection of CO_2.

Natural gas fields represent potentially a very large CO_2 storage capacity. For example, the storage potential of the Groningen field in the Netherlands has been estimated at about 2 Gt of carbon (van der Harst and van Nieuwland, 1989) based on an estimation of the original reserves in place of about 2.5×10^{12} m^3, or about 3 TWyr of natural gas. As Groningen is still a producing field, it would take many decades before this capacity could start to become utilized.

The global storage capacity of natural gas fields can be estimated in the same way as that of Groningen. The original natural gas reserves in place (cumulative production

Table 5-3. Amounts of CO_2 that could be stored in natural gas fields based on estimates of original reserves in place and undiscovered conventional natural gas reserves (Reserve estimates: Masters *et al.*, 1987; 1991), in Gt of carbon.

	Original natural gas reserves (Gt C)	Undiscovered conventional natural gas at probability		
		95%	50%	5%
North America	33	10	14	28
Western Europe	8	2	4	7
Former USSR and Eastern Europe	49	19	30	71
Oceania	2	1	2	4
Asia	8	7	13	29
Middle East	38	15	24	48
Africa	7	4	8	21
Latin America	5	3	7	18
World	150	61	102	226

and known reserves) are estimated at about 200 TWyr, corresponding to a potential CO_2 storage capacity of about 150 Gt of carbon. Table 5-3 shows the global distribution of original natural gas reserves (expressed in terms of CO_2 storage potential in Gt of carbon), together with probabilistic estimates of undiscovered conventional natural gas (see Masters *et al.*, 1991). The total potential of all natural gas fields might be on the order of about 250 Gt of carbon, if the 50% probability estimate of future natural gas discoveries is assumed. This corresponds exactly to an earlier (independent) estimate by Turkenburg (1991) of the global CO_2 storage potential of depleted natural gas fields. This also represents a large potential equivalent to a few decades of global CO_2 emissions. Again, the practical storage capacity is likely to be only a fraction of this potential. If the annual consumption of natural gas of about 1.1 TWyr (in 1990) were to be replaced by CO_2, this would correspond to a storage rate of only about 0.8 Gt of carbon per year.

There are other factors that might actually increase the future storage capacity. In principle, the injection of CO_2 could be used for enhanced natural gas recovery. As in the case of enhanced oil recovery, the major cost component is a function of the cost of transporting CO_2 from the source to the wellhead at the site of deposition. Together with the capital and operating costs of CO_2 compression and adaptation of existing gas wells for injection storage, the total costs are estimated at less than $15 per tonne of carbon (or about $10 per tonne without CO_2 transportation costs). Despite the large degree of uncertainty inherent in such cost estimates, it is clear that the actual deposition of CO_2 in gas wells would be cheaper than in oil wells, although if the value of recovered oil is subtracted, then enhanced oil recovery certainly looks more attractive.

Deep subterranean sandstone aquifers are another promising candidate for long-term CO_2 storage (Fujii, 1992), and appropriate sites are available throughout the world. They have been used for underground storage of gas, so that the storage of CO_2 would also certainly be possible. The global capacity is not known with any degree of confidence, but one study has estimated the total capacity at about 90 Gt of carbon (Koide *et al.*, 1992). It is highly likely that this is a conservative estimate of the actual potential since the capacity of CO_2 storage in aquifers in the Netherlands alone has been estimated at 10 Gt of carbon (van Engelenburg and Blok, 1992). Much lower estimates also exist for the Netherlands, however, placing the storage capacity at between 0.1 and 1.5 Gt (van de Meer, 1992). The disposal costs are very difficult to estimate due to great diversity of various site characteristics; van Engelenburg and Blok (1992) estimate the costs at \$4–8 per tonne of carbon stored. Koide *et al.* (1992) give an estimate that is at least ten times higher at \$79 per tonne of carbon (including \$33 for depreciation and \$12 for interest at 10% per year).

Other underground storage possibilities such as salt domes and other caverns are definitely more limited than aquifers and involve even higher uncertainties concerning possible leakage, available capacities and likely costs. The storage of large gas volumes in salt domes excavated for this purpose has been a routine procedure for years. Horn and Steinberg (1982) estimated that if just 1% of the salt dome volume in the United States were excavated for CO_2 storage, almost 100 Gt of carbon could be deposited. They estimate the costs at between \$60 and \$200 per tonne of stored carbon for the continuous deposition of about 0.5 Gt of carbon per year. Clearly, the global potential is likely to be significantly higher.

5.4.3 Chemical Feedstocks and Basic Materials

CO_2 is widely used as a feedstock by the chemical industry and has some limited uses as a basic material. The largest amounts of CO_2 are used in the synthesis of urea. At present, this process uses little more than 10 million tonnes of carbon (37 Mt of CO_2) per year. Other chemical uses include the production of polycarbonates (Kemi, 1987) and alcohols. All of these processes are important as replacements for other sources of carbon, but none of them represents a permanent disposal option, since after consumption and use, many of the chemicals degrade and release CO_2.

Another possibility is to use CO_2 as a source of carbon for conversion into useful materials or energy carriers. In the hydrocarb process advanced by Steinberg (1983), for example, elementary carbon could be removed from fossil fuels and biomass (see Chapter 4), and stored underground in depleted mines. Alternatively, the production of carbon fibers, fulirens and the manufacture of other carbon-based structural and support materials would require new construction processes and methods. It is clear that in the higher-value niches this would be possible in a relatively short time, since carbon-based materials are already being used as substitutes for more expensive structural materials in aircraft and automobiles. Perhaps carbon could become the raw material of the twenty-first century. At the same time, the amount of carbon that can be utilized as a feedstock material is orders of magnitude lower than the potential offered by either enhanced oil recovery techniques or storage in natural gas fields. It is also quite likely that the costs will be much higher in comparison with those of underground storage methods.

5.4.4 Carbon Disposal in the Deep Ocean

The global carbon cycle involves the annual exchange of around 200 Gt of carbon between oceans, the atmosphere and the biosphere. The largest amount of carbon is "stored" in the ocean and is estimated to be about 36,000 Gt. As the largest carbon reservoir on Earth, the deep oceans might be a possible repository for the carbon sequestered.

There are various disposal schemes: to pump CO_2 in high-pressure pipes to the ocean floor, to inject liquid CO_2 at depths of about 3 km that would then continue to sink, to release solid CO_2 (ice) that would sink by itself to the bottom, and to disperse CO_2 into a suitable sinking 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 CO_2 into sinking thermohaline currents that eventually reach the deep ocean bottom where the CO_2-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 Gt per year, easily exceeding all anthropogenic sources of CO_2. The disposal costs are likely to be lower than those of other alternative schemes for deep ocean disposal since only injection equipment would be required. The theoretical mitigation potential 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.

Another more drastic, and in the meantime much more widely studied, solution has been proposed by Nordhaus (1975), which involves injection of CO_2 by a long pipe directly into the deep ocean. If injected at depths of about 3 km, CO_2 would continue to sink to the bottom. There are many possible sites for such disposal, including the 3 km-deep Atlantic region some 300 km west of the Bay of Biscay, which would be accessible either by shuttle ships from the Spanish and French coasts or by offshore pipelines from Europe (Seifritz, 1991). Another site is the 7 km-deep trench off the coast of Japan (Matsuhashi, 1991).

In the presence of water under high pressure and low temperatures, CO_2 forms a solid hydrate called clathrate. Clathrates are expected to form if CO_2 is released in water through an appropriate diffuser. Subsequently, they would form sinking plumes, eventually settling on the ocean floor (Saji *et al.*, 1992; Nishikawa *et al.*, 1992; and Austvik and Løken, 1992). A variant of this scheme has been proposed by Dacey *et al.* (1992), whereby CO_2-rich gases are released at depths greater than 500 m resulting in spontaneous clathrate formation in a sinking plume.

Another alternative is to dispose of CO_2 in solid form. For example, CO_2 ice can be produced by cryogenic separation (see Schüßler and Kümmel, 1989). It is important in this scheme that the solid ice "torpedoes" are large enough to reach depths of at least 3 km so that CO_2 can continue to sink spontaneously even in liquid form.

Clearly, all of these different schemes for storing CO_2 in either liquid or solid pools on the ocean floor 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 CO_2 in the oceans and their effects on local chemistry in the vicinity of storage sites.

5.5 "Geo" and "Cosmo" Engineering

Human civilization has fundamentally altered the global environment. After centuries of agriculture, the area that is actively managed has grown to more than 15 million km^2, or more than 10% of the land area of the planet. The recent report of the US Academies on the policy implications of greenhouse warming (COSEPUP, 1991) recognizes that we have been and continue to be involved in a large, inadvertent "geoengineering" project by altering the chemistry of the atmosphere and the heat balance of the Earth through many agricultural, industrial and other activities with adverse effects on the global environment. The report suggests that engineered countermeasures also need to be evaluated that could combat or at least counteract the effects of global warming in case other mitigation options prove to be insufficient in achieving a stabilization and eventual reduction in atmospheric greenhouse gas concentrations. Since we are dealing here with uncertainties that almost match those of global warming issue itself, it is important that these options possess the potential of being "turned off" should unintended and adverse effects occur. Most of the options in this category explore the possibility of technical measures for compensating for a rise in global temperatures by reflecting a fraction of the incoming solar radiation.

According to Ramanathan (1988), it would be sufficient to increase the planetary albedo by 0.5% to compensate for the global warming resulting from a doubling of atmospheric CO_2 concentrations. Based on the US Academies' report (COSEPUP, 1991), we briefly summarize some of these measures: orbital shades such as "venetian blinds", space sails and smart mirrors; and suborbital shades of dust and sulfuric acid in the stratosphere. For the purposes of this tentative assessment, it is assumed that an albedo change of 1% by any of these options is "equivalent to avoiding" (i.e., that it could compensate for) 1000 Gt of cumulative carbon emissions.

Orbital Shades

The concept of venetian blinds would involve wrapping the Earth in a screen that could block out 1% of sunlight. Such a screen could be an enormous sheet of material around the Earth or an orbiting dust cloud. A continuous sheet or an orbital parasol is probably a better choice due to the difficulty of distributing and controlling dust particles in orbit due to, for example, the solar radiation pressure.

The required area of the "sheet" would be about 5.5 million km^2 (or about one-third of the area devoted to agricultural activities). The weight of the required construction material to be lifted into orbit would be about 5.5 million tonnes. An optimistic cost estimate is about $1 million per tonne of parasol material, corresponding to mitigation costs of $55 per tonne of cumulative carbon emissions (1000 Gt of carbon and $55 trillion; see COSEPUP, 1991). On the whole, this is a very cumbersome mitigation strategy that will probably never emerge beyond the pre-feasibility phase.

A related alternative concept involves smart space mirrors. To block even smaller fractions of sunlight, this system would have to be quite elaborate leading to higher costs, estimated to be perhaps up to thousand times that of the "simple" parasol (COSEPUP, 1991).

Suborbital Shades

Suborbital systems could include the enrichment of stratospheric dust or sulfuric acid aerosols. A screen could be created in the stratosphere at a height of 20–40 km by adding more dust to the natural component, mostly consisting of volcanic aerosols and dust (COSEPUP, 1991). The amount of dust released by all natural and anthropogenic sources is estimated at 1–3 Gt per year. Based on a study of the effect of atmospheric dust in the stratosphere by Ramaswamy and Kiehl (1985), about 0.02 g/m^3 of dust particles with a radius of about 0.3 mm might block about 1% of solar radiation. The total mass of the required dust particles would be about one million tonnes or about one tonne of stratospheric dust per 100,000 tonnes of carbon released in form of CO_2 (COSEPUP, 1991). Of all possible dust delivery systems, naval guns appear to be the cheapest with estimated costs of about $10,000–30,000 per tonne of dust in the stratosphere, or about $0.1–0.3 to mitigate 1 tonne of carbon. Despite the large uncertainties involved in the feasibility of this scheme and the possible (irreversible!) effects, it would be by far the most cost-effective mitigation strategy. The delivery of dust by rockets is assumed to be about five times and by stratospheric balloons about four times more expensive.

Aircraft could also be used to deliver the dust particles. Penner *et al.* (1984) suggest using commercial aviation fleets to deposit particulates at altitudes of 10–40 km. Turning 1% of fuel into 1.5 million tonnes of soot during combustion would deposit the required amount to change the planetary albedo by 1%. The alternative route would be to deliver the dust directly by specialized cargo planes. This would be clearly much more expensive than the delivery of dust by naval guns or balloons. The first alternative is clearly more attractive but would require drastic changes in flight regimes to increase the share of traffic in the stratosphere. In any case, the actual costs would not be very high, in the range of less than $0.1 per tonne of carbon mitigated by the emission of soot in the stratosphere (COSEPUP, 1991). The difficulty with this strategy is not the actual costs but the potential adverse environmental effects.

Sulfur aerosols could be used as an alternative to dust particles. Budyko (1982) estimated that less than 100,000 tonnes of sulfur per year deposited after burning in the stratosphere at altitudes of about 20 km would spontaneously turn into the desired sulfuric acid aerosols capable of changing the planetary albedo by 1%. The global commercial aircraft fleet generates about 150,000 of sulfur (by consumption of 150 million tonnes of jet fuel with an average sulfur content of 0.1%). Thus, increasing the share of flights in the stratosphere to two-thirds of all operations (by logistic changes in flight patterns, by the introduction of a fleet of re-engineered high-flying planes or by new supersonic and hypersonic transports) might do the job.

Aircraft could be also used to deliver sulfur to the stratosphere. About 1000 flights per year would be required if the sulfur were to be deposited by Boeing B747 cargo transports or about 400 flights per year if Antonov An225 heavy lift aircraft were employed. In theory, two An225 planes could do the job. Again, possible environmental impacts of such a mitigation option are largely unknown at present.

Energy Vol. 18, No. 5, pp. 499–522, 1993
Printed in Great Britain. All rights reserved

0360-5442/93 $6.00 + 0.00

Chapter 6

Enhancing Carbon Sinks†

6.1 Introduction

Large amounts of CO_2 are continuously removed from the atmosphere through natural processes such as photosynthesis, weathering of rocks, and absorption by the oceans. With current anthropogenic CO_2 emissions amounting to 7.6 ±1.5 Gt of carbon (IPCC, 1992) and an atmospheric concentration increase of 1.8 ppm per year (3.8 Gt of carbon) global CO_2 sinks may absorb between 2.3 to 5.3 Gt of carbon. In the event that anthropogenic sources of CO_2 continue to increase in the future, the question is whether it would be possible to devise technical measures for enhancing these natural carbon sinks.

Measures to enhance terrestrial photosynthesis include the establishment of plantations, afforestation, and reforestation. Halting current rates of deforestation is probably one of the most urgent mitigation measures. Estimates (see Section 6.2 below) indicate that the net annual flux of carbon to the atmosphere ranged between 0.6 and 2.8 (median IPCC value = 1.6) Gt of carbon during the 1980s as a result of land-use changes and deforestation. This compares to slightly less than 6 Gt C from burning of fossil fuels, manufacture of cement, and flaring of natural gas. In contrast, our estimate is that 1.6 Gt of carbon could be sequestered from the atmosphere by a "global plantation" program. This estimate includes existing local reforestation schemes. Other measures for enhancing CO_2 absorption by terrestrial photosynthesis include the cultivation of plants and other organisms that absorb carbon in largely artificial environments. Finally, another class of measures to enhance photosynthesis focuses on increasing marine photosynthesis in natural environments by cultivating, for example, algal and plankton blooms.

The current global ocean sink is estimated at 2.0 (± 0.8) Gt of carbon (IPCC, 1992). Since the ocean is an oxidizing environment, it is important that a possible enhancement of CO_2 absorption does not lead to a delayed return of carbon to the atmosphere.

The weathering of primary rocks is another natural CO_2 sink, but this is a very slow process so that it may be premature to expect any practical technologies for the enhancement of this process in the foreseeable future.

---

†Arnulf Grübler (Sections 6.1 and 6.2), Sten Nilsson (Section 6.3), and Nebojša Nakićenović (Section 6.4).

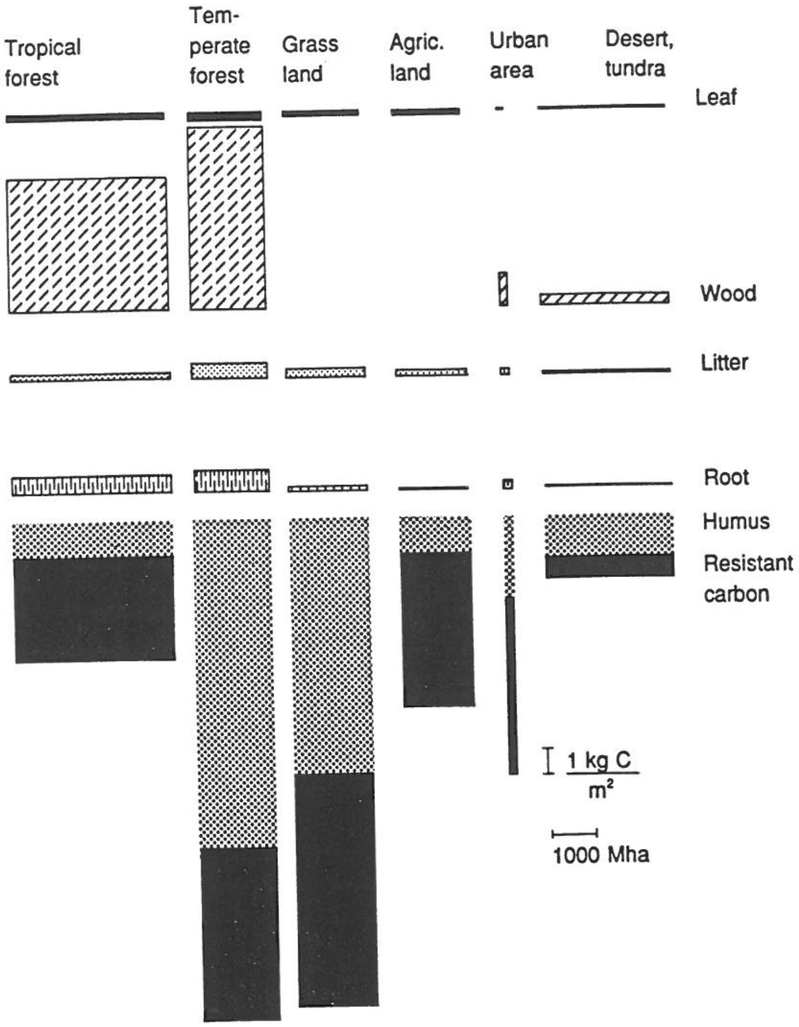


Figure 6-1. Biotic carbon reservoirs, phytomass and soils of different ecosystems (Source: Goudrian, 1991). The width of each bar is proportional to the ecosystems area, the height to carbon per m^2, and the area to total carbon.

6.2 Biotic Carbon Reservoirs and Carbon Flows

Important changes in the carbon balance of terrestrial vegetation and soils have been induced by human activities. Since carbon storage and fluxes in/between terrestrial carbon pools are large, it is difficult to estimate the exact order of magnitude of human impacts.

Figure 6-1 shows that the total amount of carbon stored in vegetation and soil amounts to some 2000 Gt of carbon (600 Gt in phytomass and 1400 Gt in soil humus). This compares with some 4000 Gt of carbon stored in fossil fuel resources (see Chapter 4). The largest pool of phytomass carbon is the stemwood of trees in tropical and temperate forests. The carbon stored in the soils of various ecosystems is much more evenly distributed. The term "resistant carbon" used in Figure 6-1 refers to the carbon stored in soils that is not oxidized in the course of land-use changes.

The net annual carbon uptake (gross uptake from the atmosphere minus respiration by plants), usually referred to as the *net primary productivity*, amounts to 50–60 Gt of carbon annually, or about 10 times the level of industrial carbon emissions (IPCC, 1990). Subtracting the plant material that is consumed by other organisms (heterotrophic consumption) results in the net absorption by undisturbed terrestrial ecosystems of about 4–7 Gt of carbon per year (Goudrian, 1991). Changes in land-use patterns and vegetation cover are therefore important because large quantities of carbon are sequestered by undisturbed natural vegetation and soils. The vegetation and soils of undisturbed forests can hold 20 to 100 times more carbon than agricultural systems (Houghton, 1991). Consequently, land-use changes can release significant amounts of biotic carbon to the atmosphere.

6.2.1 Deforestation Rates and Carbon Releases

Carbon emissions from biota result mostly from the burning of biomass that accompanies land-use changes, from the organic decay of biomass, and from the oxidation of soil carbon in conjunction with changing vegetation cover. Finally, carbon is also released by the oxidation of wood products such as paper or burning of fuelwood.

The large uncertainties concerning biotic carbon fluxes are a result of the difficulty in estimating the extent of land-use changes and the secondary uses of deforested areas. Only rough estimates exist for the carbon content of biomass, and especially of soils in disturbed areas, and of the response profile of terrestrial carbon reservoirs to changes in land use. For instance, only 50–60% of the annual biotic carbon flux of the early 1980s are calculated to have originated from land-use changes in that period, with the remainder consisting of vegetation decay and soil carbon releases from deforestation of previous years. All of these combined elements result in an uncertainty range for biotic carbon sources of up to a factor of four. These uncertainties are compounded by the fact that estimates relying on the same models and same sources of data for deforestation and carbon stocks often yield very different results, and the reasons for such differences remain unclear (Houghton, 1991).

In the early 1980s, the net biotic carbon flux (deforestation minus afforestation) was estimated by the IPCC to range from 0.6 to 2.6 Gt of carbon, i.e., 10–45% of industrial CO_2 sources. Current scientific consensus assumes a similar range for the remainder of the 1980s, although preliminary assessments indicate that deforestation rates have accelerated in some regions (Lanly *et al.*, 1991). In this context, one should note that deforestation rates vary significantly in different assessments as a result of differences in the methodologies applied and interpretation of survey data. There is a consensus, however, that most of deforestation is currently taking place in the tropics. Historically, however, deforestation in temperate zones was also substantial. Richards (1990) estimates that deforestation in temperate latitudes in the period 1700–1980 amounted to some 390 million ha (3.9 million km^2), most of it in the former Soviet Union and Oceania, followed by North America, China and Europe. Over the same time period tropical deforestation is estimated to have amounted to 780 million ha, or about two-thirds of the global total (Table 6-1).

Table 6-1 also gives an overview of FAO estimates of current tropical deforestation (Allan and Lanly, 1991; Lanly *et al.*, 1991). The estimates of deforestation rates in the tropics in the 1970s range from 5 to 20 million ha for closed forests only and from 7.5 to 30 million ha for closed and open forests taken together (Ferreira and Marcondes, 1991). Estimates for the 1980s range from 3 to 20 million ha for all tropical forests and from 2.8 to 14.2 million ha for closed tropical forest (Ferreira and Marcondes, 1991). The FAO estimates for the late 1980s indicate a tropical deforestation rate of 17 million ha (Table 6-1).

Table 6-1. Estimates of areas deforested (million ha).

Ecological regions	1800–1980[a]	Late 1980s[b]
Temperate latitudes[c]	387	
Asia	173	4.7
Africa	308	4.8
Latin America	294	7.3
Total tropics	775	16.8
World	1162	~17

[a] Richards (1990).
[b] FAO (1991).
[c] Includes China with some estimated 77 million ha.

The are large variations in the estimates of deforestation rates at the regional and national levels. Moreover, estimates can vary significantly between individual years, even in regions, such as Brazil with high biotic carbon flux and which are most intensively studied. Some estimates, for instance, put the deforestation rate in Brazil in 1987 at 5 million ha/yr (Meyers, 1989) and others at 8 million ha/yr (WRI, 1990). Brazilian studies using satellite data indicate a deforestation rate of 3 million ha for the same year (IPCC, 1991). More recent results suggest that the rate is likely to have fallen even further (Fearnside *et al.*, 1990), perhaps to some 1.4 million ha in 1990 (IPCC, 1992). Therefore, it could be highly misleading to infer deforestation rates over extended time periods from point estimates of individual years.

6.2.2 Uncertainties in Carbon Releases from Land-Use Changes

Deforestation and land-use changes are currently concentrated in tropical latitudes, but the corresponding net carbon release figures are affected by considerable uncertainties, and are widely debated in scientific and policy circles. The wide range in the estimates is the result of a multiplication of uncertainty ranges in three areas: the extent of the area deforested; the carbon content of biota and soils in the deforested land; and the dynamic release profile of biotic and soil carbon after disturbance. The range of estimates is large and has not narrowed compared with the figures estimated in the early 1980s. The uncertainties relate not only to the difficulty in estimating deforestation rates, but also to the paucity of reliable and detailed field measurements of the carbon content of biomass in the tropics, and especially of the amounts of carbon released by disturbed tropical soils. The uncertainties in the latter are so large as to accommodate even the highest estimates of deforestation rates with the lower range values of biotic carbon emissions given in Table 6-2, under low assumptions of biomass and soil carbon content and release rates.

The data uncertainties with regard to historical biotic carbon emissions are somewhat smaller than for current emissions due to a good knowledge of historical energy- and industry-related CO_2 emissions and measurements of atmospheric concentration increases. The IPCC (1990) estimates of historical biotic carbon releases indicate cumulative emissions of some 115 (±35) Gt of carbon over the 1850–1985 period. Compared to the current regional imbalances in biotic carbon emissions, the estimated historical record appears more evenly distributed: about 55% of historical biotic carbon releases originated in the tropics, and about 45% in temperate latitudes (Grübler and Fujii, 1991) where significant land-use changes and deforestation took place in the 19th century.

Table 6-2. Ranges of estimates of biotic carbon fluxes in the early and late 1980s, (in millions of tonnes of carbon per year); negative values indicate a net carbon uptake by terrestrial biota. Figures have been rounded.

	Late 1970s/ early 1980s (Mt C)	Late 1980s (1985–1987) (Mt C)	Per capita emissions (late 1980s)	
			Biota (t C/capita)	Industrial (t C/capita)
Temperate zones				
North America	+25[a] – +38[b]	−139[c] – +6[d]	−0.51 – +0.02	5.28
Europe (West & East)	−28[a] – 0[b]	−62[c] – 0[d]	−0.13 – 0	2.44
Former USSR	+35[a] – 100[b]	−140[c] – 0[d]	−0.49 – 0	3.83
Oceania	+28[a] – 80[b]	−3[c] – 0[d]	−0.17 – 0	3.69
China	+69[a] – 105[b]	−106[c] – 0[d]	−0.10 – 0	0.56
Tropical zones				
India	+9[e] – 80[f]	+5[g] – 150[c]	+0.01 – +0.18	0.21
Other Asia	+190[e] – 1058[f]	+300[h] – 730[d]	+0.39 – +0.95	0.21
Africa	+200[e] – 753[f]	+170[i] – 390[d]	+0.35 – +0.82	0.25
Brazil	+175[e] – 805[f]	+140[j] – 800[d]	+0.97 – +5.55	0.41
Other Latin America	+176[e] – 458[f]	+130[k] – 330[d]	+0.46 – +1.17	0.84
World	+600[e] – 2600[l]	+800[m] – 2800[d]	+0.16 – +0.55	1.11

Emissions in Japan and North Africa and the Middle East are negligible.

[a] Houghton *et al.* (1987). [b] Houghton and Skole (1990). [c] Subak *et al.* (1991). [d] WRI (1990). [e] IPCC (Response Strategies) (1991); low estimate. [f] OECD (1991). [g] Pachauri (1991). [h] Houghton (1991). [i] USAID (1990; pp. 3–9). [j] Alves (1991). [k] Assuming same uncertainty range as in 1980. [l] IPCC (Response Strategies) (1991); high estimate. [m] IPCC (Response Strategies) (1991); only closed forests. Lowest range value from IPCC (1992): 600 Mt C.

6.2.3 Carbon Releases from Deforestation

Table 6-2 summarizes a number of estimates of CO_2 releases from deforestation in the 1980s. There is agreement that current biotic carbon releases from the Northern Hemisphere are quite small, if not negative. The range of estimates also indicates that biotic carbon releases or uptakes (reforestation and sequestration in forest products) are small compared with industrial CO_2 sources (maximum 10%). Due to the lack of quantitative estimates and the large scientific uncertainties, indirect CO_2 (fertilization) effects that could act as additional carbon sink in the Northern Hemisphere (perhaps as large as 1 Gt of carbon) are not considered in Table 6-2. However, this would not drastically change the relative situation of the "North" versus the "South" in the current disparities in CO_2 emissions.

Deforestation and land-use changes are currently concentrated in tropical latitudes, but estimates of the resulting total amount of carbon released in the late 1980s vary substantially (Table 6-2). The policy relevance of these data uncertainties is obvious: high biotic carbon emission estimates would increase the CO_2 emissions in most developing countries by a factor of between two and four. In the extreme case of Brazil,[1] the highest deforestation estimates would imply an increase in energy- and industry-related CO_2 emissions by a factor of ten. If this were the case, Brazil's total per capita carbon emissions would surpass even the highest per capita emission values of industrialized countries. The largest biotic carbon fluxes due to deforestation stem from a relatively small number of countries. Meyers (1989) estimates that the 10 largest emitting countries[2] accounted for three-quarters of biotic carbon releases in 1989. This also implies that effective policies for sustainable forestry management and limiting land-use changes could have a relatively rapid and substantial impact on future carbon emissions as only a few national actors would be involved.

6.2.4 Scenarios for Future Deforestation

Projecting future land-use changes and their related carbon emissions is perhaps the most uncertain domain in scenarios of future greenhouse gas emissions. A number of individuals (e.g., Esser, 1991; Houghton, 1991) and organizations (EPA, 1990; IPCC, 1991) have developed a range of scenarios of possible future carbon releases from deforestation. Common to them is the combination of assumptions concerning the two largest uncertainty domains of deforestation carbon emissions: rates of land-use changes and carbon stocks per unit of ecosystems area affected. Consequently, Figure 6-2 compares a range of scenarios with a combination of high/medium/low carbon content of forest biomass and soils and high/medium deforestation rates, or a trend reversal towards sustainable forestry practices, reforestation and afforestation programs, respectively.

Annual carbon fluxes, assuming high deforestation rates and high carbon contents, could reach up to 3 Gt of carbon per year in the first half of the twenty-first century (see scenarios H2 and H3 in Figure 6-2). In one extreme case (scenario H1 from Houghton, 1991), annual fluxes are projected to peak as high as 5 Gt of carbon by 2050 and to decline drastically thereafter. The decline in annual carbon releases towards the end of the

---

[1] Table 6-2 excludes the preliminary (and subsequently revised) WRI estimate of 1200 Mt of carbon for Brazil in 1987, which would imply biota emissions of 8.3 tonnes of carbon per capita.

[2] In descending order of carbon releases from deforestation of closed forests as estimated by Meyers (1989): Brazil, Indonesia, Myanmar (Burma), Mexico, Thailand, Colombia, Nigeria, Zaire, Malaysia, and India.

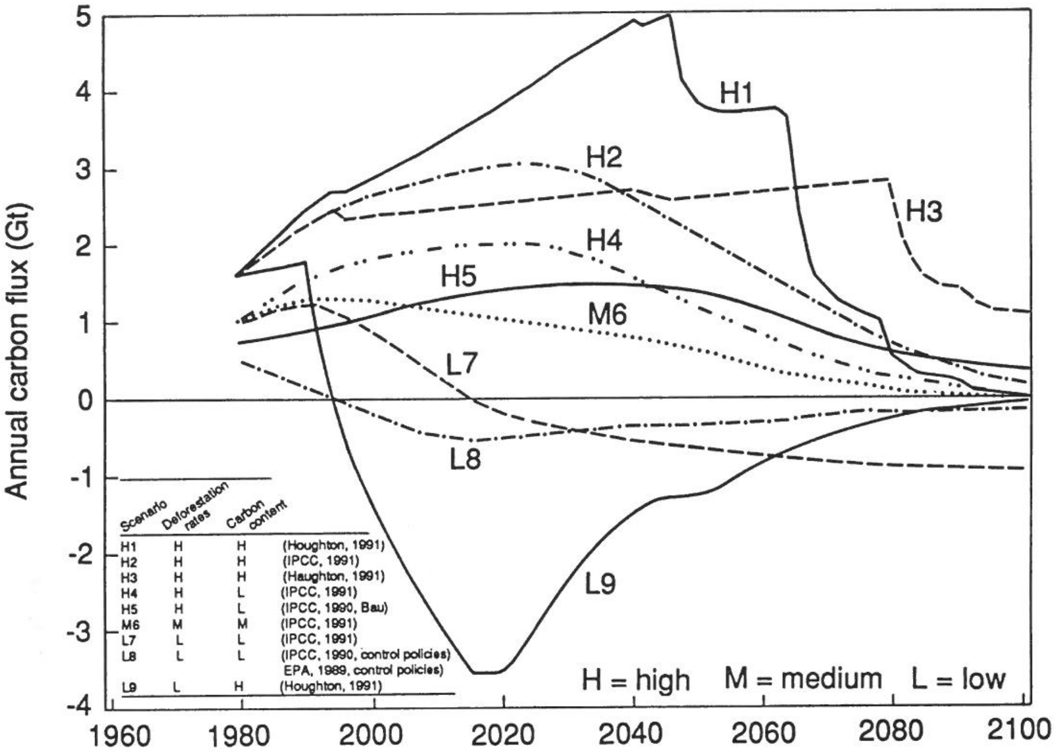


Figure 6-2. Biotic carbon emission scenarios from different sources (in Gt of carbon).

next century in all high deforestation scenarios is simply due to the fact that all tropical forests are assumed to have disappeared by the year 2100. Moderate deforestation and sustainable forestry practice scenarios result in significantly lower carbon fluxes, typically declining throughout the next century from present-day values. Forestry response strategies to combat CO_2 build-up in the atmosphere could even sequester carbon from the atmosphere (see scenarios L7 to L9).

The wide range given in the scenarios illustrates that, depending on which forestry policies will be chosen in the future, significant amounts of carbon would be either released to or sequestered from the atmosphere. In a worst case scenario, combining high deforestation rates with high carbon content estimates (H1 in Figure 6-2), up to 340 Gt of carbon, might be released into the atmosphere over the next 100 years. Conversely, Houghton (1991) estimates that, by afforesting some 870 million ha of abandoned and degraded land, some 150 Gt of carbon could be withdrawn from the atmosphere over the next 100 years (scenario L9 in Figure 6-2). The afforestation potential and resulting scenario discussed in Section 6.3 below could sequester some 120 Gt of carbon at an estimated cost of more than $500 billion over the next 100 years. Perhaps more important than the absolute difference between such scenarios is to highlight the ranges in their underlying assumptions and projections of the future impacts of anthropogenic activities.

High deforestation rate scenarios usually project current rates of increase in tropical deforestation into the future, a process that is only stopped by the complete disappearance of tropical forest cover. Tropical forests were estimated at about 2 million ha in 1980 (FAO, 1991) or about 40% of the 5 million ha of global forest area. Since 1980, tropical forests have been estimated to have declined at a rate of 1.2% per year. Using current land productivity figures (which are highly likely to improve further in the future) as a guide, the expansion of arable land in the tropics over the next 100 years may be significantly below half of the tropical forest area. In such a case, future biotic carbon releases are more likely to follow the moderate/low emission path scenarios outlined in Figure 6-2.

6.3 Carbon Sequestering Potential by Global Afforestation

6.3.1 Background and Objectives

The global forest area is about 3.6 billion ha (36.25 million km^2) and constitutes about 28% of the total land area. An additional area of almost the same size, about 3.4 billion ha (33.93 million km^2), is covered by what is classified as "other wooded land"[3] and not classified as forests. This group has a tree or bush cover less than 10–20% of the land area. Included in this group are open woodland, brushland, and woody fallow land generated by the clearance of former forests. Together, forests and other wooded areas cover more than half of the global land area. Table 6-3 gives the respective areas by region and by main ecological zones.

The world's forests contain an estimated 500–800 Gt of carbon, approximately the same amount as that is present in the entire atmosphere in the form of CO_2. It has been identified that forest resources experiencing net growth will sequester CO_2 from the atmosphere, so that any build-up of forest biomass will help to reduce the build-up of atmospheric CO_2. The forestry options for mitigating carbon build-up are: slowing the rate of tropical deforestation, increasing the productivity of existing forests, and increasing afforestation. The rate of deforestation has been described in Section 6.2 above and will not be repeated here.

The Noordwijk Declaration [based on the Ministerial Conference on Atmospheric Pollution and Climatic Change held in Noordwijk, The Netherlands, in 1989, with about 70 countries and international organizations participating (Anon, 1989)] called for a net increase in global forest cover of 12 million ha per year by the year 2000. Given an annual loss of around 17 million ha of tropical forests implies an annual target for forestation to be about 30 million ha.

In recent years a number of studies have been carried out to assess the magnitude of the forestry options available as CO_2 mitigation measure. For example, Sedjo and Solomon (1989) identify that to sequester 2.9 Gt of carbon per year, one of the following alternatives is required: to expand the area of boreal forests by 3.5 billion ha and to halt the decline of other forests elsewhere; to expand the area of existing global forests by 3 billion ha; or to achieve the afforestation of 465 million ha by establishing fast-growing plantations. Marland (1988) estimates that 670 million ha of plantations in the southern USA or 520 million ha of plantations in the tropics would be required for the removal of 5 Gt of carbon per year from the atmosphere.

A summary of other estimates on the area of forest plantations that will be required to achieve various CO_2 sequestration targets is presented in Table 6-4. None of these studies, however, actually addresses the question of whether the areas proposed are technically, economically or politically feasible. At a workshop held in Bangkok in 1991 (IIED, 1991), an attempt was made to explore the feasible options for increased CO_2

---

[3] FAO terminology.

Table 6-3. Areas of forest and other wooded land in 1980 by continent and main ecological zones in (million ha) (Source: Allan and Lanly, 1991).

Ecological zones	Africa	Americas	Asia[a]	Pacific	Europe[b]	Total
Boreal forest		203.0			717.0	920.0
Nonboreal forest	8.1	310.8	188.4	48.7	211.5	767.4
Tropical forest	701.2	889.8	303.4	42.6		1937.0
Total	709.3	1403.6	491.8	91.3	928.5	3624.7
Woodlands	6.6	269.1	66.0	64.3	231.4	637.4
Brushland	623.4	322.0	111.2	2.4		1059.0
Woody fallow land	630.0	591.1	177.2	66.7	231.4	1696.4
Total	1200.0	1182.2	354.4	133.4	462.8	3392.8

[a] Includes the Middle and Near East, but excludes the Asian part of the former Soviet Union.
[b] Includes all of the former Soviet Union.

fixation by forests, and the results from this workshop are employed as one source in the following brief assessment of the global afforestation potential.

6.3.2 Plantations, Afforestation, and Reforestation

Plantations are forest stands that have been established artificially, either on lands that have previously not supported forests for more than 50 years (afforestation) or on lands that have supported forests within the last 50 years (reforestation) and where the original crop has been replaced with a different one (Brown *et al.*, 1986). Here we estimate the total global plantations of land suitable and available for afforestation and reforestation. Excluded is the reforestation that takes place immediately after clear cutting in a sustainable forestry system.

Dixon *et al.* (1991) estimate that the area of land artificially forested[4] in 1990 totaled about 130 million ha, of which 25–30 million ha were in the tropics. The World Resources Institute (WRI, 1990) estimates the average reforestation rate during the 1980s (including natural regeneration) to be about 15 million ha per year. Postel and Heise (1988) and Mather (1990) present an estimate of the area of industrial forest plantations established during the period 1975–1985 of about 80–90 million ha, although these figures also include high plantation rates for the former Soviet Union, which are not real industrial forest plantations but merely reforestations. Mather (1990) estimates that roughly 10 million ha of forest plantations per year were established during the 1980s. Grainger (1988) estimates that 11.5 million ha of tropical plantations were established in 1980 alone, of which 7 million ha were industrial plantations and the remainder devoted to fuelwood and other nonindustrial purposes.

The Finnish consultant company, Jaakko Pöyry, has estimated that in 1985 the global area of industrial plantations was 39 million ha, and this area is expected to increase to 50 million ha by year 2000. Subregional figures presented by Sedjo and Lyon (1990) confirm these findings. Thus, it is estimated that about 50 million ha of industrial plantations driven by socioeconomic and technological developments will have been established during the twentieth century. This figure can be compared with the estimated requirements for plantations for sequestering and stabilizing the carbon balance of 500–600 million ha (roughly one-third of the area devoted to agricultural activities).

---

[4] Including reforestation after clear cutting (sustainable forestry), reforestation, and afforestation.

Table 6-4. Estimates of forest areas required to achieve various CO_2 sequestration targets (Source: Andrasko, 1990).

Estimate	Location	Carbon sequestration rate assumed (t C/ha/yr)	Offset goal	Area required (million ha)
Dyson and Marland (1976)	Temperate zone	7.5	5 Gt C (total annual fossil fuel use)	700
Marland (1988)	Tropics	9.6	5 Gt C (total annual fossil fuel use)	500
Myers (1988)[a]	Tropics	10.0	2.9 Gt C (net annual increase C)	300
Sedjo and Solomon (1989)	Tropics or temp.	6.2	2.9 Gt (net annual increase C)	465
Woodwell (1987)	Tropics	5.0	1–2 Gt (net annual C increase tropics)	200–400
Postel and Heise (1988) (Brown *et al.*, 1988a)	Tropics	6.8	0.7 Gt (C benefits from new fuelwood plantations and restored forests)	110
Dudek (1988a,b)	USA	10–12	0.05 Gt (1987–96 new electric plant C)	3.4–4.5
Andrasko (1989)	USA	3.5–10	0.05 Gt (1987–96 new electric plant C)	4.5–13
Andrasko and Tirpak (1989)	USA	4.4	0.12 Gt/yr	10.5[b]
USFS/EPA (1989)	USA	5.7	0.06 Gt/yr	8.1[c]
		5.7	0.12 Gt/yr	15.0[d]

[a] See also Booth (1988).

[b] Assumes 10.5 million ha planted and 23.5 million ha intensively managed.

[c] Assumes 8.1 million ha planted and 4.3 intensively managed.

[d] Assumes 15.0 million ha planted and 10.8 million ha intensively managed.

6.3.3 Land Use and Large-scale Plantations

Land may be suitable for afforestation but may not actually be available for it. Grainger (1991) stresses that "even if environmental quality and economic productivity are both low, those who use the land may be unwilling to convert it to forest". Trexler (1991a) claims that "for at least a decade social, political and infrastructural barriers will keep plausible reforestation rates very modest". The FAO (1991a) stresses that the obstacles for mass plantations in the tropics include degraded soils, limited knowledge of suitable species and planting systems, and institutional capabilities, among other things. Andrasko *et al.* (1991) indicate that large-scale plantations may interfere with higher priority uses of land: "No matter how much money is made available for plantations, local land tenure, land use customs and laws, and cultural characteristics will strongly affect the possibilities to carry out plantations in the tropics". Trexler (1991b) has identified a number of parameters that will have to be investigated to determine both land availability and implementation rates for plantations, and concludes that tree plantations "will work best if they yield an economic return". In other words, planting trees just to soak up carbon is a difficult concept to work with, and one that local people are unlikely to accept.

Swisher (1992) argues strongly and correctly that heavy provision for protection of the forest resources and forest plantations must be provided to secure sustainable development of the plantations. The difficulty is to estimate how much protection is required in different regions of the world. The degree of protection will also vary widely. It has been shown in Brazil (Cottie *et al.*, 1990) that a clever design of the plantations (species mixes, size of parcels, landscaping, etc.) can minimize the need for protection.

Spears (1983) has identified a number of factors for successful industrial plantations, three of which are: the need for a clear definition of the goals at the outset of a plantation program, specific end-use objectives, and an early commitment to utilize the project output. These criteria will be difficult to fulfill with plantations that are devoted merely to the fixation of carbon. He also points out that the greatest problem is to secure governmental and political commitment so that reforestation programs can reach maturity.

An interesting study has been carried out by Frankena (1987) concerning forestry for large-scale energy production in the USA, in which he illustrates a number of cases where large-scale projects have failed. This study shows that it is a mistake for decision makers to expect general public support for policies affecting natural and renewable resources. Another lesson is that large-scale projects are perceived to pose a threat to local environmental values. This is also valid for large-scale plantations for CO_2 fixation.

For Australia, Russell (1990) has highlighted many problems with large-scale plantations and states that many policy makers are skeptical about the feasibility of plantation programs for carbon fixation. Nilsson (1992) states "The ongoing negotiations on a climate convention have in an unfortunate way been focused on the concept of large-scale plantations for fixation of carbon". This is often perceived by the developing countries as a way for the industrialized countries to continue increased energy consumption and emissions which could be compensated by large-scale plantations in the developing countries. Thus, it is crucial to start with national forest sector plans that satisfy all requirements in the forest sector and not just a carbon fixation function.

6.3.4 Suitable and Available Land for Plantations

The objective of this assessment is to determine global land area that would be suitable and available for carbon-sequestering plantations. This has been done on a regional basis, and Table 6-5 summarizes the salient results. The approach used to assess the availability of land can, at a first glance, look like a top-down approach. An approach which is criticized by Swisher (1992), who proposes a bottom-up approach based on local or national sustainable forest development strategies. But Swisher (1992) also admits that it is difficult to carry out a complete bottom-up approach on a global scale due to the lack of relevant data.

In this case, it can be said that we have followed something between a top-down and a bottom-up approach in assessing the availability of land for plantations. For example, for tropical countries we have used information from Trexler (1991) based on a large number of land use parameters following a bottom-up approach. For the European countries and former European USSR we have used data from detailed analysis carried out by governments in individual countries (Nilsson *et al.*, 1992a; Nilsson *et al.*, 1992b). For other regions we have been in contact with national organizations to obtain the required basic information on possible future land use. These basic analyses are not possible to present here due to available space, but are presented in Nilsson (1992). However, we cannot argue that we have been able to come up with a complete bottom-up approach.

Our analysis shows that the total land available for forest plantations is about 265 million ha and another 85 million ha for agroforestry. The area of suitable land is much larger but due to numerous limitations, it is not likely to be devoted to carbon sequestration. In addition, Table 6-5 gives the average annual plantation growth, rotation and plantation periods. Despite the global scale of this assessment, not all regions could be included in the analysis due to the lack of data, or failure to obtain relevant information.

The estimates on available land for plantations presented in Table 6-5 (265 million hectares for forest plantations and 85 million hectares for agroforestry) can be contrasted with a recent study on land availability carried out by Winjum *et al.* (1992) as shown in Table 6-6, indicating a potential land availability between 600 and 1200 million ha. However, this latter estimate is not directly comparable due to the fact that the authors have applied other definitions of afforestation in comparison with the definitions used here. In addition, the latter estimates are based on information on land availability generated by Grainger (1991) and Houghton *et al.* (1991) etc. In Nilsson (1992) we have concluded that these estimates are likely overestimates of the real availability. Centeno (1992) has calculated an availability of 420 million ha only in the tropics for large-scale plantations. Thus, the estimates on availability of land for large-scale plantations used here are lower and may be somewhat conservative estimates.

6.3.5 The Carbon Fixation Rates of Forest Ecosystems

A large number of studies have been carried out to estimate the carbon fixation rates of different forest ecosystems. The basic approach has been to express the fixation rate as the sequestering capacity in tonnes of carbon per ha, but large uncertainties still exist in these estimates. To estimate the rate of carbon uptake in forest plantations, average fixation rates per ha are not sufficient. The time scale of the carbon fixation has to be taken into account and to do that we have to work with fixation rates linked to the wood increment, expressed as m^3 of stemwood. Studies are still not available for direct

Table 6-5. Aggregated estimates on suitable and available land for plantations and corresponding management programs.

Region	Area suitable for plantations (million ha)	Area available for plantations (million ha)[a]	Average mean annual increment (m^3/ha/yr)[a]	Rotation period (years)	Plantation period	Plantation rate (million ha/yr)
Canada						
NSR–Land B.C.		0.8	8	60	1995–2020	0.034
NSR–Land Rest of Canada		18.9	3	60	1995–2020	0.760
Converted farmlands		4.4	3	60	1995–2020	0.176
Unimproved farmlands		4.2	3	60	1995–2020	0.166
USA						
Plantations		9.0	15	35	1995–2025	0.300
		9.0	10	50	1995–2025	0.300
Agroforestry		1.5	8	35	1995–2025	0.050
		1.5	6	40	1995–2025	0.050
Europe						
Nordic		0.4	5	60	1995–2020	0.014
EEC–9		3.8	8	40	1995–2020	0.151
Central		0.5	6	60	1995–2020	0.019
Southern		2.2	10	20	1995–2020	0.087
Eastern		1.3	6	60	1995–2020	0.053
Former USSR	132.0	44.0	3	80	1995–2025	1.470
China	86.6	62.5	2	80	1995–2020	2.500
Temperate Asia		12.5	12	40	1995–2020	0.500
Temperate S. Africa		1.9	16	30	1995–2020	0.075
Temperate S. America		4.6	15	25	1995–2020	0.182
Japan			not applicable			

Figures are rounded.

Table 6-5. Continued.

Region	Area suitable for plantations (million ha)	Area available for plantations (million ha)[a]	Average mean annual increment (m^3/ha/yr)[a]	Rotation period (years)	Plantation period	Plantation rate (million ha/yr)
Australia						
Plantations	9.7–54.8	0.8	23	30	1995–2030	0.023
Agroforestry	7.0	3.5	6	30	1995–2030	0.100
New Zealand		5.0	25	25	1995–2045	0.100
Tropical forests						
Latin America						
Plant. deg. land	240					
Plant. fallow forest	295					
Total Plantation	535	36.9	25	20	1995–2050	0.671
Agroforestry	274	28.0	8	20	1995–2050	0.510
Africa						
Plant. deg. land	284					
Plant. fallow land	456					
Total plantation	740	5.6	16	30	1995–2050	0.102
Agroforestry	213	30.0	8	30	1995–2050	0.545
Asia						
Plant deg. land	55					
Plant fallow land	107					
Total plantation	162	36.7	16	20	1995–2050	0.667
Agroforestry	304	20.0	8	20	1995–2050	0.364
Total		Plantation 264.8 Agroforestry 84.5				

Figures are rounded.

Table 6.6. Preliminary estimates on land availability for forest plantations according to Winjum *et al.* (1992), expressed in million ha.

Region/Practice	Available land estimate Lower	Upper
Boreal		
Reforestation	50	100
Natural reforestation	50	100
Temperate		
Reforestation	75	150
Natural reforestation	75	150
Afforestation	50	100
Tropical		
Reforestation	100	200
Natural reforestation	100	200
Agroforestry	100	200

Table 6.7. Estimated carbon build-up in root and litter in connection with afforestation for different regions. After Schopfhauser (1992).

Region	Root carbon (tonnes/ha)	Litter carbon (tonnes/ha)
Boreal forests	11	0.5
Temperate forests	17	2.8
Tropical forests	14	3.7
Tropical agroforestry	3	0.8

estimates of carbon uptake corresponding to m^3 of stemwood at the subregional level, so we have had to work with rather rough aggregate estimates of this factor. Thus, as carbon fixation rates for the total biomass above ground we used the following: 0.3 tonnes C/m^3 of above-ground biomass and stemwood for Canada, the USA, Europe, the former Soviet Union, China, and temperate Asia, and 0.4 tonnes C/m^3 stemwood for New Zealand, Australia, and the tropics.

The changes in below-ground biomass and related carbon fixation in connection with afforestation are even more uncertain than the above-ground biomass carbon fixation rates. Schopfhauser (1992) has tried to estimate the carbon sequestering potential of below-ground biomass, litter and soil by large scale plantations. His calculations concerning root carbon build-up due to afforestation are presented in Table 6-7. In the same study the litter carbon build-up in connection with large scale plantations was assessed. Litter has much less influence on the carbon content in forest ecosystems than the roots. The estimate on carbon build-up by litter in connection with afforestation is presented also in Table 6-7. Some studies have also indicated that the establishment of plantations may increase the carbon uptake by soil (e.g., Holt and Spain, 1986). Resulting estimates by Schopfhauser (1992) on the changes of soil carbon in connection with afforestation indicate an increase in soil carbon content of 17% globally with a range between 5% to 25% depending on climate zone and type of vegetation cover and soil. These estimates on carbon build-up in roots, litter and soil have been employed in the following calculations.

6.3.6 Development of Forests Over Time

In order to estimate carbon uptake in above-ground biomass over time, we must take into account how the mean annual wood increment and corresponding carbon uptake are distributed over time. Nilsson (1982) has generalized a function to describe the development of stands of trees in even-aged and sustainably managed industrial forests. The function expresses stand development in terms of relative yield over relative age. It portrays an S-shaped growth path that has been used in a number of industrial forestry development projects around the world[5] for estimation of growth and sustained yield at industrial plantations.

Cooper (1983) used a similar concept to describe the relative development of biomass in a forest stand, which results in an equivalent growth path. In this case, the approach used by Nilsson (1982) has been employed to plot the distribution of mean annual wood increments and corresponding carbon uptake levels over time for the different world regions. Row and Phelps (1990), Row (1990), Thompson and Matthews (1989), and Lunnan *et al.* (1991) have utilized simplified revisions of this approach for local calculations of the growth of individual plantations.

6.3.7 Estimated Total Carbon Uptake by Plantations

The plantation growth model has been employed to estimate the potential of a global carbon sequestration program based on afforestation concerning the above-ground biomass. Specific calculations have been carried out for each individual world region given in Table 6-5. Here, the results are presented only for the global level.

The plantation program is assumed to start in the year 1995; a few years will be required to prepare such global plantation activity.

Estimates of annual wood increments and carbon fixation rates for above-ground biomass and for the build-up of carbon in roots, litter and soil are presented in Table 6-8. For estimates of the underground fixation, a relation was established between above-ground and underground (roots, litter, and soil) carbon fixation. The model (see Schopfhauser, 1992) is a strong simplification of the distribution of underground carbon fixation over time but generated plausible results.

It can be seen that 40–50 years would be needed for the proposed plantation program to have a significant impact in terms of the amounts of carbon fixed, and the full effects would be achieved only after about 60 years. Therefore large-scale plantations are not a "quick-fix" solution. The other important conclusion is that the feasible plantation program could only sequester an estimated 1.6 Gt of carbon per year, which is much less than the current carbon accumulation in the atmosphere.

6.3.8 Plantation Program Costs

The direct costs for large scale plantations vary a lot between regions. The available cost estimates are also connected with large uncertainties. We have used a large number of sources in attempting to make consistent regional cost estimates for schematic cost analyses of a global afforestation program. The sources are further discussed in Nilsson

---

[5] The generalized function follows the following formula: $Y(R) = a(1 - b^{-R/100})^c$, where R is the relative age, expressed as a percentage of the age of maximum volume production; Y is the relative yield, as accumulated yield as a percentage of accumulated total yield at the age of maximum volume production; and a, b and c are coefficients.

Table 6.8. Estimate of yearly wood increment (million m^3/year) and above- and underground carbon fixation by proposed plantation program (million tonnes/year).

Year	Yearly increment (million m^3)	Yearly above-ground carbon fixation (million tonnes C)	Yearly underground carbon fixation (million tonnes C)	Total (million tonnes C/year)
2015	1271	474	132	606
2025	1987	727	203	930
2035	2696	990	277	1267
2045	3052	1132	316	1448
2055	3498	1312	367	1679
2070	3332	1242	347	1589
2085	3239	1218	341	1559
2095	3305	1255	351	1606

(1992) and aggregated cost estimates are presented in Table 6-9. The cost estimates reflect the 1989/1990 cost level and are expressed in $US/ha. The presented costs do not include:

- costs for obtaining the land for plantations;
- costs for establishment of infrastructures;
- fencing;
- costs for education and training;
- costs for nursery facilities.

In areas such as China, the former Soviet Union and the tropics, the costs to establish the required infrastructure may be 3–5 times higher than direct plantation costs. A strong educational and training program has also to be conducted in most developing regions before the plantation starts. In many areas in Europe, Australia and New Zealand, fencing is required to avoid damage to the plantations by animals. These latter cost items may double the establishment costs presented in Table 6-9. For areas such as the former Soviet Union, Australia and the tropics, establishment of a new plant nursery infrastructure is necessary. In many regions, like in the US, there is a cost involved to obtain access to the land for plantation. This cost is, for example, in temperate Latin America typically 1.5 times higher than just the plantation cost.

Currently, there are no possibilities to estimate the costs discussed above in a decent way, but a conservative guess indicates that the costs presented in Table 6-9 should be increased by 2–3 times to reflect all of the costs involved by a global large-scale plantation program. This statement is valid for the first generation of the plantation program, subsequent rotation periods may more closely follow the estimates presented in Table 6-9.

Figure 6-3 summarizes the results of our global analysis, showing the annual wood increment, carbon fixation rate and investment costs. The (undiscounted) investment costs are irregular as a result of the dynamics of forest resources. The initial plantations have to be maintained (e.g., new plantations will need to be planted after the first rotation period) in order to sustain the fixation capacity. In this case, we regard the subsequent costs of plantations succeeding the initial one as investment costs, and not as part of the harvesting costs. This explains the increase in investment costs around the year 2025 when both initial and replacement plantations will need to be planted.

Table 6-9. Estimates on establishment and intermediate silvicultural costs for plantations, expressed in $US/ha.

Region	Establishment	Intermediate silviculture	Total
Temperate Areas:			
Canada:			
Backlog land	1150	100	1250
Converted farmland	425	100	525
Unimproved farmland	575	100	675
US:			
Temperate	1000	200	1200
South	600	100	700
Agroforestry	500	–	500
Europe:			
Nordic	1100	150	1250
EEC-9	1500	125	1625
Central	1500	125	1625
Southern	500	100	600
Eastern	400	100	500
Former USSR	400	100	500
China	400	150	550
Temperate Asia	400	100	500
Temperate Latin America	375	–	375
Temperate South Africa	350	–	350
Australia:			
Plantation	850	150	1000
Agroforestry	500	–	500
New Zealand	1000	125	1125
Tropical Areas:			
Latin America:			
Plantations	650	25	675
Agroforestry	625	–	625
Africa:			
Plantations	600	50	650
Agroforestry	400	–	400
Asia:			
Plantations	600	25	625
Agroforestry	625	–	625

Similar information for one high cost and one low cost region is presented in Figure 6-4 to highlight the large regional differences with respect to carbon fixation and costs. The high cost region is represented by EEC-9 region (the original EEC countries) and the low cost region by tropical areas in Latin America.

The estimated costs of our global plantation program would be $3.5 billion in the year 2095 for a carbon sequestration of 1.6 Gt C, i.e., some $2.2 per tonne of carbon removed. Due to the irregular pattern of costs and carbon fixation over time cumulative reduction costs would be higher. The global program shown in Figure 6-3 would cost some $520 billion over the period 1995–2095, sequestering some 120 Gt (i.e., 4.4 $/t C). However, as indicated above, our cost estimates may be underestimating the real costs perhaps by a factor of 2 to 3.

Figure 6-4 illustrates the large regional variations in costs and carbon fixation rates across regions. Plantation costs, some 100 years from now, range between $1.2 per tonne

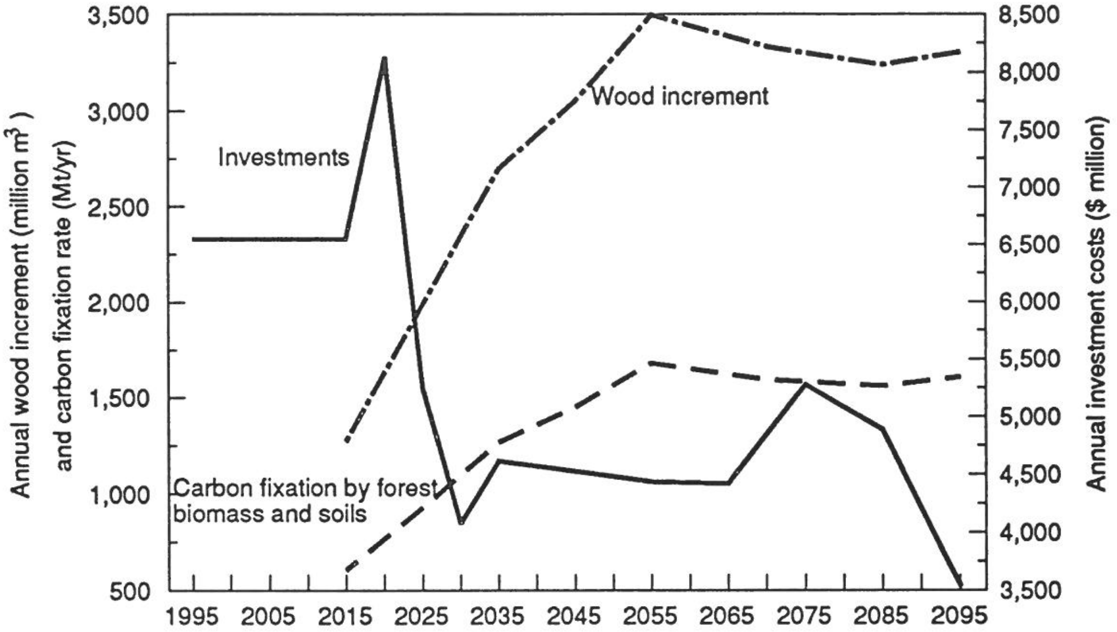


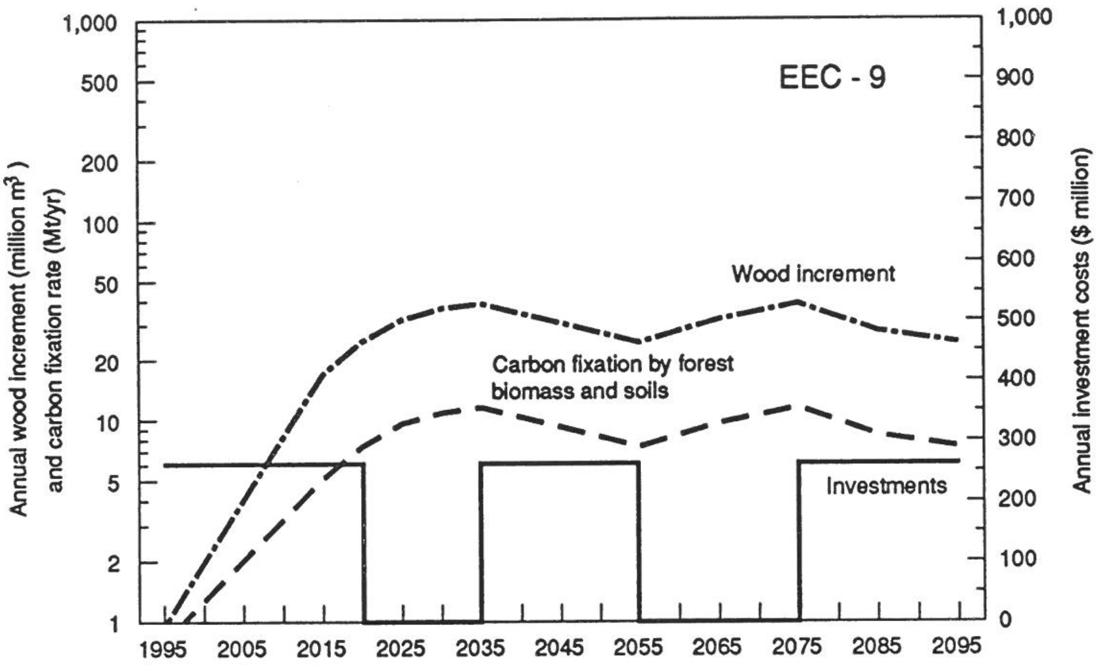
Figure 6-3. Annual investment costs, wood increment and carbon fixation rates of a global plantation program.

carbon in tropical Latin America and \$35.5 per tonne of carbon in the EEC-9 region, i.e., they vary by a factor of 30. Integrated over time to account for differences in rotation periods, etc., the program would, over a period of 100 years, involve expenditures of some \$17 billion in the EEC-9 for a cumulative carbon fixation of 800 million tonnes, i.e., \$21.4/t C. Conversely, in tropical Latin America, some \$64 billion could sequester an estimated 27 Gt C, i.e., at a cost of \$2.4/t C, which still presents a difference in sequestration costs of a factor of 10.

We therefore conclude that the potential for enhancing global carbon sinks by a massive plantation program is limited. The most important restrictions on massive afforestation programs include social, cultural, ethical, market and organizational constraints. The analysis indicates that around 265 million ha would be available for new plantations and around 85 million ha for agroforestry. This is substantially lower than the existing estimates of suitable land for plantations and agroforestry, in the range of 1.5 and 1 billion ha, respectively, (exceeding the area devoted to agriculture). It would require about 40–50 years before any significant effect on the level of carbon fixation by the feasible plantation program would be achieved. Finally, the carbon fixation capacity of such a program, about 60 years after the plantations are established, would only be around 1.6 Gt of carbon per year. Still, over 100 years the global program outlined could sequester some 120 Gt of carbon.

6.3.9 Impacts on the World Timber Market

Excessively large plantations for carbon fixation will dramatically influence world markets for wood products. Grainger (1991) illustrates that a forest of 240 million ha with industrial roundwood production would produce a wood volume equivalent to the projected world demand for industrial wood, according to Kallio *et al.* (1987). From such a



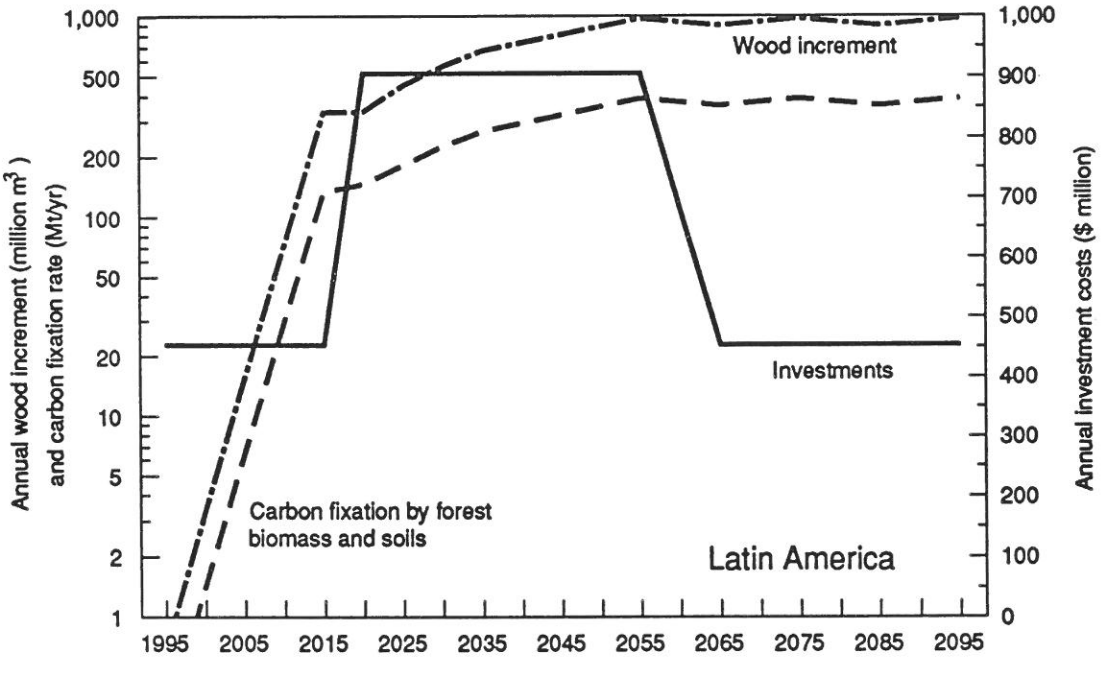


Figure 6-4. Annual investment costs, wood increment, and carbon fixation rates of afforestation in a high-cost (EEC-9) region (top) and a low-cost (tropical Latin America) region (bottom).

perspective the plantation program outlined above would indeed create complete havoc on the world timber market, although we get a different picture if we look at the future demand for both industrial wood and fuelwood.

Wood is a major source of energy in the developing world. In 1989, FAO (1991) estimated the wood consumption for fuelwood and charcoal in the developing countries to be about 1.75 billion m^3 (solid over bark; s.o.b.). The same organization estimates the consumption in year 2010 for wood for energy to be about 2.5 billion m^3 s.o.b. in the developing world.

Based on estimates by Libäck (1992) global consumption of industrial and fuelwood for the year 2025 could amount to 7 billion m^3 s.o.b. Based on information on existing harvesting levels (FAO, 1991b) and the land available for plantations (see Section 6.3.4 above), we obtain a negative global wood balance of about 1 billion m^3. From such a perspective, a plantation program would be needed irrespective of the issue of carbon sequestration. In fact, the feasible plantation program described above may even be inadequate in meeting the global demand for wood in the year 2025.

From a greenhouse gases' emission point of view, there are still some problems connected with traditional fuelwood uses:

- carbon is released into the atmosphere by burning, and to keep an atmospheric balance the burned wood has to be replaced by new plantations;
- traditional fuelwood burners and stoves burn at low temperatures and may cause releases of methane, N_2O, and other gases with greenhouse effects;
- large-scale incineration requires a lot of transportation of the wood, which will increase the consumption of fossil fuels and increase emissions;
- we agree with Swisher (1992) that in order to prevent carbon emissions the most important issue is to move from unsustainable (deforestation) to sustainable harvesting practices.

Hall *et al.* (1990, 1991) argue that instead of planting trees to sequester carbon, the biomass produced should be used for energy production to offset fossil fuels. Such a strategy may have a larger impact on greenhouse warming, than a pure carbon-sequestering strategy. Especially, as biomass energy will often be less costly than fossil fuel energy. However, the authors underline that pure carbon-sequestering strategies will still have an important role to play in areas remote from energy markets or in areas for environmental protection. This is in line with conclusions presented by Marland and Marland (1992). They stress that a strategy combining wood for energy production and carbon-sequestering seems to be reasonable. To sum up the discussion concerning what to do with the wood produced by a potential global afforestation program, a sound strategy appears to be a combination of pure carbon-sequestering, energy production (to offset fossil fuels) and meeting increased demand of industrial wood. The most suitable mixture of this strategy will vary from region to region.

6.4 Other Means of Absorbing Atmospheric CO_2

Large amounts of CO_2 are absorbed from the atmosphere by plants in photosynthesis, weathering of rocks and by the oceans. Enhancing the natural rate of carbon fixation by photosynthesis has been summarized in Section 6.3. At present, oceanic photosynthesis might be removing as much as 35 Gt of carbon per year although a large proportion of this amount is returned to the atmosphere through the decomposition of marine organisms. Another important link in the global removal of CO_2 from the atmosphere is the weathering of primary rocks. In this section we briefly look at possible ways in which human intervention could enhance these natural processes.

6.4.1 Enhancing Carbon Fixation by Photosynthesis

Afforestation is frequently heralded as a great opportunity for removing large amounts of CO_2 from the atmosphere. In Section 6.3 we have arrived at the conclusion that this is an important, yet globally limited, option. In the context of removal strategies, photosynthesis by plants, algae or by synthetic methods are all viable and already feasible ways for absorbing atmospheric carbon. Here we focus on ways of enhancing other paths of carbon fixation by photosynthesis, including the enhanced growth of algae, plants and other organisms that absorb CO_2. The possible processes can be categorized into those that increase their populations in natural environments and those whereby organisms are cultivated in artificial environments.

6.4.2 Iron Fertilization of Polar Waters

Enhancing oceanic photosynthesis is a possible strategy to increase the rate of carbon removal from the atmosphere. It is estimated that oceanic photosynthesis removes about 35 Gt of carbon from the atmosphere annually (COSEPUP, 1991). In order to enhance this cycle, it is required to interrupt the degradation process by a more direct sedimentation of fixed carbon in the deep ocean.

A scheme for enhancing the rate of marine carbon fixation has been proposed by Martin *et al.* (1990), which involves the addition of trace amounts of iron to the ocean surface with excess nutrients. The proposal resulted in an intense debate concerning both the feasibility of the scheme and its possible adverse effects. Peng and Broecker (1991) have argued that most of the CO_2 sequestered by iron fertilization would remain fixed in the stock of phytoplankton and algae, and that little of the carbon would be actually transported to the deep ocean. Others have criticized the credibility of the iron fertilization hypothesis itself.

Martin (1990) estimates that less than 0.5 Mt of iron would be required per year to remove 2–3 Gt of carbon per year. Assuming the delivery of iron (compounds) by ship, the costs of the whole operation would be between \$10 and \$110 billion per year (including the vessels and iron fertilizer), resulting in an average sequestration cost of between \$3.5 and \$55 per tonne of carbon.

Another related proposal has been advanced by Marchetti (1992b), whereby CO_2 would be sequestered from the atmosphere by gigantic plantations of water lilies. Part of the problem of all schemes for photosynthetic removal of carbon is that the oceans are oxidating environments so that as organic matter decays, carbon is released to the atmosphere, and only a small amount actually sinks to the bottom. The Black Sea is unique in this respect since it is reducing below a depth of 100 m. Hence, Marchetti (1992b) suggests the Black Sea for such a plantation scheme. Since water lilies sink spontaneously after their useful life, the bottom of the Black Sea could provide a large storage pool for sequestered carbon. At 1% photosynthetic efficiency, a water lily plantation as large as the Black Sea could be expected to remove about 2 Gt of carbon. As in the case of the iron fertilization hypothesis, some enhancement of water lilies' growth would be needed, so that the total system costs of the two mitigation schemes could be expected to be roughly the same. Here again, the feasibility of the whole approach needs to be investigated with special attention to its possible environmental and ecological impacts.

6.4.3 Enhanced Terrestrial Photosynthesis

Afforestation is one of the most obvious ways of enhancing carbon fixation on land by photosynthesis, as described in the previous section. Here, we briefly consider alternative ways of enhancing terrestrial photosynthesis by cultivation of microorganisms such as green algae, cyano and hydrogen bacteria. Most of the schemes for fixation of atmospheric CO_2 by microorganisms involve their cultivation in especially designed reactors (that simulate natural environments such as ponds) with control of temperature, sunlight and nutrient availability. In the simplest case the reactor consist of open pools of green algae (with the disadvantage that an enormous area would be required for effective carbon sequestration); in more complicated proposals the reactors involve sophisticated environmental management. In most of the proposed schemes, this approach to enhance photosynthesis involves the fixation of CO_2 from concentrated sources (such as stack gases from power plants) rather than the trace amounts from the atmosphere. One such study (Nishikawa *et al.*, 1992) indicates that high microalgae densities could be achieved in a reactor with light intensity magnified and distributed by optical fibers, the liquid in the reactor being recycled and CO_2-enriched gas pumped through it. In any case, the required land (reactor) areas would be indeed vast. In the best case, 66 dry g/m^2 of microalgae would be required to absorb 1 tonne of carbon in form of CO_2, costing an estimated \$230 per tonne of carbon removed. Dried algae could be used as forage substitutes. At prevailing prices of imported forage in Japan, the costs of carbon removal would be fully compensated. Thus, although the potential for CO_2 removal by this strategy is relatively small by global standards, it could make an important contribution since the marginal costs are estimated to be very low compared with those of other alternatives.

6.4.4 Enhanced Weathering of Primary Rocks

The weathering of primary rocks is an important component of the global carbon cycle. Some of the CO_2 washed from the atmosphere dissolves limestone into calcium hydrocarbonate that eventually reaches the ocean waters. In nature, this is a relatively slow process but it has an enormous capacity. An important barrier to this process is that the marine organisms actually reverse the above reaction in the production of their calcium carbonate shells and release the CO_2. On balance, such a scheme appears quite infeasible.

Weathering of calcium silicate rocks is another potential natural process that could be enhanced for additional CO_2 fixation. With the help of marine organisms and other natural processes, the final products are silicates (mainly SiO_2) and calcium carbonate. In this way about 5 tonnes of calcium silicate rock are required to sequester about 1 tonne of carbon from the atmosphere. From this perspective alone, the scheme is not very promising since the material fluxes would need to be gigantic. Seifritz (1991) has proposed large-scale artificial primary rock weathering by reacting ground calcium silicate stone in water pools with injected CO_2. This does not appear to be possible both because of the high energy requirements for producing small stone particles and the required process volume. Marchetti (1992b) suggested a design for creating porous rock structures to enhance the natural weathering effect and subsequent injection of

CO_2 (collected from energy conversion plants). For example, rock could be fractured by explosions or by hydraulic means and CO_2 injected underground. In addition, water could be used to enhance the reaction and remove the products.

In general, primary rock weathering schemes do not appear to be too promising because of the required large material fluxes. The natural rate of atmospheric carbon removal by this process is estimated at about 100 Mt of carbon per year (requiring about 7400 years to remove the present carbon content of the atmosphere; see Seifritz, 1991). To use this process as a global CO_2 mitigation strategy would imply the acceleration of this natural process by at least a factor of ten.

Energy Vol. 18, No. 5, pp. 523–538, 1993
Printed in Great Britain. All rights reserved

0360-5442/93 $6.00 + 0.00

Chapter 7

Technology Transfer to Developing Countries†

7.1 Introduction

In the formulation of prudent strategies to slow global warming, emissions from all countries must be considered; it makes little difference where on the planet CO_2 is emitted. Indeed, although much of the burden for controlling greenhouse gas emissions may rest with the industrialized countries, it is likely that many of the lowest-cost opportunities exist within developing countries. In addition, insofar as demands are placed upon developing countries to control their emissions as part of some global strategy to protect the climate, they will surely demand compensation from industrialized countries for the additional cost of shifting to less greenhouse-intensive technologies and behaviors. Such is the very familiar argument for technology transfer. This is not a new issue, but it has regained salience because of the global nature of the greenhouse problem.

This chapter summarizes the issues related to transfer the of less greenhouse-intensive technologies and is organized into four main sections. Section 7.2 gives an overview of wider issues that influence adoption and diffusion of innovations and ultimately also technology transfer. In Section 7.3 we give some examples of technologies that might be transferred and where they are likely to be most effective in controlling emissions. Because the greenhouse problem is an energy issue, and energy technologies are pervasive in the economy, it should already be evident that the range of possible technology transfers is very broad. Section 7.4 reviews the "normal" processes of technological innovation and diffusion and their relationship to economic development. That discussion is important because, as we will show, the normal working of the market results in a great deal of technological diffusion and change. Normal processes and patterns provide the context within which technology transfer to manage the greenhouse will take place. Finally, in Section 7.5 we discuss overt technology transfer, the goal of which is to diffuse less greenhouse-intensive technologies around the world more rapidly and more extensively than would otherwise be the case.

---

†Nebojša Nakićenović with conbributions by David Victor (in particular, Section 7.5).

7.2 Adoption and Replication of Innovations

A recent report to the United Nations Conference on Environment and Development (UNCED) defines technology transfer as a process by which technology, information and knowledge developed in a given institution, in one country, or for a particular purpose are applied and utilized by another institution, in another country or for another purpose (AEI, 1991). The concept includes all activities necessary for the successful transfer, adaptation and adoption of the technology to the recipient country. This includes, for example, provision of related, enabling technologies, techniques and practices required for full implementation of the technology to be transferred. It also includes the related capacity building required for full absorption of technologies and the development of indigenous capabilities for further adaptation, replication and innovation.

In some sense this is also the ultimate purpose of technology transfer; namely, to lead to more rapid adoption and replication of innovations. In the long run, economic development and per capita consumption are limited by the growth in productivity. Productivity is *inter alia* a function of the capital vintage structure, skills, knowledge, and the capacity for learning and managing innovations. Thus, all of these factors are important in the context of technology transfer. Only the first one refers to the physical embodiment of technology in the form of infrastructures, hardware, machinery or equipment. The other two are related to the establishment of internal and external learning processes, capacity building for innovativeness and capability of appropriating economic and social benefits from innovation adoption. Ultimately, the issues of technology transfer cannot be separated from the broader context of economic and social development.

The vintage structure determines to a large extent the capabilities of a given country for further economic growth and technological change. An old and inefficient vintage structure hampers development and erodes the relative competitive position. Obsolete and old infrastructures can be major obstacles to the successful adoption of transferred technologies. At the same time, the general lack of capital goods and severe capital scarcity in most of the developing countries constrain the investment in new and more efficient technologies. For example, despite a high national savings rate of over 20% in India, an acute shortage of capital prevails, the available total being on the order of $150 per capita per year. There are many desperate needs such as the creation of new jobs for the burgeoning population estimated to cost at an average of about $2000 per workplace. In most of the developing countries, the chronic capital scarcity is compounded by the increasing burden of external debt. In fact, the annual transfer of funds from developing countries toward the outstanding debt now exceeds the value of economic aid and technology transfer to the South.

But even a more generous and intensive transfer of capital goods and equipment to the developing countries alone would not suffice for achieving more sustainable development. An enhanced flow of goods and services is also required to sustain the useful absorption of capital goods until the domestic capacity is in place to guarantee internal support. This also includes "paper and software" embodied technology in addition to physical goods and services. Manuals, operating procedures and programs are all an integral part of enhancing local skills and know-how. Skills and know-how in turn have to be acquired both through formal education and training programs and by "learning by doing". The human embodiment of technological knowledge is perhaps the most important part of technology transfer because it does not only determine the internal capabilities for appropriating economic and social gains from transferred technologies, but it also determines the capacity for further innovation and adoption of new technologies and practices. From this perspective, technology transfer and diffusion can be seen as two complementary facets of the same adoption process of new technologies and practices.

In the context of global climate change, technology transfer plays a special role. This is particularly so in the case of strategies for mitigating CO_2 emissions in the developing countries. They account for almost 80% of the world's population but for less than 30% of energy-related CO_2 emissions. Their share in the responsibility for the historical increase in anthropogenic CO_2 concentrations (loading) is even smaller, at about 16% (Nakićenović, 1992). Nevertheless, the developing countries may have to share the responsibility for curbing future emissions, given that their energy consumption will, in the course of time, be comparable with that of industrialized countries (AEI, 1991). This view implies that the developing countries will catch up to the level of now industrialized countries during the next decades, and this indeed was the case with Japan during the last hundred years, and more recently with a number of newly industrialized countries (e.g., the Four Tigers). In fact, Japan has achieved more than a mere catch-up. The most striking phenomenon has probably been the impressive capability of quickly adopting, improving and introducing new technologies. These capabilities, together with somewhat different organizational arrangements, have also resulted in the rapid growth of Japanese international competitiveness. Should the economic development gap between the North and the South close in an analogous manner during the next decades, it is almost certain that technology transfer is an investment in our common future and should also be focused on the most recent systems being introduced in the industrialized countries. The development model would be universal and equivalent throughout the world. Thus, the transfer and availability of the latest technology to the developing world would aid significantly their ability to limit CO_2 emissions.

The alternative view holds that developing countries need "appropriate" technologies which are adapted specifically to their individual needs, and social and cultural settings. This might for example imply that robustness and simplicity might be of greater advantage than optimization of efficiency through technological and operational sophistication. It is not only necessary that favorable financial arrangements are created for the transfer of technology, but information leading to the choice of the most appropriate technology by the developing country as well as its successful absorption within the recipient country are essential prerequisites (AEI, 1991). Brazilian alcohol program could be considered as an appropriate technological development path distinctly different from the predominant trajectory of the industrialized countries (see Chapter 3). In general, more appropriate technologies would presumably focus on renewable sources of energy for more local and usually rural applications. At the other end of the spectrum, one could also consider the Chinese nuclear program as an alternative model for developing countries. China currently offers nuclear power plants at fraction of the costs prevailing in the OECD countries and is developing even cheaper small-scale units. In any case, the focus of technology transfer on more appropriate technologies for developing countries that are distinctly different from those in the industrialized countries implies that a more permanent difference in development and consequently also CO_2 emissions between the North and the South would be sustained over the next decades.

7.3 Which Technologies to Transfer?

The range of technologies that might be transferred in order to control greenhouse gas emissions is very large. It encompasses the full set of energy technologies, as well as technologies that affect any other greenhouse-producing behavior. Because the climate issue is largely an energy one, it is logical to examine (as we have done in preceding chapters) a range of energy technologies that might help slow global warming. Especially important are technological measures and options to mitigate CO_2 emissions. However, there are also many other technologies, outside the realm of energy, that could also be candidates for transfer. In this context, there are basically three related areas for technology transfer to the developing countries: technologies to improve the overall effectiveness and efficiency of energy use and monitoring of resulting emissions; technologies to stabilize and mitigate greenhouse gases; and technologies to adapt to adverse impacts in the event of climate change. From this perspective, technology transfer focuses on the same generic groups of technologies as climate change mitigation and response strategies in general. Thus, most of the discussions about the relative contributions, timing and appropriateness of individual measures and options from the preceding chapters also apply here. The main difference, however, is that some of the mitigation measures might be much more cost-effective if applied to the developing countries. Dollar for dollar, it is quite likely that many measures would lead to lower global emissions if applied in developing countries. In some cases, this could be so cost-effective as to pay for the transfer!

For example, as discussed in Chapter 6, there is some potential to deal with the climate problem through afforestation, or at least by halting deforestation. The global afforestation potential was estimated to reach about 1.6 Gt of carbon per year over the next six decades. Almost 80% of this potential was identified in the developing countries. Furthermore, the minimum cost estimates ranged from $2 per tonne of sequestered carbon in Tropical Latin America to $20–$35 per tonne in Europe. Another study of the mitigation potential in India by the year 2000 identified afforestation as the largest and cheapest option, averaging less than $40 per tonne of sequestered carbon (Mathur, 1991). Thus, there is up to a factor of 20 difference in the estimated afforestation costs. The cost estimates presented in Chapter 6 indicate that for a dollar spent on CO_2 mitigation through afforestation up to 10 times more could be achieved by investing in Latin America rather than in Europe. A possible (cost-effective) implementation of this strategy might also include a range of related technologies and expertise associated with forest management to be transferred in order to build local capacity so that the generated value added would remain in the recipient country. More appropriately, the needed technologies and expertise might be developed *in situ*, under the sponsorship of industrialized countries, since the expertise and technologies developed within high-latitude forests are unlikely to be fully appropriate for tropical forestry. This kind of cost-effective technology transfer opportunities might become an integral component of future carbon offsets and tradable permits.

In addition to more conventional measures such as higher power plant efficiencies or vehicles with lower fuel consumption, there are many exotic technologies discussed in Chapter 5 which, if proven effective, would be logical candidates for transfer. These include: (1) technologies to reduce carbon emissions resulting from deforestation and soil erosion; (2) devices for removal of CO_2 from flue gases and its disposal; and (3) equipment and materials for increasing the Earth's albedo. Furthermore, as mentioned periodically, the greenhouse issue is not solely one of energy consumption but is also related to other industrial and agricultural practices. In addition, it appears that the complete set of possible technological and behavioral opportunities in this area is far from fully developed even in the industrialized countries, but if so they could become part of technology transfer effort.

To close this section, note that throughout we have seriously addressed matters of mitigation cost, since it must be part of any evaluation of which technologies to transfer at what time and place, and elsewhere in this study the issue of cost is addressed in more detail. Here we underscore that cost is only one of the many factors affecting which technologies diffuse throughout the market and which might be successfully incorporated into a system of technology transfer.

7.4 Diffusion of Innovations and Technology Transfer

Unfortunately, most discussions on technology transfer have taken place largely without also considering normal processes of innovation and diffusion. Yet most technology is developed and diffused outside governmental channels of "technology transfer". Even a multibillion dollar program for the transfer of environmentally benign technologies will be small when compared with a $20 trillion world economy. Thus, when considering the prospects for overt technology transfer, one must first consider how technology normally moves across borders and, especially, how diffusion from industrialized to developing countries is related to different trajectories of economic development.

Our discussion of normal diffusion will be in four parts. First, we show the normal processes of spatial diffusion, emphasizing the relationship between processes of diffusion in core markets and those in more distant locations, especially on the periphery. Developing countries are on the periphery in nearly all processes of technology diffusion, so this discussion of the relationship between core and periphery is an especially important background for our later discussion of overt transfer to those countries.

Second, through the example of automobiles, we speculate on the normal rates of diffusion, both within and between core and periphery. Most popular discussions on technology transfer assume that transfer is automatic and immediate; we hope to help set some bounds on the appropriate rates at which normal and overt diffusion might take place, although clearly the rates of potential and actual diffusion will depend on the particular technologies.

Third, we reflect on the coevolution of technology, infrastructure and economies. Technologies do not appear and diffuse randomly in time but arrive (and depart) in clusters. Those clusters of major technologies, in turn, appear linked to the distinct phases of global economic development, suggesting there are powerful macroeconomic interdeterminants on the set of technologies that dominate a given economic era. Will greenhouse effects, or environmental consequences more generally, prove to be an important selection mechanism on the set of technologies that dominate the next era?

Fourth, and finally, the discussion of clusters of technologies suggests that there are also clusters of economic development. In Section 7.4.4 we reflect on the "normal" trajectories of economic development and their relationship to technology. By implication, the transfer of technology might affect development trajectories, although the exact relationship and opportunity for shaping development trajectories with technology transfer is far from clear.

7.4.1 Spatial Diffusion from Core to Periphery

The old continent of Europe is often referred to as a single entity. In comparison with the New World and other parts of the globe this indeed may be appropriate. It is, however, a definition that is far removed from the actual demographic, cultural, social or economic conditions that prevail. Europe is very heterogeneous. The spatial distribution with respect to economic development levels is almost unimodal: the highest density of activities being in the "core" and tapering off toward the rim. Moving outwards toward the more distant peripheries in the south and east, this decreases even further. This spatial heterogeneity is mirrored in almost all indicators of economic activity and interactions, as reflected in the flows of people, information and goods (Grübler and Nakićenović, 1991a).

In terms of economic, human or spatial interaction indicators, the "functional distance" (i.e., the friction of distance intervening in the interaction) defines whether a particular region or country can be considered as part of the core or periphery. Thus, there is no rigid spatial delimination of core or periphery, instead there exist fuzzy, interlaced overlaps depending on the particular indicator considered (Grübler and Nakićenović, 1991a).

This kind of structure can also be observed for the spatial innovation diffusion. Starting at innovation centers, the adoption spreads gradually toward the periphery. With intensification of adoption the original innovation centers eventually merge into the core, maintaining relatively high adoption intensity compared with the more peripheral regions. These patterns in innovation diffusion have been observed for many different technologies and commodities, starting with railways, automobiles, telephones, television, and many other innovations ranging from infrastructures to fashion. Innovation adoption offers a model for better understanding of possible technology transfer patterns of CO_2 mitigation technologies. In any case, historical experience suggests the need to generate "diffusion centers" throughout the world that would help enhance their further and early adoption away from the traditional centers in the North.

Another possible consequence of this kind of spatial structure is that environmentally compatible technologies can be transferred in conjunction with the natural diffusion process from core to periphery possibly accelerating and intensifying the adoption. In this case, transfer of technology could take the form of appropriate incentives for higher rates of innovation adoption. These could include subsidies from donor to recipient countries, education and training programs to promote internal learning, or transfer payments to compensate for risks and costs of early innovation and for differential economic returns compared with more efficient countries in the North.

7.4.2 Diffusion Clusters and Development Trajectories

We can now combine the awareness that there are different levels of consumption and extents of diffusion between core and periphery with a more careful study of how innovation is adopted and related to economic and social development in general. A view with respectable consensus among students of economic development holds that from a longer-term historical perspective all the processes of economic growth and social change cannot be explained without reference to the introduction and diffusion of major technological innovations from the steam engine to electricity, the internal combustion engine, railroads, fertilizers, plastics, jet engines, and uncountable other innovations (see Chapter 1; Dosi *et al.*, 1988; Nakićenović, 1984; Freeman and Perez, 1988; Dosi, 1991).

Furthermore, there is a growing recognition that *history matters*; that past technological achievements influence future ones, for example, through the specificity of knowledge that they entail, through the development of specific infrastructures, the emergence of various sorts of increasing returns, or by "locking-in" a particular set of technological options (Arthur, 1988). These concepts and "facts" about innovation diffusion and economic development give a particular context to the discussion of technology transfer. For example, the technology transfer policy that focuses on the development of infrastructure and education promises a long-term effectiveness with a profound effect in the recipient country while the policy that focuses only on efficiency improvement in energy end-use and services might achieve greater effects in the short to medium term but has the risk of making very small, if any, impacts in the long run.

This section offers such an example by illustrating the growth and diffusion of the automobile. The illustration is somewhat lengthy, but it shows an important example of how innovation diffusion spreads from the core to periphery and what adoption rates are achieved in peripheral regions compared with the core. We compare the process of diffusion in several countries in order to illustrate similarities and differences, and the extent to which innovation and diffusion in one country influences the rate and extent of diffusion in others. The diffusion of the automobile captures and illustrates many features of pervasive diffusion processes including the differences in rates and extent of diffusion between leaders and latecomers.

The diffusion of the automobile has occurred in two phases: the first was dominated by the process of substituting cars for draught animals, and the second marked by less rapid growth in the number and use of automobiles. The first phase of automobile diffusion, which we will not discuss here, lasted from the turn of the century through the early 1930s and entailed the substitution of the automobile for draught animals (horses and mules). This substitution is indicated in Figure 7-1 by very rapid growth rates of automobile use around the world, and is discussed in greater detail by Nakićenović (1986). Within a period of three decades, most of the draught animals were replaced by automobiles in practically all industrialized countries (Grübler, 1990). This substitution took place at approximately the same time and at similar rates in most of the industrialized countries, although the outcome did vary markedly. Notably, automobile densities were the highest in the United States, which was among the first countries to adopt the innovation. By the 1930s, automobile ownership densities reached 200 cars per 1000 inhabitants, which is comparable to the car density of present-day Japan (240 cars per 1000 inhabitants in 1987).

One of the greatest successes with the introduction of motor vehicles and the replacement of draught animals was the removal of environmental pollution in the form of horse manure in urban streets. At that time, the replacement of horses by a fleet of about 30 million cars in the world did not pose any substantial environmental problems, but today, with almost 500 million motor vehicles worldwide, the situation is different. After the replacement of draught animals a slower and more pervasive phase of automobile diffusion began. This phase in the growth of the global automobile fleet was marked by very large heterogeneity in both the diffusion rates and the remaining growth potential to the estimated saturation level. The time required for the fleet expansion from 1–50% of the estimated saturation of diffusion process varied from 16 years in Japan to over 50 years for North America. Furthermore, diffusion rates appear to accelerate, the later the diffusion process began. Both the diffusion rate and the level of saturation appear to be functions of when the diffusion process was initiated, measured by the year when 1%

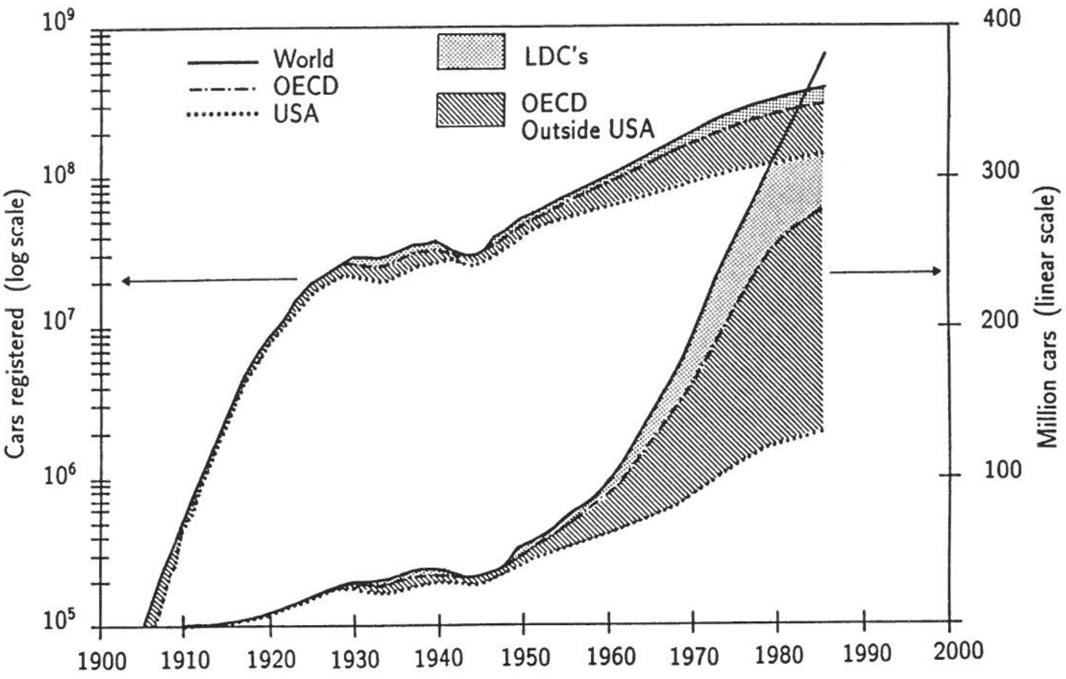


Figure 7-1. Passenger cars registered worldwide, linear and logarithmic scale.

of the saturation level was reached. Early starters grow more slowly and achieve higher ultimate density levels. But late starters have higher diffusion rates and therefore tend to catch up the with leaders, albeit with lower saturation levels. This phenomenon was repeated in the spread of railways and many other systems. For instance, the automobile diffusion process was initiated in North America around the turn of the century, grew slowly but achieved very high car density levels, as shown in Figure 7-2. The diffusion process in Japan started some 60 years later but, because of higher diffusion rates, grew more rapidly (caught up) and appears to saturate at the same time as North America but at a lower level.

We again point to the strong heterogeneity in the ultimate saturation density levels that emerge from our analysis. Early starters such as the USA and Canada may reach saturation density levels as high as around 600 passenger cars per 1000 inhabitants, whereas late starters such as Japan or Spain may reach saturation density levels between 250 and 300 cars per 1000 inhabitants. In some of the other countries analyzed, particularly India, Indonesia, South Korea, the Philippines, and Thailand, we were unable to determine estimates of saturation level, because the growth process is still in its early (exponential) phase. This implies that the ultimate saturation levels for these countries might be higher than the present car density by at least a factor of three. However, considering the present low density levels of passenger cars per 1000 inhabitants in these developing countries (two for India, 11 for Thailand, and 16 for South Korea), growth by even a factor of three would not noticeably affect our average estimated saturation density of less than 70 cars per 1000 inhabitants at the global level. Of the developing countries analyzed, only Venezuela appears to have a motorization pattern that allows for significant growth well into the next century. Venezuela appears to be an example of a country that started early and grew slowly to high density levels.

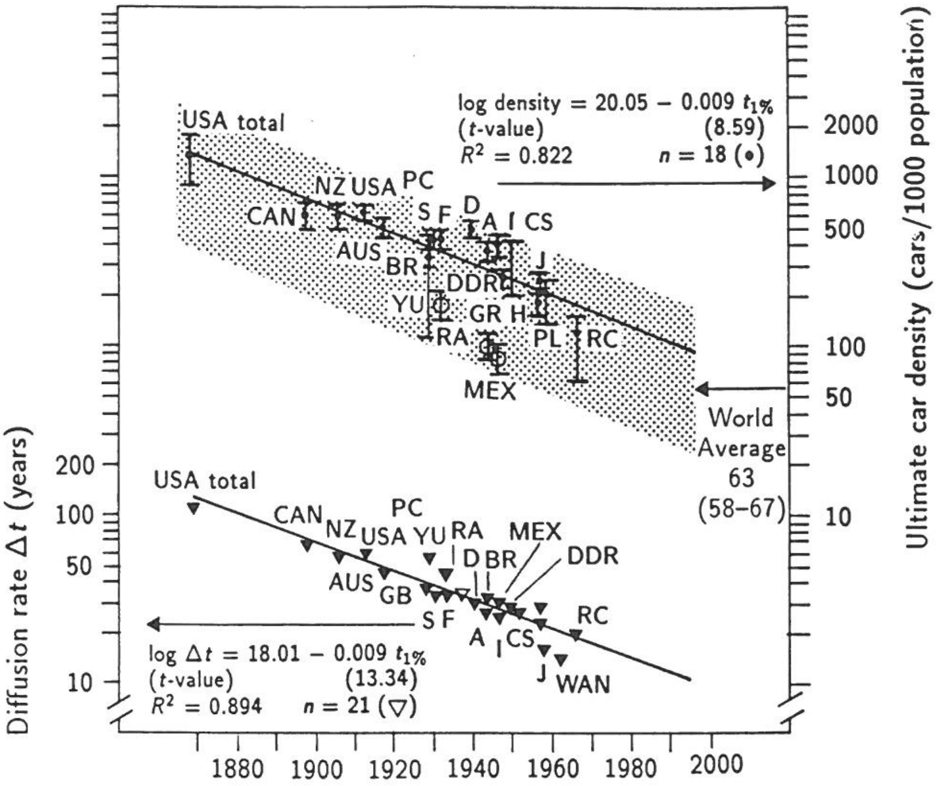


Figure 7-2. Diffusion (growth) rates and densities of passenger car ownership as a function of the introduction date of the automobile.

Taiwan, on the other hand, is similar to Japan: both countries were late starters but caught up quickly (as shown by their rapid Δt of diffusion).[1]

This brings us to the perhaps most important result of our analysis. We have observed an *acceleration* of diffusion rates and a *decrease* in ultimate diffusion levels as a function of the "learning time", i.e., the time period between the beginning of the diffusion process and the time available for growth (i.e., Δt). Figure 7-2 summarizes the result by analyzing the relationship between the length of the growth process of automobile diffusion (Δt), the ultimate saturation level of this process, and the time a country started motorization. The acceleration of diffusion for late starters is not a unique observation; we observed similar relationships in the growth of railway networks and many other systems. Similar analyses for the development of inland navigation and canals in a number of countries indicate identical patterns (Grübler, 1990).

Perhaps the most striking finding that emerges from Figure 7-2 is the straightforward mathematical expression for the "acceleration" phenomenon of diffusion in relating the log of Δt's to the time period in which private cars achieved a 1% saturation level. The data confirm the acceleration tendency at a statistically high level of significance, and explain as much as 89.4% (R^2 adjusted for degrees of freedom) of the variance in the observed data. If one extrapolates the catch-up tendencies, one arrives at the conclusion that a country starting the diffusion of private cars now would have a diffusion rate lower than ten years. Such rapid diffusion of car ownership appears quite infeasible from a practical viewpoint and could not in any case result in a significant growth of both absolute and relative car registration figures.

---

[1] The duration of the diffusion process is conveniently measured as the time that elapses between the achievement of 10% and 90% saturation levels. We call this measure Δt. It also corresponds to the time that elapses between the achievement of 1% and 50% saturation level.

We continue by analyzing the relationship between the estimated ultimate car diffusion level and the start of motorization. Early starters such as the USA and Canada will have significantly higher car density saturation levels (up to 600 passenger cars per 1000 inhabitants) than countries such as Hungary, Japan, or Taiwan, where density levels of about half the level appear typical.

Developing countries can be regrouped into three categories. Countries such as Argentina, Brazil, and Mexico appear to follow the same declining density trend as the industrialized countries, albeit at a significantly lower level. Venezuela and Taiwan are midway between the developing and industrialized countries. All the developing countries, however, seem to follow a similar declining density trajectory similar to the industrialized countries. Only Nigeria falls far below, indicating that motorization levels between the developing countries will be even more divergent than in the industrialized countries. In the same way that the USA does not provide a model for car diffusion in a country like Japan, so car diffusion in Brazil or Mexico does not imply a realistic model for Nigeria, India or even China. A density level of less than 10 passenger cars per 1,000 inhabitants appears more likely for these countries.

The declining density envelope and the trend line of Figure 7-2 suggest that any country starting diffusion now would experience a rapid growth in the number of cars registered but the result would be lower diffusion levels than in the leading countries. If we extrapolate the density envelope trends for the future, we arrive at the conclusion that a country starting motorization now would experience a very rapid growth in automobile use (Δt of around 10 years) but at the same time would achieve a density level below 100 passenger cars per 1000 inhabitants. Newly industrialized countries (NICs) may achieve figures close to our estimated world average of around 70 cars per 1000 inhabitants, whereas developing countries such as Brazil or Mexico might achieve density levels in the vicinity of 20–30 passenger cars per 1000 inhabitants should a widespread motorization begin now. For developing countries (such as India or China) that do not have the necessary initial conditions for motorization to take off (primarily in terms of disposable incomes), even these values are probably an order of magnitude too high: these countries fall outside the diffusion density envelope and are not part of the *automotive bandwagon* shown in Figure 7-2. We conjecture that within the next 20 years, car densities similar to those in industrialized or newly industrializing countries will not emerge in any of the developing countries, and particularly not in China or India. The mass transportation and more modest individual vehicles such as bicycles and three-wheelers will continue to grow at rapid rates (e.g., exceeding 5% per year in India).

We postulate, therefore, that the acceleration tendency in private car diffusion has two implications. First, it appears unlikely that a similar diffusion will occur in countries that are not part of the present diffusion *bandwagon* of industrialized and industrializing countries. The second implication is that, with very few exceptions, the expansion in passenger cars registered will approach saturation by the turn of the millennium. Based on such a scenario, one could expect a significant structural discontinuity in the evolution of the world automotive industry.

The relative diffusion levels ultimately resulting from motorization are different between individual countries as a result of their different geographical, economic, etc., boundary conditions, and the related accumulated "experience" involved in the diffusion process. Our observations of the different car densities in various countries are consistent with the results of our analysis of the spread of other technologies such as railways, air transportation, oil and gas pipelines, electric power plants, de-SO_x and de-NO_x scrubbers for power plants, various steel technologies, and many other systems, institutions and commodities.

In summary, there are three characteristics of the diffusion of pervasive systems derived from historical analysis and from theoretical modeling of the role of technology and technological change in socioeconomic development:

1. The *interrelatedness* of a cluster or set of technological and institutional innovations explains their pervasive effects throughout the economy.
2. The *international nature* of the diffusion of such innovation clusters, in that a set of core countries display interrelated dynamics in the development (growth) of such innovation clusters, with latecomers catching-up.
3. We observe *heterogeneity*, i.e., explicit differences in the ultimate diffusion or density of adoption levels achieved in different countries, taking part in the realization of a particular development trajectory.

7.4.3 Transfer, Development, and Path-Dependency

Technological change and social and economic development are inseparable processes. Furthermore, history matters because the past experiences and achievements influence the future ones via the accumulated knowledge that they entail. It is in both of these areas that technology transfer can help enhance the earlier and more widespread adoption of environmentally benign technologies in the developing countries. First, the information and knowledge base must be established so that domestic networks and learning capacity can emerge. The linkages between different technologies and their broader economic and social context must be established. This means that single technologies and activities cannot be "transplanted" by themselves, but must be allowed to be adopted and adapted to specific economic and cultural settings in the recipient country. It is the linkages between different technologies and their mutual positive feedbacks that can lead to productivity growth and sustainable development paths. For example, the transfer of a few efficient power plants alone would not do. Counter examples are plentiful. They include the Ashuganj 90 MW combined-cycle natural gas plant in Bangladesh operating at 27% efficiency, almost half of what the best ones can achieve (e.g., the Siemens plant in Ambarli, Turkey, operates at 53% efficiency).

Successful technology transfer can only occur in conjunction with appropriate linkages to other technologies and infrastructures, and with appropriate capacity building. This might include ample supplies of spare parts, training programs, and downstream and upstream technologies. For example, the maintenance of a combined-cycle plant is related to the maintenance of jet aircraft engines, thus the programs could be combined to establish a broader expertise base. That way both an earlier and more pervasive adoption might be achieved for a whole system of related technologies, generating various sorts of increasing returns which again create new inventive structures and transfer opportunities. In this way a new technoeconomic development trajectory could be established with a local knowledge base and capacity. In this context the role of the technology transfer would serve as a catalyst for generating internal and endogenous development and growth.

The whole point of this argument is that this form of technology transfer which is consistent with the standard (or "normal") process of innovation diffusion could help the adoption to start earlier, leading to a perhaps slower and longer diffusion process but one that ultimately achieves much higher adoption densities and levels, and thus making innovation adoption a more pervasive and fundamental process and generating a whole host of positive externalities. This would be analogous to an earlier start of the adoption of automobiles in Figure 7-2 and a higher adoption density. This naturally leads to the second argument concerning path-dependency.

Past achievements influence and determine future ones so that an earlier and more pervasive adoption of a whole family of related technologies generates new network effects through the specificity of acquired knowledge, leading to further internal and external learning. The innovation adoption and development process in general becomes self-generated, and this is the ultimate goal of appropriate technology transfer.

7.4.4 Environmentally Compatible Development

This path-dependent model of technology transfer is inherently related to the issue of environmentally compatible development in general and the mitigation of greenhouse gas emissions in particular. In the longer historical perspective, an increase in productivity leads to economic growth and improved well-being. This means achieving more with less. Thus, productivity increases range from efficiency improvements of all factor inputs, including energy and labor to dematerialization and decarbonization. In general, productivity increases will lead to better environmental compatibility with the exception of some well-known externalities. For example, labor productivity has been increasing by substitution of first human by animal work and later by fossil energy. As mentioned above in the case of transport, this initially cleaned the urban streets of animal excrement and dirt, but has led with increasing scale of adoption to a nonlinear increase in automotive pollution. There is a threat that such cases will be repeated in many of the developing countries. India and China have large coal resources and are in desperate need to increase energy services. Thus, a logical consequence is to consume coal in order to increase economic productivity. This of course would lead to an enormous increase in anthropogenic CO_2 emissions. Should China actually consume two billion tonnes of coal per year in the next century, it might render almost useless the other efforts to reduce CO_2 emissions globally.

From this point of view, technology transfer should be focused on the most efficient systems that rely on less carbon-intensive energy sources. They should focus more on organizational, institutional and educational factors than on the transfer of physical capital such as the newest equipment and devices. For example, we have shown in Chapter 2 that energy systems in the former centrally planned economies of Europe have lower specific efficiency of all primary to useful energy conversion chains, but their overall primary to useful energy efficiency is higher than in European market economies. Yet, despite such a high overall energy efficiency, the economic efficiency of energy use was low in the planned economies due to material intensiveness and an emphasis on primary sector. Environmentally compatible energy technology transfer should achieve these dual goals – higher overall efficiency due to less intensive structure of energy services and lower energy intensiveness of the economy. Furthermore, the rapid growth in energy consumption in most developing countries is due to the currently very low energy efficiency (see Chapter 2) and is due to rapid substitution of the traditional and unusually unsustainable use of noncommercial energy by fossil fuels. This is desirable from the point of view of efficiency improvement, and often it also leads to lower CO_2 emissions.

At present, deforestation is an important source of these emissions, but it should be noted that energy use is not the prime cause of deforestation. Great opportunities exist in this area to reduce overall CO_2 emissions by gradually shifting from traditional noncommercial energy sources to the sustainable use of biomass and other renewables. Appropriate technology transfer could enhance such process provided it extends beyond the shipment of more efficient equipment and devices: experiences in many countries indicate that more often than not such programs are doomed to failure. In India, for example, solar cookers were distributed to replace the use of scarce fuelwood, but it turned out that the cookers are now used as storage cabinets rather than for cooking, and the women continue to cook on inefficient wood stoves.

In Chapter 3 we identified many opportunities to enhance the use of renewable energy. The gist of our argument is that full appreciation of the broader sociocultural settings, and especially educational programs, are essential prerequisites for the successful transfer of appropriate technologies. Existing institutional frameworks are of fundamental importance especially with respect to education and, in particular, with respect to the acquisition of appropriate scientific, technical and organizational skills in recipient countries. Knowledge and skills are preconditions for environmental awareness. Clearly, local environmental and health issues must come first, but the virtue of most of the measures to increase the efficiency and sustainability of energy use is that they can achieve multiple ends by also reducing burdens on the local environment *and* reducing CO_2 emissions. Sustainable renewables achieve both of these ends. The efficient use of low-carbon fuels such as methane is also a step in the right direction. Further growth in coal use would be a step in the opposite direction and the related technology transfer ought to focus on most benign use of coal. With current technologies, this means coal gasification and conversion to electricity in combined-cycle plants.

7.5 Overt Diffusion as Technology Transfer

A wide range of technologies might be "transferred" to developing countries as part of international strategies to slow global warming. However, despite several decades of debate and experiment, there are few general lessons to guide the successful transfer of technology. In part, this is because of the difficulty of defining "successful", and in part because of complex and shifting factors that influence when, and how rapidly, a new technology is adopted. Here we distinguish between "normal diffusion" and "overt transfer" in an effort to separate the regular process of technical innovation and diffusion from what might be additionally possible under a strategy to control emissions of greenhouse gases in developing countries. The normal diffusion of technology is a pervasive feature of interlinked economies: technologies ultimately do make it to the far reaches of the periphery. Overt diffusion is an attempt to speed up that process. But, how can that be done without undermining the incentives that spur innovation? Is it possible to develop new, more appropriate technologies for developing countries? If so, how will decisions be made and by whom, regarding when, where, and at what cost a technology is appropriate?

As shown above, based on the normal processes of innovation and diffusion, a certain degree of diffusion to developing countries should be expected as the normal state of affairs. The issue of technology transfer arises because it may be possible to speed up the normal diffusion of particularly desirable technologies (or, as a corollary, to block the diffusion of technologies with undesirable characteristics, such as high energy intensity).

Similarly, it may be possible to reduce, or even eliminate, the lag between the diffusion of desired technologies within the core and diffusion within the periphery.

Technology transfer involves choosing the technologies for transfer and then employing some mechanism to achieve the transfer. Earlier in this chapter we identified some examples of the types of technologies that might be transferred; we now turn to the more difficult issue of designing mechanisms to achieve transfer.

Despite several decades of attempts to transfer technology, there are no general lessons yet evident on how to achieve successful technology transfer. Nonetheless, it is clear that technology transfer depends not only on technologies but also on the extent to which local conditions are "receptive" to the technology and, by extension, the ability of the technology itself to adapt to those conditions. The current practices of the international technology transfer have often been found to be disadvantageous from the developing country's viewpoint. Frequently, it is difficult to achieve sufficient absorption and adaptation of transferred technologies. According to a recent report by the Asian Energy Institute (AEI, 1991), the complaints of developing countries include: (1) the technology transferred is inappropriate or obsolete; (2) the imposition of conditions on technology recipients often leads to overpricing or restrictions on business practices; and (3) cartels and market imperfections are favored by the imposed intellectual property rights. The practical lesson of these findings is that not only do choices need to be made as to which technologies to transfer but that careful attention must also be paid to the compatibility between the technology and locality. Unfortunately, there are no clear guidelines on how best to achieve a match between technique and locale, but we can offer some insights into the options for technology transfer mechanisms by examining four possible approaches to the transfer of less greenhouse gas-intensive technologies to developing countries.

First, technology could be transferred using existing diffusion mechanisms – that is, letting the market work on its own – but with additional financial aid from industrialized countries. Although there might be some offers of technical advice from industrialized countries and/or restrictions on how the money would be used, the developing countries would be largely free to make their own choices. Following traditional market theory, the sum of decentralized local actions would produce the best match between local conditions and technological investments. The problems with this approach are many, notably, a simple infusion of financial help would not guarantee that the investments would be used to reduce the greenhouse gas intensity of the economy. Left on their own, firms and economies would presumably act to maximize profits, not to minimize greenhouse gas emissions.

A second approach to technology transfer could be to use existing aid institutions but to give them the additional mandate of making less greenhouse-intensive grants, concessions, and investments. The international response to global environmental problems is already pursing this approach. For example, the newly created multibillion-dollar Global Environmental Facility (GEF) within the World Bank has a mandate to fund projects in developing countries only in cases where the project would not otherwise be funded if global environmental criteria were not considered. Although the GEF is a pilot project, one strategy for environmentally benign technology transfer would be to make permanent some facility similar to the GEF and give it the task of funding technological investments in developing countries which would otherwise not be pursued if it were not for their environmental benefits. Furthermore, there could also be an effort to disseminate greenhouse criteria throughout the operations of the Bank and similar institutions so that, with every project, an effort is made to satisfy not only traditional Bank requirements but also the new goal of controlling greenhouse gas emissions. While this approach to technology transfer would have the support of the Bank and probably also industrialized countries, which are already familiar and more or less satisfied with the operation of the Bank, the developing countries have frequently expressed reservations about allowing new funding to be managed by the Bank because of the many restrictions and institutional power of the Bank.

A third approach could be to establish some new institutions for technology transfer. Given the importance of local conditions in the successful transfer of technology, a dispersed rather than centralized network of institutions could help match technologies and locales and assist in the process of adopting less greenhouse-intensive technologies, and in making appropriate auxiliary investments in training and infrastructure, within any given area. The same applies to technological development which may also be fruitfully conducted within the receiving local conditions rather than in distant institutions in industrialized countries. There are some important and successful models for such a dispersed network. The Consultative Group for International Agricultural Research (CGIAR), a network of 11 agricultural research institutions, has effectively conducted a program of primary research on crops and, consequently, has played a major role in the successful adoption of new high-yield strains. The success of the CGIAR is attributed not only to their research producing the strains, but also to their active role in the local diffusion of those strains to farmers. There have been proposals for similar regional networks of scientific and technological institutions in the context of global change.

A fourth and perhaps most important approach involves measures to strengthen appropriate scientific skills. In the longer term, this would put the developing countries in a position to effectively absorb technology and develop the local modifications and add-ons, without which any technology transfer must remain limited in its capacity to contribute to the solution of the most urgent local problems (Grübler and Nowotny, 1990). Salam (1988) has criticized the governments of both developing and industrialized countries for failing to recognize the crucial importance of science for technological and economic development. The widening gap between the North and the South, he maintains, is principally a science and technology gap, which is due to the fact that expenditures on science and technology are orders of magnitude higher in industrialized than in developing countries. This is the case in terms both of absolute amounts and also percentages of GNP. Typically, science and technology expenditures range between 2 and 2.5% of GNP in the industrialized North, compared with some 0.2% in the developing South. Thus, science transfer should always accompany technology transfer. There are four different levels of science transfer. First and foremost, scientific literacy and science teaching must be promoted and reached at all levels of education. This might include, for example, at least one complete science library as a minimum infrastructure in all developing countries. Second, the indigenous scientific community of developing countries should be consulted to determine which technologies would be relevant and worth acquiring. Third, at least a limited number of developing countries should be able to address and solve the problems of agriculture, local pests and diseases, and how to make most effective use of local resources and material. The fourth and ultimate level of scientific transfer is to generate conditions for basic research, the development of new technologies and general science-based research. Furthermore, science and technology transfer should be enhanced by collaborative networks. New international networks are needed, both between research institutions within the developing countries and also through new and stronger links with developed countries.

In conclusion, it should be stressed that all policies directed toward successful technology transfer to developing countries should include at least the three most important aspects of any development strategy: (1) to strengthen education, technical and managerial skills, both social and natural sciences, and general communication and information possibilities; (2) to strengthen general national policies that affect technology transfer such as investment, tax structures, protection measures, foreign exchange and property rights, etc.; and (3) to strengthen specific technology areas such as efficiency improvements and decarbonization, and the associated barriers to and opportunities for early and faster adoption.

Energy Vol. 18, No. 5, pp. 539–581, 1993
Printed in Great Britain. All rights reserved

0360-5442/93 $6.00 + 0.00

Chapter 8

Emission Reduction at the Global Level†

8.1 Introduction

In order to assess carbon reduction potentials, we first need a base line with which reduction scenarios can be compared. Such a base line could consist of current emissions or a reference scenario of future emissions. Since the implementation of reduction options requires considerable time, both from policy as well as technology diffusion viewpoint, current emissions are an insufficient reference point for quantifying the reduction potentials, constraints, or costs of future carbon reduction measures.

Thus, the discussion of emission reduction potentials inevitably entails the formulation of one or more scenarios, i.e., a vision of future developments in demographics, economic growth, energy systems development, and resulting carbon emissions. Usually, a "business-as-usual" (BAU) scenario provides the basis for such comparisons. However, the notion of "business-as-usual" requires a precise definition. According to one view, the future is simply an extrapolation of "more of the same" of the present, technology and economic structures are treated mostly as static and based on the currently perceived incentive structures, which typically exclude global environmental considerations. Consequently, emissions rise unabated, typically at constant or even accelerating growth rates. Representative scenarios of this type are the EPA's (1990) "rapidly changing world" (RCW) scenario or the various BAU scenarios elaborated within the IPCC process.

According to another view, the changes in both technological and economic structures have been and will continue to be an inherent part of the evolution of social and economic systems. Adopting this view, we contrasted such "conventional" BAU scenarios with a different scenario of our own, ECS '92, which does not pursue any particular carbon emission reduction strategy but which assumes that past trends of technological and economic structural change will continue to prevail in the future. We thus characterize this scenario as "dynamics-as-usual". Its interesting feature is that, even under a strict cost minimization assumption (ECS '92 is based on the linear optimization model MESSAGE), future energy system developments can be depicted that serve to some extent economic and environmental objectives at the same time. This is primarily the

---

†Arnulf Grübler with Sabine Messner (Section 8.2) and Leo Schrattenholzer (Section 8.5), and contributions from Andreas Schäfer (Sections 8.3, 8.4 and 8.6).

result of a more comforting resource situation (see Chapter 4) that does not require the massive use of coal and coal-based synfuels but also of continued technological progress and economic structural change. As such, the ECS '92 scenario, described in more detail below, intends to illustrate a future development path which incorporates a number of "no regrets" options and results in proportionally lower emissions.

After outlining our "reference" view of the future, next we examine emission reduction potentials in the three major end-use sectors: industry, transportation, and households and services. The estimated reduction costs (and cost ranges) of individual measures and *combinations* of measures along the "energy chains" concept adopted for this study are outlined. Where appropriate, measures upstream of the energy chain are included in the relative comparison of different options, thus emphasizing the *integrative* and comprehensive character which the ultimate emission reduction measures will have to embrace. The chapter concludes with a brief summary of the energy sector proper (which has been discussed in more detail in Chapters 3 and 4).

Another reason for focusing the discussion of emission reduction *chains* from the perspective of end-use sectors is methodological. Only detailed, comprehensive accounting of a diverse range of options, i.e., via an energy modeling framework, can ensure consistency and avoid "double counting" of individual options (such as fuel substitution) across different sectors. Such modeling exercises were, however, not subject of the present study. Thus, the individual and combined measures and their emission reduction potentials discussed below must be considered as only indicative. However, the options and *option chains* discussed provide a clear indication of priority areas of technologies to be considered in future work. They serve to narrow down data uncertainties and they can be used as a basis for detailed modeling exercises of CO_2 reduction measures.

8.2 The Reference ECS '92 Scenario

The reference scenario used in our analyses of options to mitigate global warming describes an essentially surprise-free future, and projects economic growth and long-term improvements in energy intensity in harmony with observed historical rates, i.e., under the premises of a "dynamics-as-usual" scenario philosophy. Population projections are from the United Nations (UN, 1991b). A comparatively stable oil price of US$ 20/boe is assumed for the period through 2020.

The total economic output, GDP, is derived from the projections of GDP per capita (GDP/CAP) and the development of population (POP). In turn, GDP and scenario assumptions of final energy use per unit of GDP (FE/GDP) are combined for projections of final energy. The future evolution of energy system efficiency (ratio of primary to final energy, PE/FE) is used to derive primary energy consumption. Finally, the specific CO_2 emissions per unit of primary energy (CO_2/PE) yield total CO_2 emissions. Consequently, CO_2 emissions can be decomposed according to the following (Kaya) identity:

$$\mathrm{CO_2} = \mathrm{POP} \times \frac{\mathrm{GDP}}{\mathrm{CAP}} \times \frac{\mathrm{FE}}{\mathrm{GDP}} \times \frac{\mathrm{PE}}{\mathrm{FE}} \times \frac{\mathrm{CO_2}}{\mathrm{PE}}$$

We follow the factors of this identity in describing the ECS'92 scenario. The results are given for three world regions[1]: OECD, reforming (former centrally planned)

---

[1] Results are aggregated from model runs including the following eight world regions: North America; Western Europe; Japan, Australia, New Zealand; Latin America (excluding OPEC); OPEC; former centrally planned economies in Europe; China and other centrally planned economies in Asia.

Table 8-1. Development of population and GDP, by region, 1990–2020, ECS'92 scenario.

	Population (millions)				GDP ($ trillion, 1990 dollars)			
Year	OECD	Reforming economies	Developing countries	World	OECD	Reforming economies	Developing countries	World
1990	856	404	4101	5361	15.5	2.57	5.67	23.8
2000	901	429	5030	6360	18.6	3.25	8.15	30.0
2010	933	450	5968	7352	21.6	4.36	11.10	37.0
2020	950	468	6757	8174	25.2	5.69	14.90	45.8
Annual growth rate (%)								
1990–2020	0.35	0.49	1.68	1.42	1.63	2.68	3.28	2.21

economies (REF), and developing economies including China (DC) as well as for the world as a whole. Comparisons with other global long-term energy scenarios will also be made, focusing in particular on the RCW (rapidly changing world) scenario developed by EPA (1990), as no sufficiently disaggregated data (i.e., final energy demand by sector and region) for most other global scenarios are available for comparisons in subsequent sections of this chapter. A comparison with the reference scenario developed within the IPCC Energy and Industry Subgroup (EIS, 1990) will also be made in this section.

As shown in Table 8-1, the world population as a basis for the ECS '92 scenario grows at an average annual rate of 1.4% between 1990 and 2020. By then, the total population will have increased by 50%, i.e., from 5.4 billion in 1990 to 8.2 billion in 2020. The annual growth rates in the OECD and former centrally planned economies are below 0.5% compared with an average rate of 1.7% per year in the developing countries. Due to these different growth rates, the share of the world's population living in developing countries is projected to increase to 83% from the current 76%.

Likewise, the projected average annual GDP growth rates are markedly different in the three regions: 1.6% in the OECD area, 2.7% in the reforming economies, and 3.3% in the developing countries. The resulting world average is a GDP growth rate of 2.2% per annum. On a per capita basis, GDP grows at 1.3% in the OECD, 2.2% in the reforming economies, and 1.6% for the DCs (see Figure 8-1). The global average growth of GDP per capita, 0.8% per year, is even lower than in individual regions. This development is due to the rapid population growth in DCs where growth rates are nearly five times as high as in the OECD, while GDP growth is only twice as high as in the OECD area.

Following the logic of the Kaya identity, we derive final energy consumption by considering the final energy intensity per unit of GDP. Final energy per unit of GDP declines for all regions at rates between 1.6% per year for the reforming economies – which are assumed to realize a considerable conservation potential in the process of economic restructuring – and 0.6% per annum for the developing countries where economic development still requires significant increases in energy use. In the OECD, the final energy per unit of GDP decreases at an average rate of 1.3% per year. All of the assumed final energy intensity improvements are consistent with observed long-term rates achieved even in periods of low energy prices (primarily as a result of continuous technological change).

The resulting final energy consumption in the world amounts to an increase of 50% (from 8.5 TWyr in 1990 to 12.8 TWyr in 2020), corresponding to an average annual growth rate of 1.4%. Again, the highest final energy growth rates are realized in the

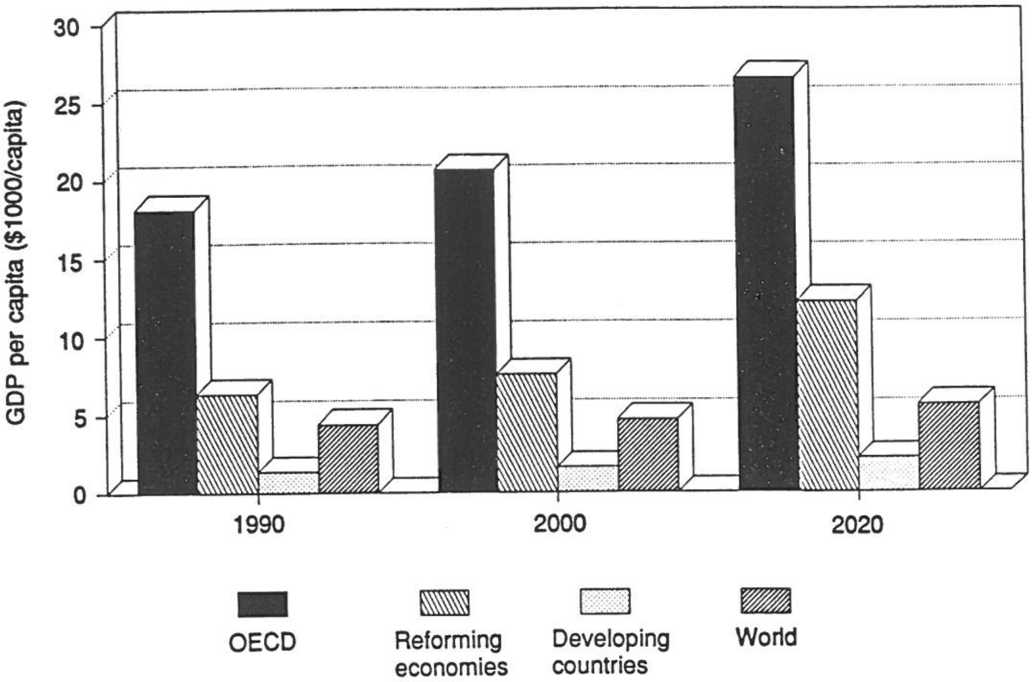


Figure 8-1. Regional development of GDP per capita, 1990–2020, ECS'92 scenario.

developing countries (2.6% per year), with 0.3% in the OECD and 1.2% in the reforming economies.

For comparison, the secondary energy consumption in the EPA's RCW scenario grows at 1.8% per year, which would give 13.3 TWyr by the year 2020, i.e., practically identical to the ECS '92 scenario. Conversely, the EIS reference scenario projects a somewhat higher final energy demand of some 16 TWyr by the year 2020.

The efficiency of the energy system itself, i.e., primary energy input per unit of final energy, determines the total primary energy consumption. This particular measure of efficiency shows a minimal deterioration of 1% over 30 years worldwide in the ECS '92 scenario. This is a result of two factors: (1) an overall increase in the efficiency of energy sector, which is more than offset by (2) an increase in the share of electricity from 15% in 1990 to nearly 20% in 2020. Since the efficiency of electricity generation is between 25% and 40% – compared with more than 95% for refineries or natural gas – this shift in the consumption pattern of final energy implies an overall efficiency reduction. The overall picture is an almost stable efficiency of the global energy system, i.e., a growth of primary consumption similar to the development of final energy.

The global primary energy consumption of 18 TWyr by the year 2020 (see Figure 8-2) for the ECS '92 scenario compares with a range of 19 to 22 TWyr in the EPA and EIS scenarios, respectively. The projected primary energy requirements in the latter two scenarios are higher due to a deteriorating efficiency of the energy system (primary to final energy ratio), decreasing by 6.5% in both the EPA and EIS scenarios (compared with a fall of 1% in the ECS '92 scenario).

Finally, the global CO_2 emissions can be expressed as the product of specific emissions per unit of primary energy and the consumption of primary energy. Specific emissions of CO_2 per unit of primary energy depend on the mix of fossil energy carriers used. With a decline in the share of coal (from 25% in 1990 to 21% in 2020), a decrease in

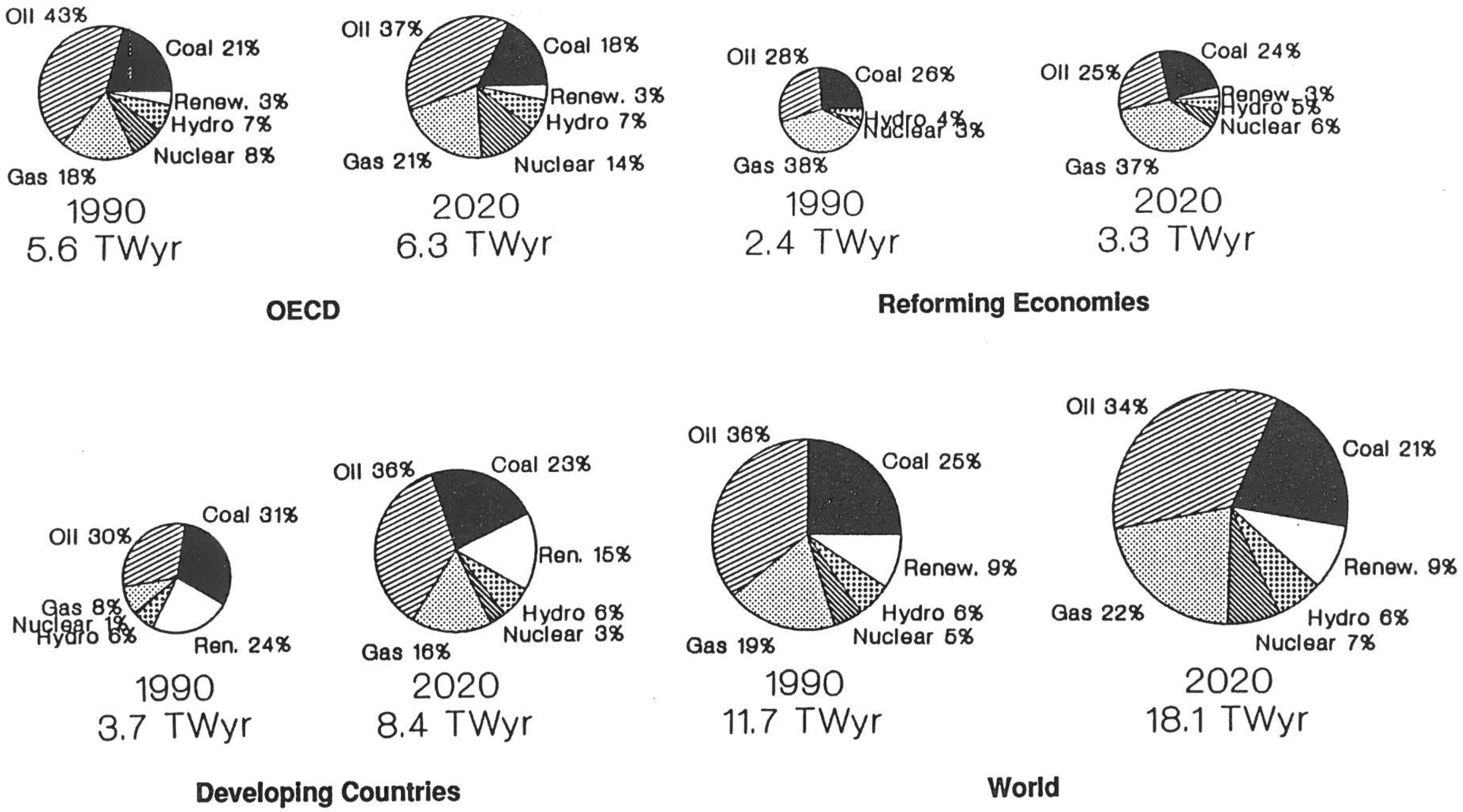


Figure 8-2. Regional development of primary energy consumption, 1990 and 2020, ECS'92 scenario.

Table 8-2. Development of energy-related CO_2 emissions by region, 1990–2020, ECS'92 scenario.

Year	OECD	Reforming economies	Developing countries	World
CO_2 emissions (million tonnes of carbon)				
1990	2666	1242	1586	5493
2020	2737	1613	3707	8058
Annual growth (%)				
9020	0.09	0.88	2.87	1.29
Percentage shares				
1990	48.5	22.6	28.9	100.0
2020	34.0	20.0	46.0	100.0
CO_2 emissions per capita (kg of carbon per capita)				
1990	3113	3072	387	1025
2020	2883	3450	549	986
CO_2 emissions per unit of GDP (tonnes of carbon/$ million)				
1990	172	483	280	231
2020	109	283	249	176

oil (from 36% to 34%) and an increase of the share of natural gas (from 19% to 22%), the specific CO_2 emissions decline slightly, from 0.470 tonnes of carbon per kWyr in 1990 to 0.445 tonnes of carbon per kWyr in 2020, in the ECS '92 scenario. In the EPA's RCW and EIS reference scenarios, the trends are different: the fuel mix becomes "carbon heavier", rising to between 0.50 and 0.55 tonnes of carbon per kWyr in the EIS and EPA scenarios, respectively.

In the ECS '92 scenario, the total energy-related CO_2 emissions (see Table 8-2) grow from 5.5 Gt in 1990 to 8 Gt in 2020, i.e., by an average rate of 1.3% per year. In the EPA's RCW scenario, carbon emissions grow at 1.9% per annum to 10.2 Gt by 2020, and in the EIS reference scenario by some 2.2% per year to 11.2 Gt. Considering the differences in final energy demand projected in the scenarios, there remain nevertheless differences in the projected carbon emissions. *Ceteris paribus* (i.e., with equal final energy demand), carbon emissions in the ECS '92 scenario are 15% lower than the EIS scenario and 24% lower than in the EPA's RCW case, illustrating the potential of cost-effective "no regrets" options in the *supply* of energy.

All scenarios agree that the regional distribution of energy-related carbon emissions will change significantly. Today, the OECD region emits 48% of energy-related CO_2, the reforming economies 23%, and the developing countries 29%. By 2020, however, the developing countries are projected to emit 46% of all energy-related CO_2 according to the ECS '92 scenario. Global CO_2 emissions per capita in ECS '92 will be lower by 4% in 2020. By that time, the per capita CO_2 emissions in the OECD will be three times the world average, while the value for the DCs is approximately 50% of the average. CO_2 emissions per unit of economic activity declines from 231 to 176 tonnes of carbon per million (1990) dollars, a reduction of 24%. The trend toward "decarbonization" of economic activities is a pervasive phenomenon for all regions: in the OECD the intensity reduction is 37%, in the reforming economies 41%, and in the developing countries 11%.

8.3 The Industrial Sector

8.3.1 Present Situation

In 1990, an estimated $6.7 trillion[2] value added was produced by some 500 million industrial employees worldwide. To generate this output, industry consumed about 3.1 TWyr of final energy (including biomass) and an equivalent of 0.6 TWyr of feedstocks. Current industrial carbon emissions due to burning of fossil fuels and cement manufacture amount to some 1200 million tonnes of carbon (Mt C). If carbon emissions from generating electricity and industrial heat are included, the total carbon emissions by industry amount to some estimated 2083 Mt C. Thus, industry accounts for about 40% of global final energy demand and, equally, of anthropogenic CO_2 emissions (excluding biotic sources).

Efficient efforts to minimize industrial carbon emissions must begin with the most carbon-intensive branches. Worldwide, iron and steel accounts for some 514 Mt C emissions (24.7% of total industrial carbon emissions), followed by cement with some 276 Mt C (13.3%), chemicals with 245 Mt C (11.8%) and non-ferrous metals (aluminum and copper) with at least 80 Mt C (3.7%). Including the paper and pulp (more than 60 Mt C) as well as glass (more than 18 Mt C) industries, these six branches account for more than 57% of industrial carbon emissions. A regional breakdown indicates that the market economies (OECD) contribute 37%, developing countries with 35%, and reforming economies with 28% to the total industrial carbon emissions.

8.3.2 Strategies to Reduce Carbon Emissions

The options for reductions in industrial energy and carbon intensity can be categorized as follows: (1) *structural changes* affecting the material intensity of industrial output ("dematerialization") and increased *materials recycling*; (2) *efficiency improvements* and industrial process changes, and (3) *fuel-mix* changes such as increased electrification.

(1) Dematerialization and Recycling

With the achievement of sufficiently high levels of per capita income, economies enter a phase of transition with regard to the requirements for basic materials. The initial process of industrialization is associated with a large increase in the consumption of basic materials, primarily for building up extensive industrial, transportation and urban infrastructures. Conversely, the post-industrial societies of the Northern Hemisphere have experienced per capita decreases in material consumption during the last decades, which is usually denoted as "dematerialization" (Herman *et al.*, 1989). As a result, the production of basic materials in industrialized countries is likely to be stagnant or even to decline in the future, whereas growth can be expected in developing economies.

Materials recycling is related to "dematerialization". The re-use of scrap metal, paper, glass, and plastics as well as composting of organic matter will increase further in the future because simple waste disposal and incineration are facing increasing constraints imposed by land availability, environmental regulation, and even social and cultural resistance.

At present, about 40% of steel, aluminum, or lead are produced from scrap worldwide. The scrap input for copper is estimated to be 15% or higher, whereas the global

---

[2] Throughout this chapter, all dollar values are 1990 dollars, unless stated otherwise.

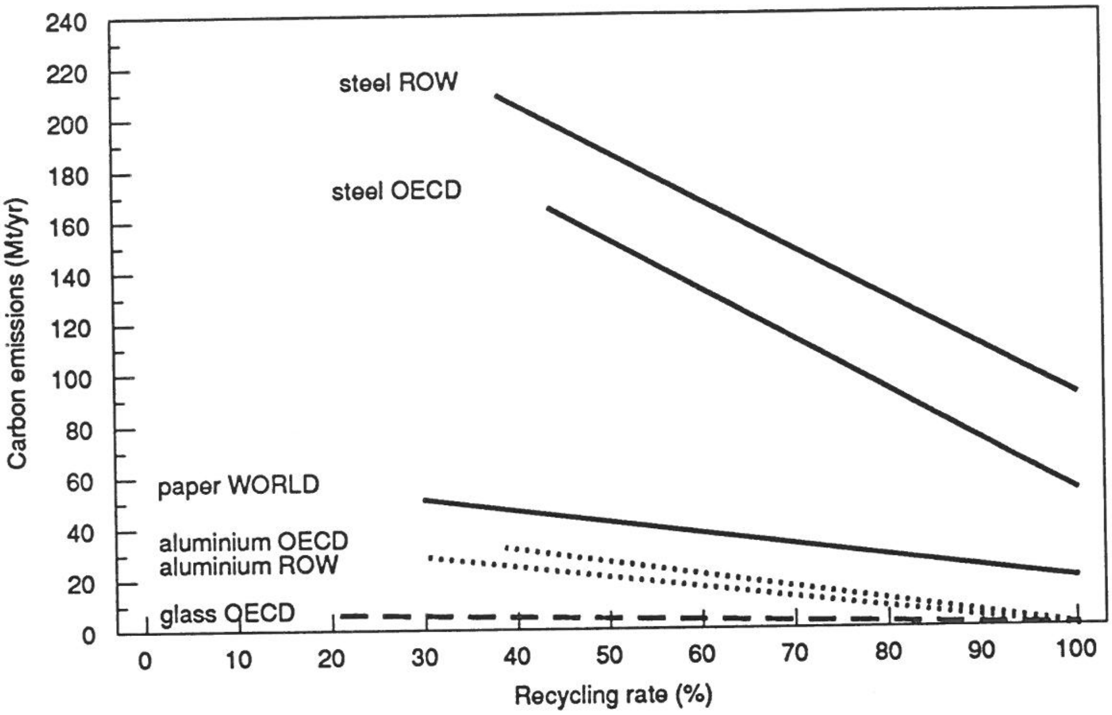


Figure 8-3. Carbon reduction potential of industry as a function of recycling rate for selected materials.

recycling rate for paper is around one-third of its production, a figure which is similar to the present recycling rate of glass bottles in OECD countries.

In the future, recycling could significantly reduce specific resource requirements and resulting carbon emissions as illustrated in Figure 8-3. The largest carbon reduction potential would be in enhanced recycling of iron and steel products in conjunction with energy-efficient electric arc furnaces. By increasing the recycling rate to some 70%, the steel industry could reduce its carbon emissions by about 110 Mt C, or by 24%. Increasing the recycling rate of aluminum, paper and glass to 70% each could reduce carbon emissions by some additional 50 Mt. Globally, an aggressive recycling strategy, e.g., to raise the recycling rate for the major energy and carbon-intensive products as high as 70% could reduce emissions by at least about 160 Mt C, or 8% of current total industrial emissions. However, future recycling rates are likely to differ significantly between countries.

(2) Efficiency Improvements and Industrial Process Changes

The history of technological change bears witness to the importance of process changes in industry that have sustained the growth of industry over the last two centuries, from the introduction of the Bessemer steel process or the Hall-Heroult process for aluminum production in the nineteenth century, to the multitude of process technologies introduced in the twentieth century for producing traditional commodities like steel or entirely new ones like plastics, man-made fertilizers, etc. Industrial process changes have helped, in particular: (1) to substitute new or more abundant raw material resources for dwindling supplies; (2) to improve the efficiency use of the factor inputs, particularly labor and energy; (3) to increase output; and (4) to develop entirely new materials with unprecedented quality characteristics and application possibilities.

A number of efficiency improvement measures aimed at reducing energy consumption in the iron and steel industry have been examined. Aggregated for the OECD region, continuous casting yields the highest energy savings potential per tonne of steel produced, followed by dry quenching of coke, hot direct rolling and sensible heat recovery at basic oxygen furnaces. Part of these measures have already been implemented and have contributed to the energy efficiency improvements of the steel industry in the OECD countries over the last two decades.

Ranked by their cost effectiveness[3] per tonne of carbon reduced, the measures analyzed could reduce carbon emissions in OECD steel industry by some 24 Mt or 14%, including 12% carbon emission reductions at negative or zero costs per tonne of carbon reduced. These negative costs are derived from a (hypothetical) comparison of an average OECD steel plant with its resulting economics with the individual efficiency measures outlined above. For instance, applying top-gas recovery turbines to blast furnaces throughout the EC, would annually cost about $60 million (1990 dollars), while the resulting energy savings are estimated to correspond to $220 million (Springmann, 1991), and annual carbon emission reductions of 0.6 Mt of carbon (hence a negative reduction cost per tonne of carbon reduced). Assuming full implementation worldwide, such measures could reduce carbon emissions in the reforming economies by some 60 Mt and in developing economies by some 16 Mt yielding a global total reduction potential of 100 Mt C, or 21% of the current carbon emissions from steel manufacturing.

In addition, energy consumption (and proportionally) carbon emissions in the steel industry *worldwide* could be reduced by about 3% (11 Mt C) if the least efficient steel production processes (open-hearth furnaces) were replaced by the average OECD basic oxygen furnace technology.

Figure 8-4 compares various steel production processes in terms of their specific energy requirements, carbon emissions, and costs. Several new process technologies offer possibilities for carbon emission reductions in steel manufacturing: direct smelting [e.g., prereduction with a coal-derived reduction gas; followed by a second stage in which sponge iron is melted down either with coal (the Corex process) or electricity (the Plasmamelt process)]; the use of electric arc furnaces in combination with direct reduction of iron ore (using, for example, the HYL III process, which is particularly interesting from a CO_2 perspective since it includes a CO_2 scrubber for hydrogen and CO recycling from the reduction gas); or the direct reduction with hydrogen followed by an electric arc furnace which can be a steel production technology with practically no carbon emissions provided both hydrogen and electricity are produced carbon-free.

Process technologies to reduce carbon emissions also exist in many other industrial sectors. Using the energy efficiency of the best plants as a guide, specific energy consumption for aluminium production in the EC could be reduced to some 47 GJ/ton (or by 36%) and for ammonia synthesis to some 28 GJ/ton (or by 22%) compared to the industry average (Worrell *et al.*, 1992). In the paper industry, a process change from thermal to mechanical dewatering in pulp mills would yield an estimated energy reduction of 0.07 kWyr (15%) per tonne of paper. In the cement manufacturing industry, the replacement of the wet by a dry process, in conjunction with precalcination and computer process control, could reduce energy requirements from 5.5 to less than 3 GJ (from 0.17 to 0.09 kWyr, respectively) per tonne of concrete, although this process change is very capital intensive (Figure 8-5b). As the CO_2 concentration in flue gases of cement

---

[3] Net costs: annualized (with 10% annuity) capital costs minus the cost of fuel saved.

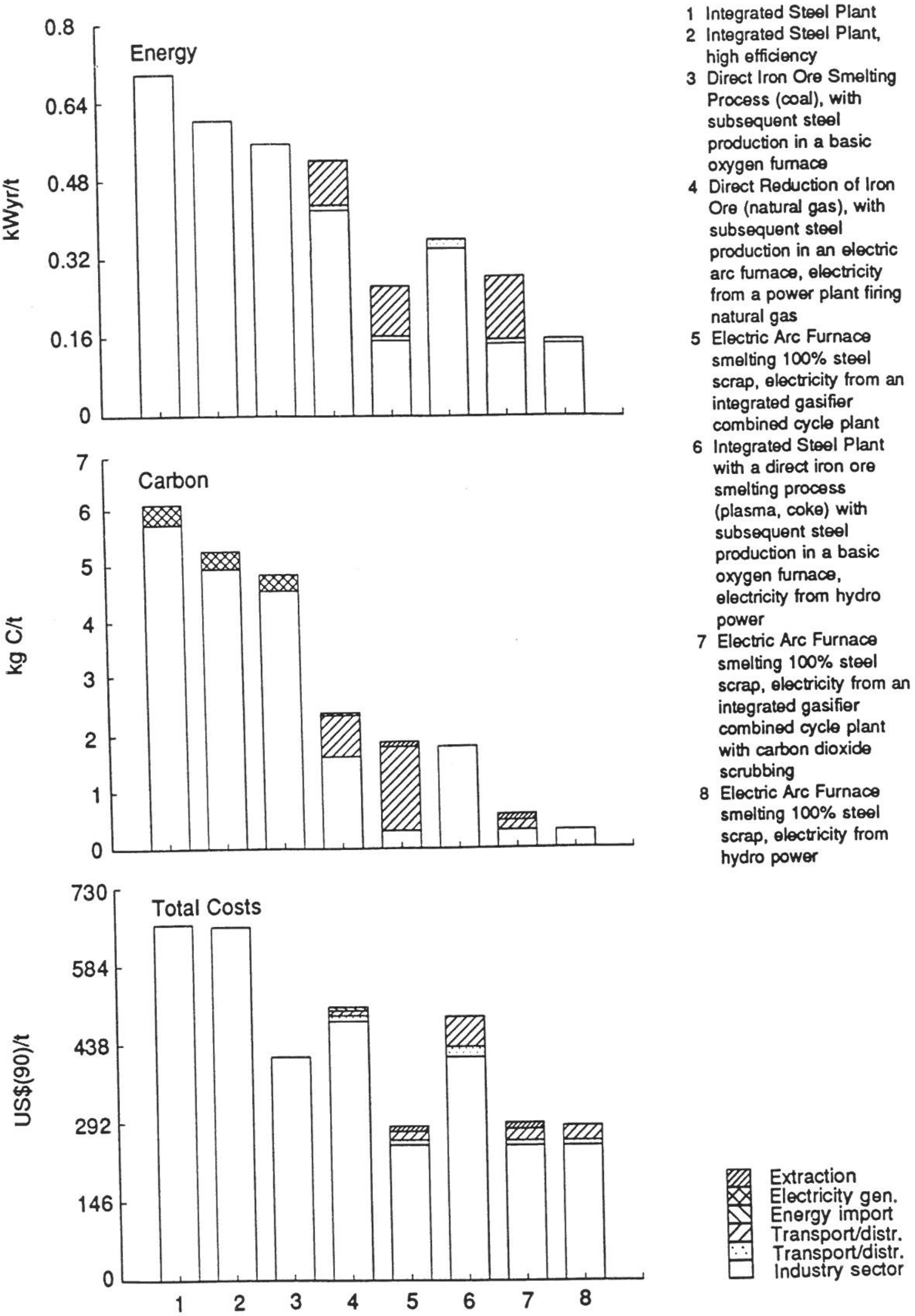


Figure 8-4. Steel production chains: energy consumption, carbon emissions, and costs of various production process routes.

plants reaches 30%, an alternative strategy might involve carbon scrubbing. Assuming a cost of $150 per tonne of carbon removed, this would correspond to an additional $50 per tonne of cement produced, nearly doubling current average cement production costs.

In addition to process technology changes, a number of more generic technology options exist to further improve industrial energy efficiency, including *waste heat recovery*, *cogeneration*, *optimized control* and *improvements of combustion*, and *efficiency improvements of electricity use*. Giovannini and Pain (1990) estimate potential savings from waste heat recovery of between 36 and 67% for the Netherlands, Germany and Japan, e.g., through heat exchangers or industrial cogeneration, or through heat upgrading with heat pumps. For industries with high demands for both steam and electricity, industrial cogeneration and *heat cascading* (e.g., via top and bottom-cycle cogeneration) appear promising. The OTA (1991b) estimates that industrial cogeneration could reduce industrial energy demand in the USA by as much as 140 GWyr by the year 2015. For low-temperature heat applications, *improved boiler efficiency* (e.g., fluidized bed boilers) and fuel substitution are possible CO_2 reduction options.

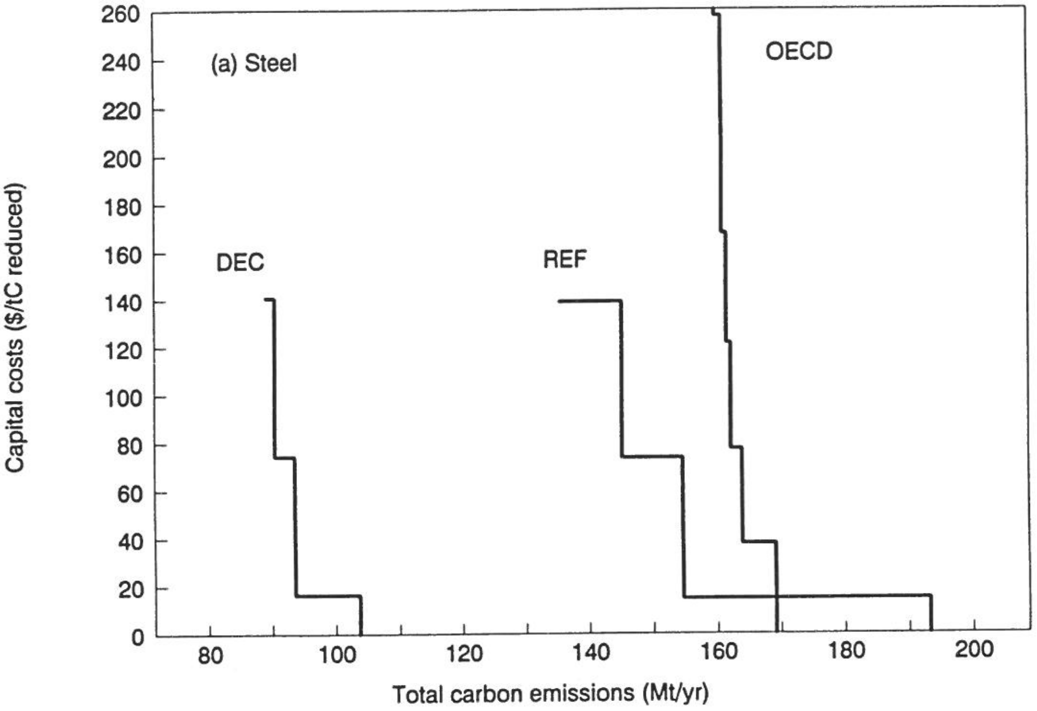
Improvements in electricity use via improved industrial drives or lighting could offer significant reduction potentials. Fisher (1990) estimates a global potential for industrial electricity reduction of 2–40% through replacement of industrial drives by the most efficient ones and the use of variable-speed drives, and a reduction potential of 60–80% through installing the most efficient lighting systems. EPRI (1990) has estimated a maximum technical potential for US industrial electricity reduction of close to 40% (compared to a "base case" in the year 2000). The electricity reduction potential in industrialized countries for high-efficiency adjustable speed drives is estimated to be around 30% (IEA, 1991). COSEPUP (1991) estimates for the USA, electricity savings through improved electric drives of 200 TWh would be at an average cost of about 2.6 cents/kWh (costs assume immediate replacement of existing units). Using an average carbon intensity of US electricity production of 0.18 kg C/kWh (Nishimura, 1991), this translates to specific carbon reduction costs of $144 per tonne of carbon.

Simpler measures to improve the efficiency of industrial motors particularly for developing countries include: proper sizing, phase balancing and high efficiency instead of standard motors. They are estimated to yield efficiency improvements of 15% or more at costs of 1–2 cents/kWh conserved (Sathaye and Gadgil, 1992). Based on the current carbon intensity of electricity production in developing countries, this translates into specific carbon avoidance costs of $60–120 per tonne of carbon.

A recent collaborative study of the Asian Energy Institute (AEI, 1991) concludes that for *developing countries* simple energy housekeeping measures offer the lowest specific carbon reduction costs in industry at investments costs of typically $10–20 per tonne of carbon. Considering fuel savings, the actual reduction costs per tonne of carbon would in fact be significantly lower.

(3) Fuel Mix Changes

Frequently, changes in fuel mix are tied intimately with changes in industrial process technologies and can significantly improve energy efficiency and help reduce adverse environmental impacts. For example, the introduction of modern steel process technologies in the nineteenth century was closely tied to the replacement of charcoal by bituminous coal as an energy source and reductant. Modern process technologies for flat glass production require continuous, clean and high-temperature heat sources usually supplied by



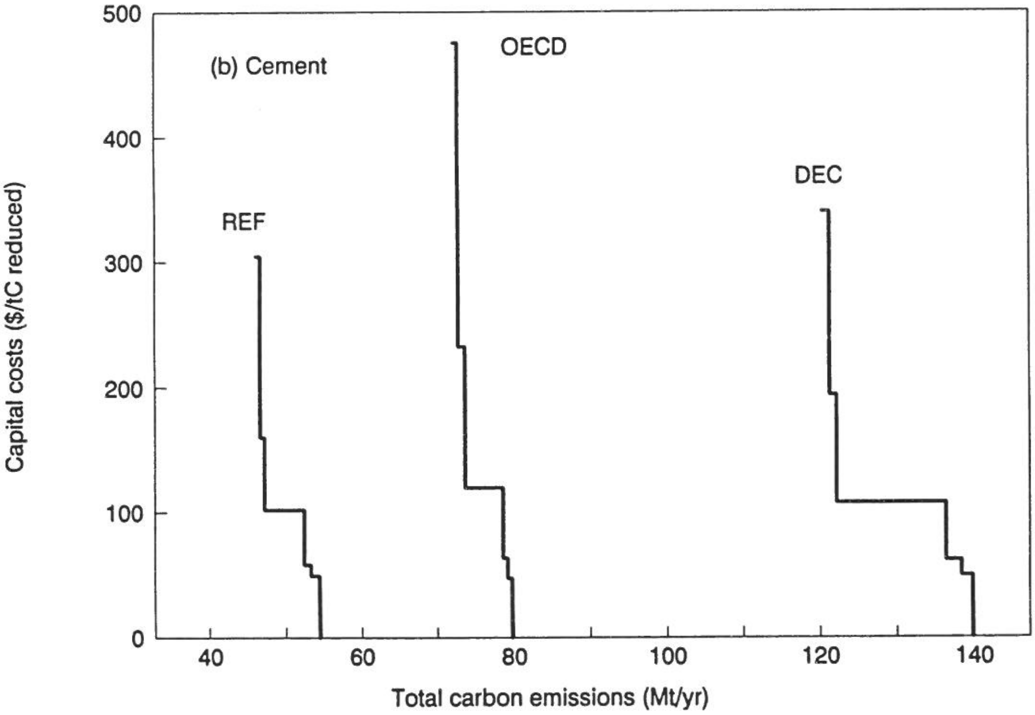


Figure 8-5. Capital costs (per ton of carbon reduced) for (a) steel and (b) cement process technology improvements for major world regions versus emission reduction potential.

natural gas or electricity. The trend toward increased recycling and remelting of metal scrap requires electric arc furnaces and further explains the increasing electrification trend in industry. For instance, Nakićenović (1990) examines the trends toward a higher share of crude steel production from electric arc furnaces and concludes that by the year 2020 electric arc furnaces could produce over half of global crude steel output.

Thus, from a longer-term perspective, industry will rely increasingly on higher-quality (denser and cleaner) energy carriers such as natural gas and electricity. Also in the wake of the post-1973 period, this fuel substitution trend toward gas and electricity has slowed down or was even partly reversed toward increasing uses of coal.

Combined Measures in the Steel Industry

The recycling of scrap, in combination with measures in the electricity generating sector, (such as the use of combined-cycle natural gas-fired power generation or even entirely carbon-free electricity supply from nuclear or hydro), currently appears to be the cheapest process change measure by which industry can reduce its carbon emissions (see Figure 8-6). Compared with the production economics of the average steel plant, electric arc furnaces could achieve carbon emission reductions combined with improved production economics which would imply negative carbon reduction costs of $250–540 per tonne of carbon. Conversely, direct smelting (e.g., via the Corex or Plasmamelt processes) could achieve carbon reductions at additional costs of $10–70 per tonne of steel[4], which translates into $140–370 per tonne of carbon reduced. The highest carbon reduction potential, however, also at the highest costs (in excess of $900 per tonne of carbon reduced), would be zero-carbon steel production via direct reduction with hydrogen in combination with an electric arc furnace. Overall, process technology change on the positive side of steel industry's carbon reduction curve all appear as high-cost carbon reduction strategies, primarily due to their high capital requirements.

Total Reduction Potential in Industry

Using the best available technologies (see Chapter 2), the utilization efficiency of final energy (useful/final energy efficiency) in industry could be raised to a level as high as 82%. In comparison, today's useful-to-final energy efficiency in the industry of *OECD region* is 67%, in reforming economies (due to the importance of cogeneration and some 290 GWyr of heat supplied directly to industry) 72%, whereas in developing economies it amounts only to approximately 47%. Achieving globally the 82% that is possible with best current technologies could reduce industrial final energy demand by some 790 GWyr, or 25% of 1990 consumption.

For the *reforming economies*, improvements in energy intensity in the short to medium term are likely to result primarily from decommissioning the oldest, most inefficient vintages. As a result, most scenarios assume significant reductions in the basic material intensity of these economies. For instance, for the former Soviet Union, Poland, and Hungary, Chandler (1990) projects decreases in cement, chemicals, and steel production ranging from 20 to 50% by the year 2025.

The situation in *developing countries* is different due to the expected increases in material requirements during the course of their economic development. Sathaye and

---

[4] Note that all comparisons refer to average steel production costs that include depreciated vintages, and/or in many countries significant subsidies. For new plants, direct smelting would be cheaper than a conventional steel plant.

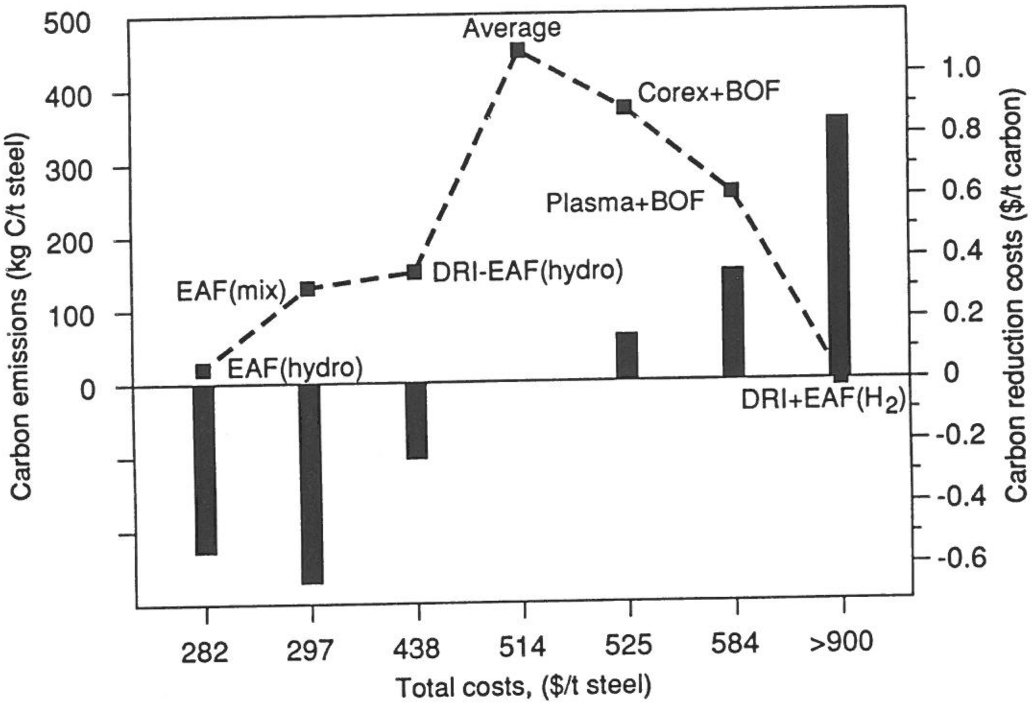


Figure 8-6. Summary of process technologies with carbon reductions in steel manufacture, carbon emissions and costs (line) versus specific carbon reduction costs (bars). For an explanation of abbreviations, see Figure 8-4.

Ketoff (1991) project the energy intensity of steel production in a number of developing and newly industrializing countries (Brazil, China, India, South Korea, and Venezuela) to decline by a rate of between 0.8 and 1.8% per year over several decades. Under such scenarios, the industrial energy intensity could be halved over the next 40 years, reducing energy demand growth for the projected increases in material consumption. Still, output growth is likely to outpace significantly the efficiency reduction potentials, implying absolute increases in industrial energy consumption and carbon emissions in developing countries.

8.3.3 Carbon Emission Reduction and Scenarios for 2020

In the absence of appropriate countermeasures, industrial energy use and carbon emissions will rise. The EPA's RCW (Rapidly Changing World) scenario (EPA, 1990) results in an industrial final energy use of 6.8 TWyr by the year 2020, which is in good agreement with the 6.3 TWyr of the ECS '92 scenario detailed in Table 8-3. However, industrial carbon releases would be different in the two scenarios. The EPA's RCW scenario, being more carbon intensive, projects industrial carbon emissions to grow at 3% per year, reaching about 5 Gt C by 2020. The ECS '92 scenario implies emissions of some 4 Gt C by the same year (corresponding to an average annual growth rate of 2.2%) due to a slightly lower energy demand and also because it relies less on coal for both direct industrial and power plant use.

Despite the considerable data uncertainties and methodological problems of cost comparisons, Table 8-3 provides a summary of industrial carbon emission reduction potentials. Disaggregated into three world regions, the emission reduction potentials are calculated for three cost categories including measures that (over the lifetime of the

Table 8-3. Regional potentials for reducing industrial carbon emissions by cost categories (in Mt carbon).

	Cost saving or at moderate cost		Cost (<100 $/t C)		Cost (>100 $/t C)		Sum[a]	
Market economies								
Efficiency improvement	15	116	45	47	84	207	144	370
Structural change/recycling	95		n.a.		25		120	
Fuel substitution	6		n.a.		n.a.		>>6	
Process technology change	0		2		98		100	
Reforming economies								
Efficiency improvement	48	233	53	113	n.a.	>46	>101	382
Structural change/recycling	165		50		n.a.		>215	
Fuel substitution	10		n.a.		n.a.		>>10	
Process technology change	0		10		46		56	
Developing countries								
Efficiency improvement	12	34	41	78	n.a.	>56	>53	168
Structural change/recycling	19		29		n.a.		>48	
Fuel substitution	3		n.a.		n.a.		>>3	
Process technology change	0		8		56		64	
World								
Efficiency improvement	75	272	139	238	84	309	>298	920
Structural change/recycling	279		>79		>25		>383	
Fuel substitution	19		n.a.		n.a.		>>19	
Process technology change	0		20		200		220	

[a] Total reduction potential could be higher because not all measures have been assessed.

n.a. = Not assessed.

investment[5]) would either yield cost savings or reduce carbon emissions at low costs; measures estimated to reduce industrial carbon emissions at positive costs of less than \$100 per tonne of carbon; and measures that would cost more than \$100 per tonne of carbon. The latter category mainly comprises investment-intensive industrial reconstruction and process change measures which can in individual cases amount to figures as high as \$1000 per tonne of carbon.

Overall, the potential for reducing industrial carbon emissions appears to be large. Our estimates indicate a potential of 920 Mt C, i.e., a reduction of about 44% of the current emissions of 2083 Mt C. About 370 Mt C of this potential is estimated to yield either cost savings or be achievable at modest costs. The greatest opportunities for such measures exist in reforming economies, but the reduction potential in market economies is also substantial. The potential of cost-saving carbon reduction measures in developing economies appears to be more limited due to severe capital constraints.

At costs of up to \$100 per tonne of carbon, a conservative estimate indicates that an additional 240 Mt C could be reduced, yielding a total reduction potential of some 610 Mt C, or close to 30% of all industrial carbon emissions. These potentials exclude much of the potential for fuel switching (e.g., from coal to natural gas) and for decarbonizing the electricity supply because only detailed modeling exercises can assure consistency and avoid double counting of fuel substitution potentials between different sectors.

At yet higher reduction costs, a further carbon reduction potential of about 300 Mt C has been identified. This potential has to be considered as conservative because the full range of possible measures could not be investigated. Also at costs exceeding \$100 per tonne of carbon, a number of (expensive) carbon reduction "backstop" technologies (such as carbon scrubbers) would become available which would mean that emissions could theoretically be reduced close to zero.

In terms of reduction potentials per policy measure, energy efficiency improvements (about 300 Mt carbon reduction) and structural changes in industry combined with enhanced recycling (about 400 Mt C) offer the largest potential. Process technology changes could also significantly reduce industrial carbon emissions (220 Mt C), although these are generally high-cost reduction measures.

The above potentials can be compared with the results of a recent study on industrial carbon emission reduction potentials from Japan. Based on the detailed technology assessment of Kaya *et al.* (1991), Matsuo (1991) reports an estimated industrial carbon reduction potential of some 730 Mt worldwide if Japanese industrial efficiency levels were to diffuse globally. This is a similar order of magnitude to the estimated potential presented above, although differences in regional and sectorial reduction potentials remain. The Japanese study indicates that the largest carbon reduction potentials could be realized in the steel, chemical and cement industries with 260, 200 and 140 Mt, respectively. If these efficiency improvement measures were to be implemented in the reforming and developing economies, the total investment requirements would be 35–114 trillion Yen[6] (\$263–857 billion), yielding carbon reductions of 180 and 320 Mt, respectively. Using again an annuity factor of 10%, these investment requirements translate into estimated specific carbon reduction costs of \$10–30 per tonne in reforming economies and \$30–100 per tonne of carbon in developing economies.

---

[5] We have assumed an annuity rate of 10% throughout our calculations.

[6] The range of this estimate is derived from different methodologies used to calculate costs, i.e., a bottom-up versus a macroeconomic top-down approach, with the latter yielding higher cost estimates.

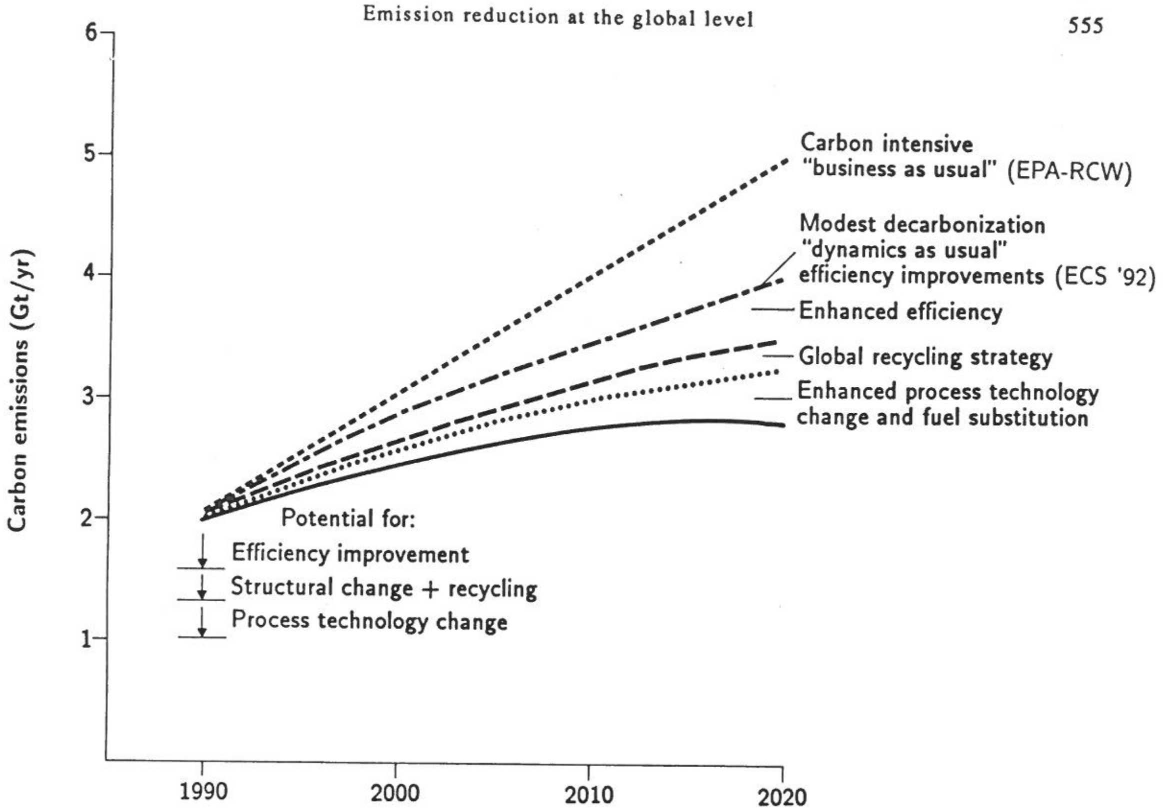


Figure 8-7. Scenarios for industrial carbon emissions, 1990–2020, in Gt C. Note that the reduction scenarios exclude aggressive fuel switching and energy decarbonization. Reduction scenarios assume that current cost saving or moderate cost measures are implemented by 2020, and other measures are applicable proportionally.

Figure 8-7 compares scenarios of industrial carbon emissions by the year 2020. The EPA's RCW scenario is considered as the typical "business-as-usual" scenario without any measures to minimize or to reduce carbon emissions. In fact, the fuel mix becomes more carbon intensive in this scenario. Global industrial carbon emissions would rise to close to 5 Gt C. Conversely, the ECS '92 scenario is considered as a "dynamics-as-usual" scenario projecting historical trends in energy efficiency improvements and in decarbonization of energy systems in the future. As such it can be considered as a "no-regrets" policy scenario that does not introduce any massive effort to limit carbon emissions that are projected to increase to some 4 Gt C by the year 2020.

In a further reduction scenario, we assume that by the year 2020 the cost saving or modest carbon reduction cost measures in industry have already been implemented (reflected, e.g., in the ECS '92 scenario) and that the further carbon reduction potentials identified above (Table 8-3) could be implemented proportionally. In such a scenario, industrial carbon emissions would still rise but to a level below 3 Gt C. This would indeed be a formidable achievement considering that the world GNP in the ECS '92 scenario approximately doubles by the year 2020. The industrial carbon intensity (per GNP) of such a scenario would decline at a rate of 1.2% per annum, indicating that such a scenario would be consistent with historical experience in energy efficiency improvements and industrial restructuring. Further reductions are possible with aggressive structural shifts in the energy supply balance, e.g., toward natural gas, or carbon-free electricity (nuclear or solar). Even further reductions are feasible from a technological viewpoint (see Chapters 4, 5, and above), especially in combination with carbon-free energy vectors such as hydrogen.

8.4 The Transportation Sector

8.4.1 Present Situation

Estimates for global demands in this sector suggest that about 20 trillion passenger-km and about the same number of tonne-km are transported. The transportation sector currently accounts for approximately 22% of global final energy consumption and emits more than 1 Gt of carbon annually.

Carbon emissions in the transportation sector are dominated by the Northern countries with their high levels of private mobility and material consumption (i.e., goods transport requirements). About two-thirds of transport carbon emissions originate in the OECD region. By far the largest single source of carbon emissions is the worldwide fleet of over 400 million passenger cars, emitting approximately 0.5 Gt of carbon (1988 data).

8.4.2 Measures to Reduce Carbon Emissions

Strategies for reducing transport energy demand (or at least to reduce its growth) and its concomittant carbon emissions are manifold. Here, we examine the following classes of policy options: (1) *Improving energy efficiency*; (2) *modal split changes* (i.e., changing the shares of transport volume carried by different transport modes and technologies); (3) *behavioral change* leading either to modal split changes or to changing usage characteristics such as increased load factors; and (4) *technological change.*

Efficiency Improvements

The specific fuel consumption of the average US automobile fell from some 18.1 liters/100 km in 1973 to 10.8 liters/100 km in 1988. The average fuel consumption of new vehicles dropped from 16.5 to 8.2 liters/100 km in the USA and from 8.4 to 6.8 liters/100 km in Italy over the period 1973–1988 (all data from IEA, 1991). Despite the fact that specific fuel consumption dropped significantly, transport energy demand in the OECD countries rose by some 470 GWyr or at a rate of 2.5% per year.

Fuel efficiency in developing countries is characterized by much slower rates of fleet turnover, resulting in a higher average age of vehicles, which are often imported from industrialized countries and which also tend to be poorly maintained. All this leads to higher specific fuel consumption. Based on IRF (1990) data, the estimates indicate specific fuel consumption outside the OECD region of close to 14 liters/100 km (less than 17 mpg), i.e., nearly 30% higher than the OECD average. Fuel consumption differences for trucks are likely to be even higher.

Overall, prevailing fuel efficiencies between countries and applications vary widely indicating a large (theoretical) improvement potential by the introduction of best-practice technology. This improvement potential has, however, to be contrasted with rapid demand growth. For instance, transportation energy demand in developing countries rose between 1971 and 1989 at a rate of 4.8% per year (or from some 170 GWyr to close to 400 GWyr). Growth rates in reforming economies have been smaller, but still running at 2.6% per year.

Today, the most fuel-efficient car available on the market is about twice as fuel efficient as the current fleet average. Models such as the Daihatsu Charade, Subaru Justy, or GM Chevette (diesel) have an average fuel consumption of less than 5 liters/100 vehicle-km (47 mpg). Experimental vehicles combining all technical and design features can achieve specific fuel consumptions below 3 liters/100 vehicle-km, as exemplified by the Volkswagen E-80, the Toyota AXV, or the Renault Vesta2. This represents an improvement over current fleet averages of between a factor of three to four.

For buses and trucks, the best current designs such as the Neoplan composite-materials bus or the new Saab-Scania turbo-compound diesel offer efficiency improvements of up to 40% over the current European fleet average.

Measures to increase system efficiency also include the improvement of traffic flow, e.g., through electronic signaling systems, and increases in the capacity factor, particularly of private cars (see also the discussion of behavioral changes below).

The costs of achieving fuel efficiency improvements are difficult to determine. US cost estimates for additional purchase costs to the consumer range from \$60–130 per car (EPA, 1990) to \$500–750 per car (OTA, 1991b) for a vehicle about twice as efficient as the current U.S. average (55 versus 27 mpg, or 4.3 and 8.7 liters/100 km, respectively). The resulting fuel savings (based on an annual average of 10,000 miles driven) total about 180 gallons or around \$200 per year (at current US fuel prices). Using an annuity factor of 20%, fuel savings imply a break-even point of additional costs of some \$1000 for an energy-efficient car. From such a perspective, the fuel efficiency improvements in passenger cars constitute an attractive cost-saving option to reduce CO_2 emissions.

Estimates of reduction potentials and costs of CO_2 emissions in the transportation sector from a few representative studies (AEI, 1991; COSEPUP, 1991; Springmann, 1991) indicate that current carbon emissions in the transportation sector could be reduced by about one-third. It was to some extent surprising to find this as a recurring reduction potential in such diverse countries as the USA, member states of the EC, Brazil, and India. Conversely, the cost estimates of this carbon reduction vary significantly. Estimates of carbon reductions achievable at negative or zero specific reduction costs range from 15% (Brazil), 18% (EC) to 21% (USA[7]). If these figures are representative, transport carbon emissions worldwide could be reduced by up to 400 Mt C (about 300 Mt C in OECD countries), including about 250 Mt C (150 Mt C in OECD countries) perhaps at negative or zero specific carbon reduction costs.

Most of the measures analyzed in the national studies discussed above focus on fuel efficiency measures. Investments in the improvement of infrastructures to increase energy efficiency appear costly as a carbon reduction strategy (more than \$1000 per tonne of carbon), but the main benefit (and rationale) of such investments is in fact not so much in reducing emissions but in improving the quality of transportation services.

On the demand side, the Mitigation Panel (COSEPUP, 1991) estimates that a doubling of gasoline prices would induce consumers to prefer cars that are between 12 and 15% more energy efficient. The commercial transportation sector is expected to be more sensitive to such price signals. Still, even there, long-run elasticities are not dramatic. Kaya *et al.* (1991) estimate that the energy consumption of trucks in Japan could be expected to drop by only about 13% if fuel prices were to be increased by 50%.

It thus appears that price signals – especially in a politically acceptable range – will not lead to dramatic reductions in transportation fuel demands. This points to the need to investigate regulatory approaches such as mandatory efficiency standards and consumer information programs to realize more fully the CO_2 reduction potential of fuel efficiency improvements.

---

[7] Estimate of Ledbetter and Ross (1989) and based on an annual discount rate of 30%.

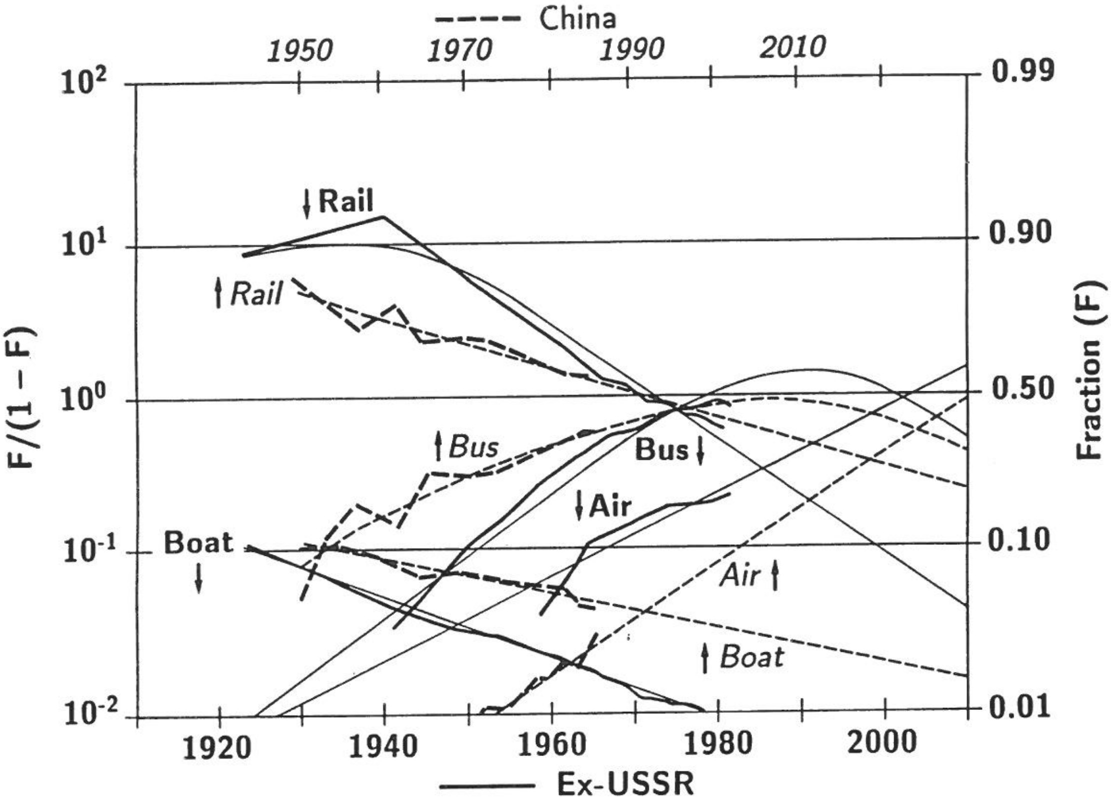


Figure 8-8. Modal split between long-distance passenger transportation systems in the former Soviet Union and China (shifted time axes), in fractional share of passenger-km.

Modal Split Changes

Modal split changes, i.e., shifts in the relative shares between different transportation modes, hold important implications for CO_2 emissions, in both the positive and negative directions due to the different energy (and carbon) intensity of various transportation modes for both passenger and freight. However, the substitutability between different transport modes is limited by different performance and quality requirements, relative economics, accessibility to infrastructures, and consumer preferences.

In industrialized countries, passenger transportation – especially over longer distances – is dominated by the most carbon-intensive systems such as cars and aircraft. Typically, well over 90% of intercity passenger transportation relies on these technologies. This pattern is often expected to be approached in the reforming and developing economies. However, a quantitative analysis reveals a somewhat different picture. Although road transport is similarly important there, it is based on public systems of buses and taxis rather than on individual vehicles.

An analysis of the dynamics of the modal split between long-distance passenger transportation systems in the former Soviet Union and China (Figure 8-8) indicates similar dynamics (although lagged by 20 years): the modal split changes progressively from rail to road transportation (buses), with air transportation expanding vigorously. From such a perspective, it appears unlikely in the foreseeable future that the long-distance transportation systems of these countries will be based on private automobiles as in the industrialized countries.

The picture is less comforting for local and short-distance travel. Urban transport around the globe relies heavily on private cars. In the 1980s, more than 4 million passenger cars were registered in the metropolitan area of Los Angeles, nearly 3 million in São Paulo, and close to 2 million in Mexico City (IEM, 1988). The resulting density of vehicular traffic and air pollution makes it difficult to imagine that such numbers could even grow much further, although such developments cannot be ruled out completely either.

Modal split changes can also affect the energy and carbon intensity of goods transport. Typically, pipelines require the lowest energy input per tonne-km transported, followed by water and rail. Conversely, the transportation of freight by road, and especially by air, can be more energy intensive than by rail, by a factor of 3 to 90, respectively. As a rule of thumb, low energy intensive transport modes also transport low-value goods. As the structure of economic activities in industrialized countries changes in the direction of higher value added, however, low energy intensity per tonne or tonne-km may not be the most important criteria for comparing different transport modes and ultimate desirability of modal split changes.

Behavioral Change

Behavioral change is an important factor in modal split changes, and is discussed separately here. Related changes in human behavior and preferences have profound repercussions on the spatial and temporal activity patterns of people. A similar statement can be made about the spatial organization of exchanges of goods among firms. In a non-monetary sense, behavioral changes must therefore be considered as rather costly.

Behavior not only influences *what* transport modes are chosen, but also *how* they are used (usage efficiency). *Usage efficiency* comprises many components ranging from traffic flow (congestion), driving modes and styles and, most importantly, to load factors. Automobile occupancy rates for US commuters are estimated not to exceed 1.15 persons per car (COSEPUP, 1991). The average in the city of Denver is 1.2, and even in densely populated Tokyo, car occupancy is low (1.4 persons/car).[8] Conversely, in cities such as London, Copenhagen, or Sydney, car occupancy is about 40% higher (above 1.7 persons/car) which means less energy use and emissions per passenger-km driven. But public transportation modes, which have to provide sufficient capacity even during rush hours, also illustrate the low usage efficiency of transport systems.

Usage efficiency is perhaps the least understood factor that could improve the (carbon) efficiency of transportation systems. Improving usage efficiency not only relies on changes in social behavior and trip organization (such as car pooling or car sharing), but also on public policy incentives, such as the provision of special driving lanes or toll reductions for car pools (as practiced in some US cities), or parking fees or city entrance fees (introduced in some European and Asian cities).

Technological Change

Supply-side technological options for reducing carbon emissions in the transportation sector include both incremental and radical changes. Incremental changes involve fuel switching in private cars as well as in public transportation systems such as railways

---

[8] Data from Newman and Kenworthy (1989).

(replacement of coal-fired steam locomotives by higher-efficiency diesel and/or electric-powered locomotives, or the replacement of diesel locomotives by electric ones).

More radical technological changes involve the introduction of new vehicle propulsion systems such as the replacement of internal combustion engines by electric motors or fuel cells and accompanying changes in vehicle design. Furthermore, entirely new infrastructure systems such as magnetic levitation trains (Maglevs) are under active development in a number of countries. These technological options offer the possibility of drastically reducing carbon emissions or even achieving zero-carbon emissions.

In Figure 8-9, a comparison of different technological options for reducing carbon emissions by passenger cars shows two categories of measures. The use of diesel and methanol fuels could reduce carbon emissions by about 20%, compressed natural gas (CNG) vehicles up to 30%. The specific carbon reduction costs[9] of diesel and methanol are slightly positive, whereas for CNG vehicles – due to fuel efficiency improvements and generally lower fuel costs – overall vehicle operating costs are lower, hence imply savings (negative carbon reduction costs). Other incremental technological change would include ethanol admixture or ethanol-fueled cars based on the successful Brazilian example. Such measures would entail additional costs, but these appear to be modest (+5%), and are subject to the inevitable uncertainty range of such cost estimates.

More revolutionary technological change would be represented by massive introduction of a new generation of electric vehicles which, due to the high end-use efficiency of electric cars, would yield lower overall carbon emissions even if electricity were to be produced in oil-fired power plants. Another alternative are hydrogen fuel cell powered cars. However, the hydrogen options have specific carbon reduction costs in excess of $2000 per tonne of carbon, which makes them high-cost carbon reduction strategies indeed.

Figure 8-10 summarizes the technological options available in the passenger transportation sector with respect to their energy and carbon intensity.[10] Only hydrogen fueled vehicles would result in zero carbon emissions provided hydrogen is produced not involving fossil fuels. Figure 8-10 also indicates the relative scope of efficiency improvements [see the example of a steam locomotive in 1855, 1955, and modern (coal-based) electric intercity train] and fuel substitution (coal- versus gas-electric intercity train, or gasoline versus CNG car). Per unit of energy service delivered (passenger-km) the relative rankings of transport modes can, however, vary due to differences in load factors. The latter is highest for aircraft (60 to 60%) and lowest for private cars and public mass transit systems (as low as 20 to 25%), however with large regional variations.

In any comparison of various transportation technology chains (Figure 8-11), it must be borne in mind that there is only a limited degree of substitutability between different transportation technologies. In addition, a comparison should not only consider technical and economic characteristics of various transport modes but also their different quality characteristics and usage patterns.

In the case of reducing carbon emissions from private car usage, CNG vehicles appear to be the cheapest (and, due to lower operating costs, a negative-cost) option (Figure

---

[9] Note that the technology specific costs in Figure 8-9 only refer to those cost components that are sensitive to changes between various technologies. These cost components should thus be representative across all regions. Other cost items (e.g., car body, additional accessories) are *excluded*. The difference to the total costs per vehicle-km can be substantial. For instance, our reference gasoline car has estimated (variable) component costs of 7.7 cents/vehicle-km. Total operating costs for a car in the USA in 1989 totaled 20 cents/vehicle-km (US DOC, 1991). Note also that the subsequent comparisons of various transport modes are expressed per seat-km rather than the vehicle-km costs discussed here.

[10] For reasons of comparability, data are expressed per seat-km.

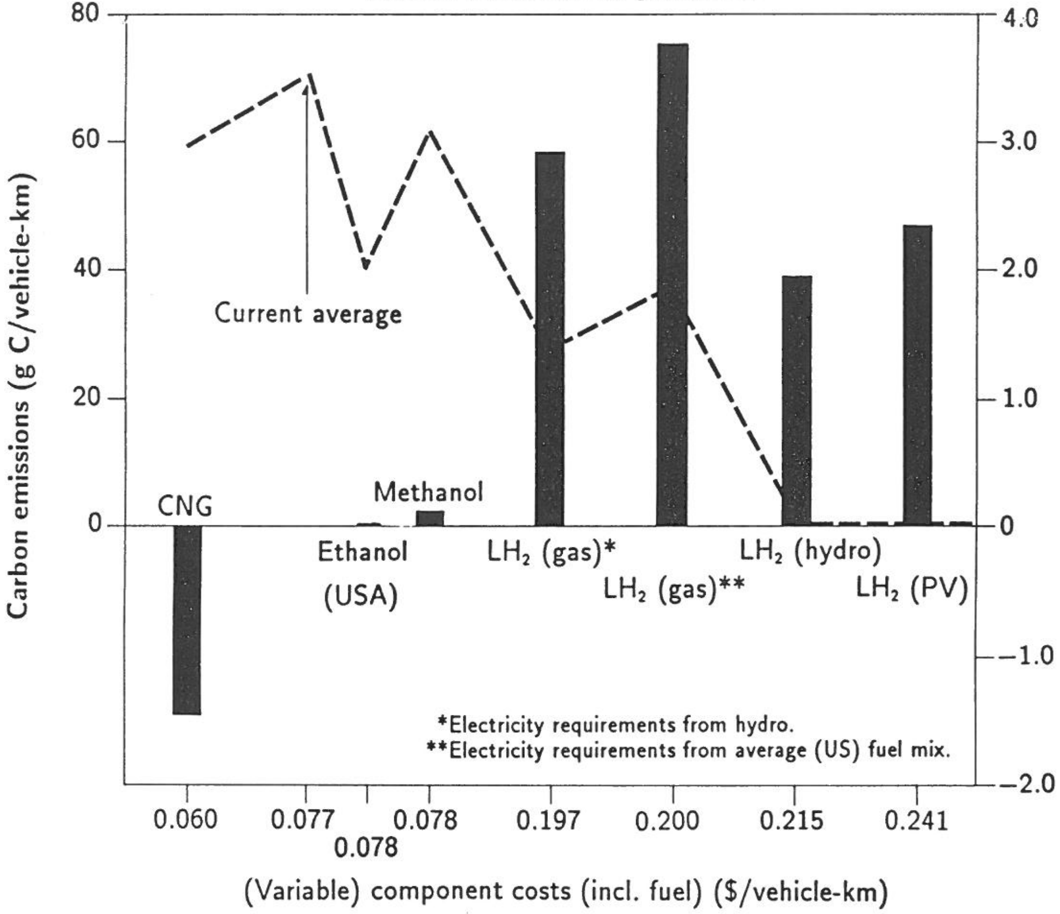


Figure 8-9. Carbon emissions (line) versus carbon reduction costs (bars) of various technological changes to passenger cars.

8-11). However, additional infrastructure costs for the distribution of CNG could not be estimated. Therefore, the attractiveness of the CNG option will vary according to specific national/regional contexts, requiring detailed further analysis. Ultimately, only electric- and hydrogen-fueled vehicles could reduce carbon emissions toward zero, but the carbon reduction costs of such options would be high: in excess of $1000 per tonne carbon reduced.

Total Reduction Potential in Transport

Although the efficiency of technological devices in the OECD is much higher than in reforming economies and developing countries, high mobility, the structure of its modal split and low *usage efficiency* result in the dominance of the OECD countries (currently over 700 Mt C) in global transport sector carbon emissions. Consequently, it is also the region with the highest absolute (and relative) reduction potentials. Estimates indicate that as much as 200 Mt carbon could be reduced by efficiency improvement measures in the current generation of passenger cars and trucks, combined with (modest) behavioral and modal split changes. Conversely, the reduction potential in reforming and developing economies appears limited (less than 80 Mt C from a total of 380 Mt C current emissions).

At carbon reduction costs of less than $100 per tonne of carbon, alternative transport fuels such as CNG, methanol or ethanol could reduce annual global carbon emissions – particularly in market economies and reforming economies – by some 140 Mt C. In developing countries, upgrades of public transport infrastructures, even improvements of

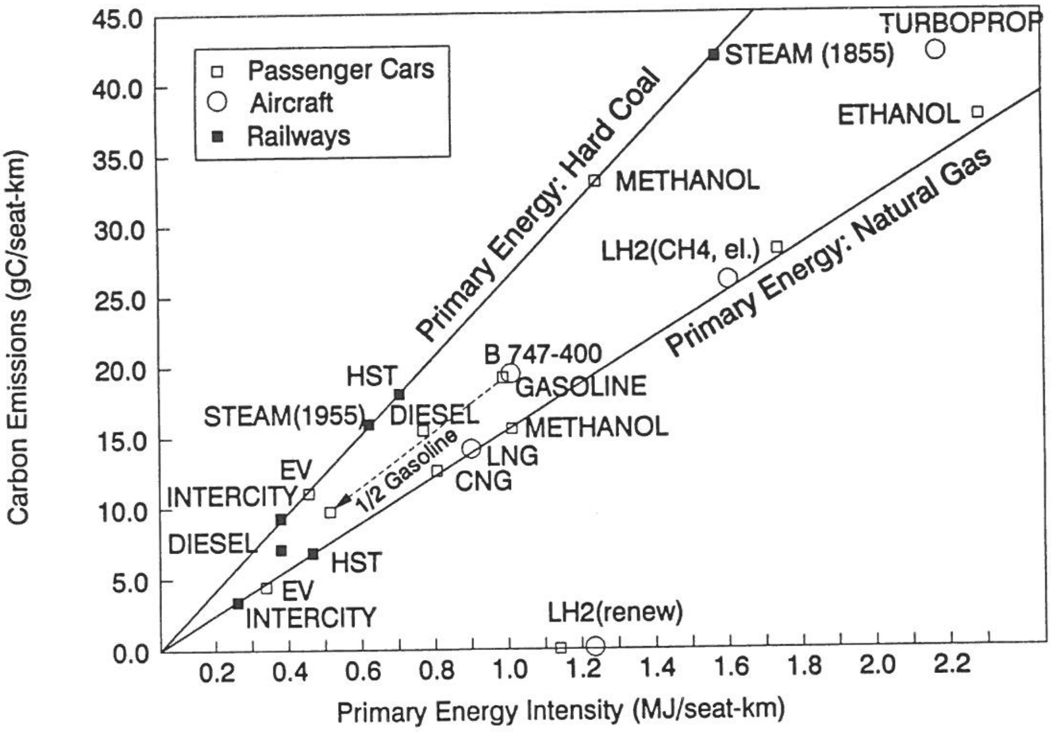


Figure 8-10. Energy and carbon intensity of various passenger transportation technology chains (Source: Schäfer, 1992).

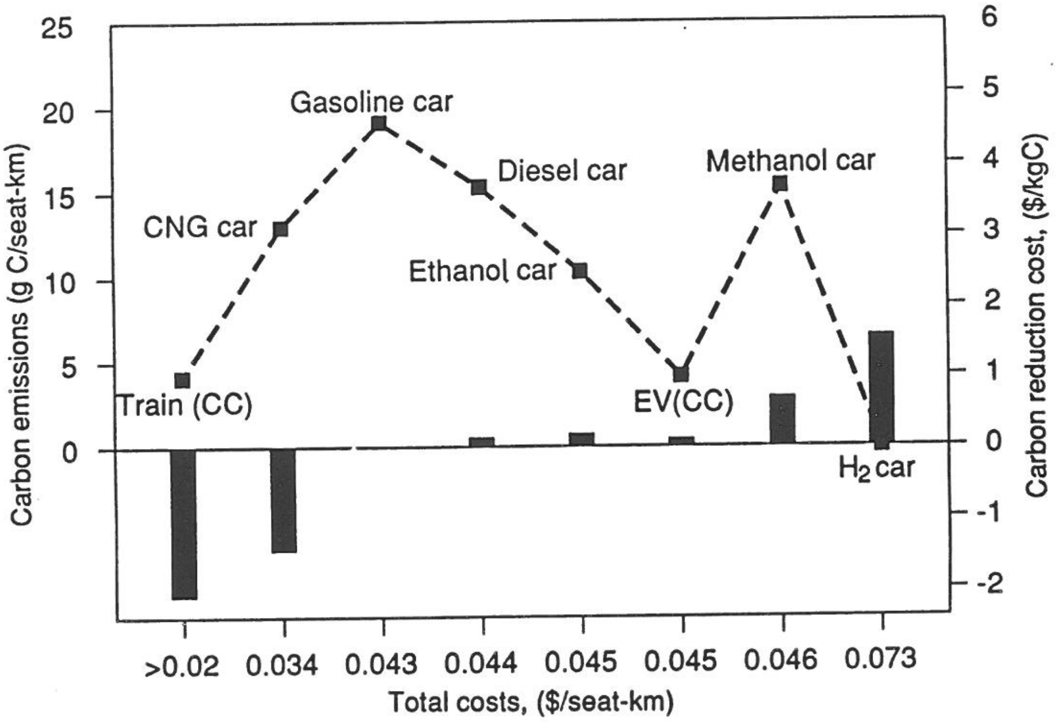


Figure 8-11. Carbon emissions (line) versus carbon reduction costs (bars) of transportation technologies, compared with a gasoline-fueled automobile.

the road network (AEI, 1991) could improve energy efficiency and stimulate some modal split changes, perhaps leading to another reduction of 30 Mt C annually. Above $100 per tonne of carbon, the technological reduction options begin to increase significantly. Further fuel substitution in the goods transport sector (e.g., replacement of steam locomotives in developing countries which is estimated to reduce annual carbon emissions by an additional 16 Mt C), the introduction of electric vehicles in the OECD region (−160 Mt C), combined with further drastic behavioral changes and shifts in the modal split (−70 Mt C), particularly over longer distances, could reduce transport carbon emissions globally to about 25% of current levels. The latter could be reduced further by a number of zero-carbon "backstop" technologies and new electricity- or hydrogen-based transportation infrastructures. However, their development and introduction will take considerable time. In the meantime, measures such as efficiency improvements, urban planning, and policies geared to stimulate behavioral changes will have to provide for the bulk of emission reductions, if the reduction potentials outlined above are indeed to be realized.

8.4.3 Carbon Emission Scenarios in the Year 2020

Representative scenarios (e.g. EPA, 1990, or the ECS '92 scenario developed for this study) indicate that the global energy demand for transport could grow at rates of between 1.3% (ECS '92 scenario) and 1.9% (EPA) annually. Regional differences, especially with respect to further growth potentials of passenger car travel in industrialized countries persist, with the EPA scenario projecting particularly vigorous growth from the already high car density levels in the OECD region. In addition, the EPA scenario relies on significant amounts of synthetic liquids produced from coal, which would further increase CO_2 emissions, doubling current levels.

In the following, we illustrate a range of carbon emission scenarios for the passenger transport sector (Figure 8-12). We concentrate on passenger transport operations since it is by itself a large contributor to carbon emissions, and also because it is perhaps the energy end-use sector that is most resistant to conventional policy interventions such as changes in relative price structure. Therefore, also alternative scenarios contrasting a more or less linear extrapolation of past trends appear interesting.

The continuation of past trends, as exemplified in the EPA's RCW scenario,[11] would lead to a further growth in carbon emissions, eventually doubling present levels to well over 1 Gt C by 2020. Using a different scenario philosophy – in particular, rates of efficiency improvements consistent with long-term historical experience and a more comfortable resource availability situation requiring no massive introduction of synthetic liquid fuels – the ECS '92 scenario projects increased passenger transport energy requirements and carbon emissions by about one-third, from some 630 Mt C currently to over 830 Mt C by the year 2020.

The third scenario takes a different methodological approach altogether (see Grübler and Nakićenović, 1991b; Grübler *et al.*, 1992). It is based on diffusion theory and, from a theoretical perspective, suggests that not only the current but also future diffusion levels of technologies differ widely between countries. These variations are the result

---

[11] A disaggregation into passenger and goods transport energy consumption and carbon emissions is not available for this scenario, so we assume a similar distribution as in the ECS '92 scenario (half of transport energy demand by 2020 for passenger transport).

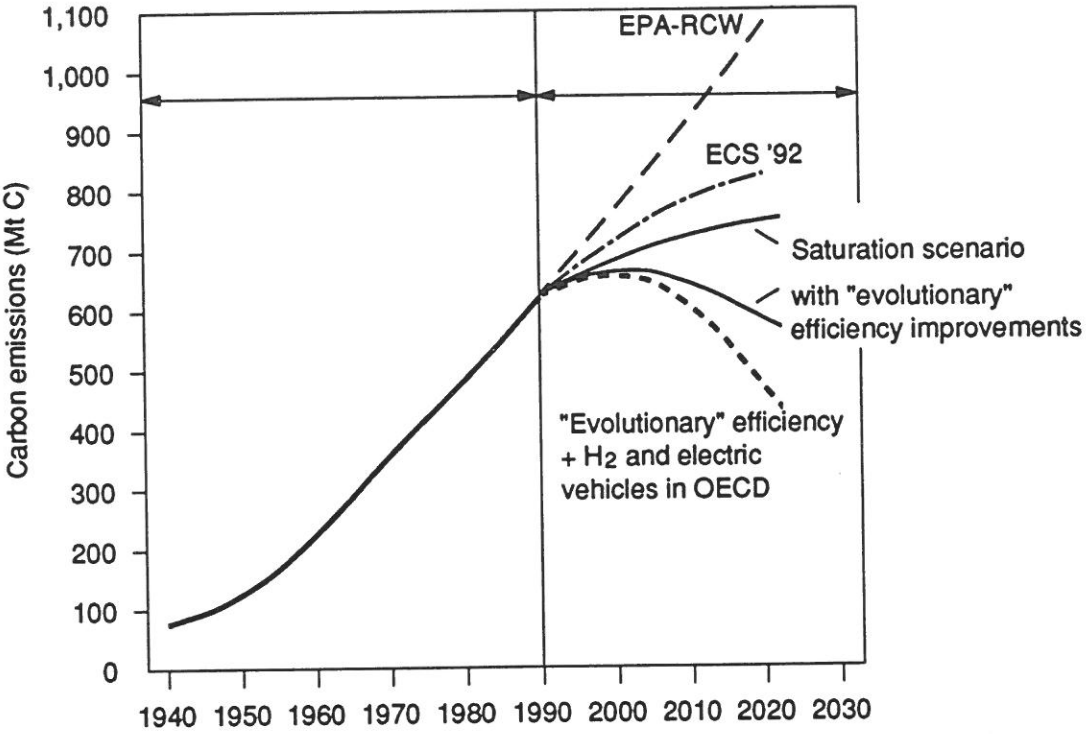


Figure 8-12. Scenarios for carbon emissions from passenger transport, in million tonnes of carbon.

of differences in initial conditions, degrees of economic development, spatial structures, and also the time available to develop particular technological systems.

In short, the scenario does not rely on motorization trends of the industrialized countries as a guide to what might occur in the developing regions. Instead, the rationale for the relatively low global levels of automobile adoption in this alternative "saturation scenario" is based on the possible saturation of automobile densities in urban areas, an increase in the use of air transport for longer journeys, the availability of new high-speed ground transportation systems, and perhaps also the increasing environmental problems associated with the further expansion of automobiles. Combining the "saturation scenario" with a continuation of historical rates of efficiency improvements would result in passenger transport carbon emissions leveling off below 700 Mt of carbon after the year 2000. Thereafter, with continuing efficiency improvements, or even with the vigorous introduction of carbon-free transportation technologies in the OECD region, emissions could even decline, perhaps to 400 Mt C by the year 2020 (Grübler *et al.*, 1992).

These illustrative cases indicate that scenarios based on diffusion theory and dynamics of technological change result in future development of individual transport with lower energy requirements and emissions. Increasing awareness of the negative social and environmental externalities associated with further intensification of the dominant technological regime start to block further adoption. At the same time, incremental technological change concentrates on improving the performance of existing technologies via efficiency improvements and environmental "add-on" technologies. Should such tendencies indeed materialize within the next decades they could provide an opportunity window, not only for slowing carbon emission growth but also for introducing more advanced and productive transport modes, eventually with no carbon emissions at all.

8.5 The Households and Services Sector

8.5.1 Present Situation

In 1990, the demand for commercial final energy in the households and services sector was approximately 2 TWyr. An estimated 1.5 Gt of carbon were emitted by burning fossil fuels and by generating the electricity used in this sector. These emission figures are only approximate estimates and so are the shares of the individual world regions, on the order of 57% for the OECD region, 18% for the reforming economies, and 25% for the developing countries.

The recent literature in the field indicates that the relative energy saving potential of the households/services sector is larger than that of either industry or transportation (see also Chapter 2). Moreover, according to several results, a significant proportion of the energy and emissions savings can be achieved economically, i.e., by saving money at the same time. The (often reported) size of the potential to reduce carbon emissions in this sector in an economical way is 50%. However, the resulting savings of dollars and emissions should not be translated too quickly into predictions of actual emission reductions. Households/services is a sector in which the market price of goods and services consumed is an inaccurate indicator of consumer preference.

8.5.2 Strategies to Reduce Carbon Emissions

The options for reducing energy and carbon intensity in the households and services sector can be classified as follows: (1) *efficiency improvements* of end-use conversion technologies, (2) *fuel-mix changes*, and (3) other *demand-side measures* such as improved insulation of buildings and "daylighting" (replacing artificial lighting by daylight).

Before discussing various emission reduction options and their reported costs and benefits, we note the large discrepancies that are to be found in the various quantifications of potential savings in recent literature. These discrepancies lie between results that predict potential negative costs of carbon emission reductions and those that find that any reduction will cost some positive amount.

A typical example of the large potential for cost-cum-emission savings is reported by the National Academy of Sciences (COSEPUP, 1991) and is reproduced in Figure 8-13. This figure shows the costs of carbon emission reductions through fuel savings in residential and commercial buildings, implying that up to 50% of CO_2 emissions could be saved at negative costs. These calculations are apparently based on an annual discount rate of 6%, which must be compared with the results of Hausman (1979) who estimated a range of implicit discount rates derived from purchases of air conditioners by private households of 5–89%. This wide range is due to Hausman's disaggregation of his results into different income classes. The overall estimate (across all income classes) is calculated as 24.1%. Train (1985), in his survey of studies of average consumer discount rates, found the following ranges: improvements of thermal integrity of buildings: 10–32%; space heating and fuel type: 4.4–36%; air conditioning: 3.2–29%; refrigerators: 39–100%; other home appliances: 18–67%. The high discount rates found in real life explain a large part of the discrepancy described above. Here, we simply intend to show that commercial interest rates indeed seem unrealistic when optimal investment decisions of households are calculated. In the above example, a tenfold increase in the annual capital recovery factor makes all monetary savings disappear.

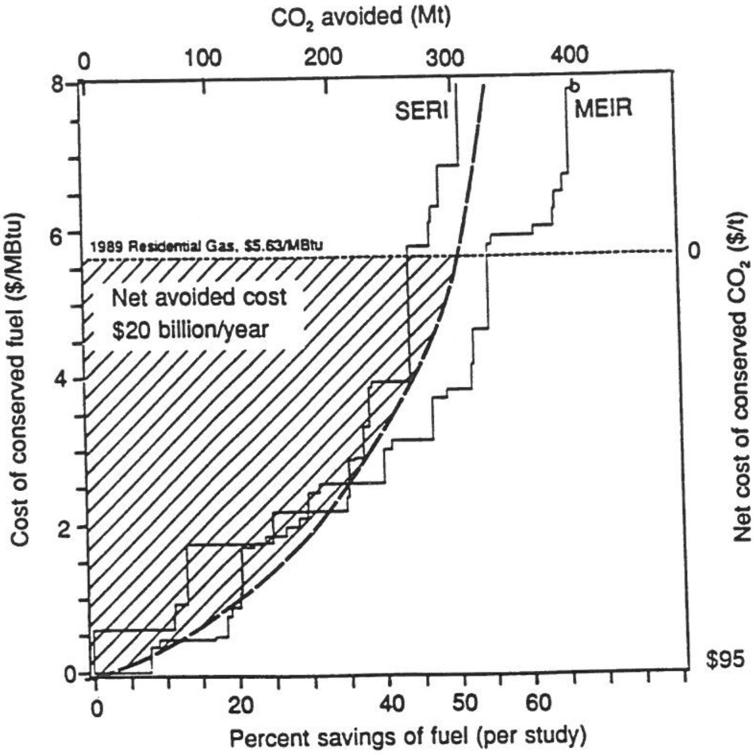


Figure 8-13. Cost of conserved energy and net cost of conserved CO_2 for the households and services sector (Source: COSEPUP, 1991).

Efficiency Improvements

There are numerous examples for improving the efficiency of residential energy appliances. Compared to the 1986 stock, the 1991 stock of refrigerators, freezers, or room air conditioners in the USA consume about 20% less, and 1991 models sold consume an average between 30 to 40% less than the average 1986 vintages (Levine *et al.*, 1992).[12] With best available and advanced technology further significant improvements in energy efficiency are possible. In the USA, refrigerators are the second largest consumer of residential electricity. In 1987, they consumed 146.6 TWh, corresponding to approximately 16% of the total electricity consumption by US households (COSEPUP, 1991). The average 1991 stock consumed about 1200 kWh/yr (down from 1450 kWh in 1986) and the best available model sold consumed 710 kWh. Further reductions to 200–500 kWh are considered within reach during the 1990s (Levine *et al.*, 1992). According to Meier (1991), more than 25% of the current US electricity demand for refrigerators could be reduced by cost-efficient measures. His calculations assume an annual discount rate of 10% which looks low in light of the above discussion. Using a rate of 30% instead results in positive costs of all saving measures considered in this case.

Efficiency improvement potentials in many other applications from lighting, hot water supply, or cooking are well documented (COSEPUP, 1991; AEI, 1991; Levine *et al.*, 1992), so that the discussion of individual technologies and their efficiency improvement potential is not repeated here.

---

[12] In absence of detailed cost data of equipment sold, it is not possible to identify what fraction of this efficiency improvement was achieved through technological progress, viz., higher equipment costs.

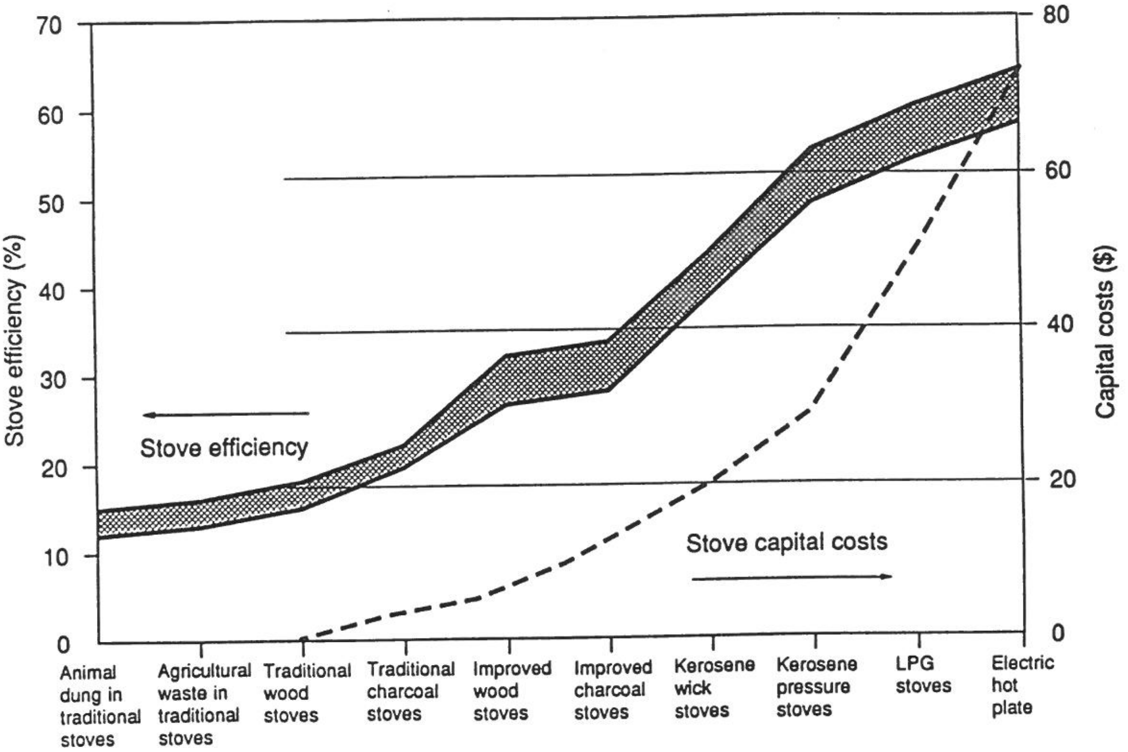


Figure 8-14. Representative efficiencies and direct capital costs for various stoves in developing countries (Source: Baldwin, 1986; OTA estimates).

However, the availability of technology alone may not be sufficient to translate efficiency improvement potentials into actual final energy demand reductions. Access to information, consumption time preferences, relative price structures, and, finally, available resources are all important factors determining which technological options will be taken up by consumers, and to what degree.

As an example describing energy demand for cooking in rural areas of developing countries, Figure 8-14 (taken from Baldwin, 1986), shows the efficiencies of various stoves as a function of their capital costs. It can be seen that the 10–20% efficiency of traditional stoves could be improved to over 60%. At the same time, this figure illustrates the difficulty of increasing energy efficiency in developing countries. The capital costs of LPG stoves and electric hotplates, the most advanced cookers considered, range between $50 and $70. This is equivalent to one-third to one-half of the average annual per-capita saving rate in India of $150 (Mathur, 1991).

Fuel-Mix Changes

In the cool and temperate zones of the world, space heating is the biggest energy consumer in the households/services sector. Heating energy is therefore the prime candidate for achieving reductions in energy demand and carbon emissions in this sector. Accordingly, several studies have identified major saving potentials, most of which could be achieve with improved building insulation. For example, more than one-third of the single-family houses in the USA lack insulation in their roofs or ceilings (COSEPUP, 1991).

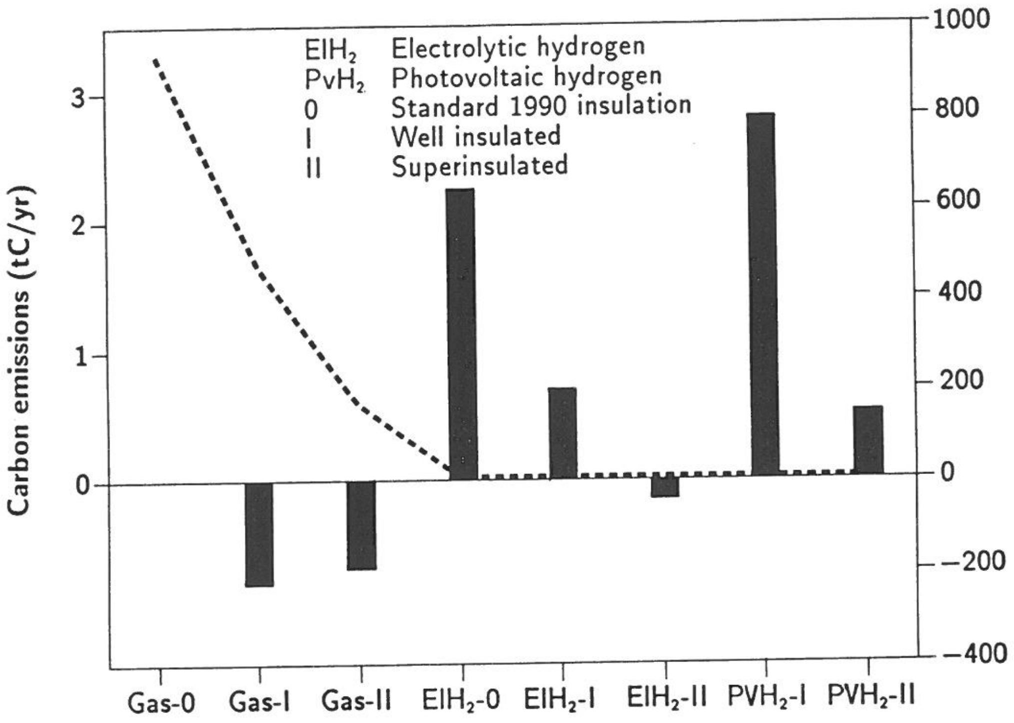


Figure 8-15. Carbon emissions (line) versus CO_2 reduction costs (bars) for residential heating. The abbreviations represent the three insulation categories in ascending order of technological sophistication (0, I, II): natural gas; a hydrogen delivery chain based on hydro-electricity and electrolysis (ElH_2); and photovoltaic electricity and electrolytic hydrogen (PVH_2).

Figure 8-15 presents the calculated CO_2 emissions and CO_2 reduction costs for residential space heating. The data represent a residence with 150 m^2 of living space at three levels of building insulation standards. The CO_2 reduction costs are calculated as the differences between the reference case (gas heating and 1990 insulation standards) and each alternative considering the levelized annual heating costs. In addition to the emissions related to residential heating systems, the CO_2 emissions of Figure 8-15 account for all emissions along the energy delivery chain.

Not surprisingly, Figure 8-15 conveys that improved building insulation is the single most important factor for immediate CO_2 emission reductions. This, and high-efficiency heating technology, even for natural gas-fueled systems, could lead to substantial emission reductions. There, the costs of CO_2 reduction are negative, i.e., the collateral benefit of lower CO_2 emissions is a lower annual heating bill.

Likewise, the combination of hydroelectricity and electrolytic hydrogen could generate net savings if used in superinsulated residences (ElH_2-II). Photovoltaic hydrogen in conjunction with superinsulation (PVH_2–II) achieves zero carbon emissions for some \$140 per tonne. Not shown in Figure 8-15 are the costs of photovoltaic hydrogen and conventional buildings/furnaces. Even with the capital-cost improvements associated with second-generation technologies, the cost of a one tonne reduction in carbon emissions would still amount to some \$500 (with existing photovoltaic technology, approximately \$1200).

Commercial heating follows the trend of residential heating. Here, the cogeneration of electricity and space/process heat production is an essential prerequisite. Improved insulation and phosphoric-acid fuel cells (PAFC) would result in CO_2 reduction costs of approximately \$25–80 per ton of carbon.

Demand-Side Measures

In recognition of the importance of the discount rate used in the calculation of CO_2 reduction costs, Rosenfeld *et al.* (1992) have investigated the sensitivity of conservation costs in the building sector to the real discount rate. Figure 8-16 shows the influence of various discount rates on the costs of electricity conservation. The rates analyzed cover the interval between 3 and 30% per year. In the range of actual electricity prices, the results imply that 30–44% of electricity could be profitably saved. In the light of the discussion above, it would be interesting to see such investigations expanded to also include extremely high discount rates, even if these might be regarded as purely hypothetical. However, this omission can be easily rectified because, beyond rates of 30%, the cost curves are nearly proportional to the discount rates. This means that the steps of the 60% curve are roughly twice as high as the steps of the 30% curve. Therefore, at a hypothetical discount rate of 60%, the profitable savings are 10% of electricity consumed by this sector.

Total Potentials

Fisher (1990), in a report for the Stockholm Environment Institute (SEI), examined global *Options for Reducing Greenhouse Gas Emissions.* The potential savings from efficiency measures reported for the residential and commercial sectors are summarized in Tables 8-4 and 8-5. Owing to the much wider scope of the SEI study, the results reported in these two tables are less precise than those reported above. For the same reason, Fisher did not discuss the question of cost-effectiveness in detail. In many cases, cost estimates are given as ranges, suggesting that a large part of these efficiency improvements would be cost-effective. Without doing exact calculations, it is clear from these tables that a reduction potential of 50% is considered typical for the sector.

Another study of the costs of pollution reduction, more detailed in substance but restricted geographically, was conducted by Springmann (1991), who calculated payback times of the "best available technologies" (BATs) and their impact on reductions in pollution emissions in the EC. From his report, we reproduce Table 8-6, showing savings of CO_2 emissions and the related costs or savings for the EC tertiary sector. Table 8-7 shows a similar compilation of measures for private households and their estimated cost savings and resulting investment payback time. Springmann uses a discount rate of 9%, and a lifetime of the equipment involved of 10 years. The two emission-saving potentials are found to be 30% for tertiary sector and 42% for households. Taking only those BATs that reduce costs and emissions at the same time, these potentials fall to 10% (households) and 14% (tertiary sector). Applying a more stringent criterion of a payback time of less than four years, the savings for households fall to 7.4%. In the tertiary sector, there is no significant reduction when this criterion is applied.

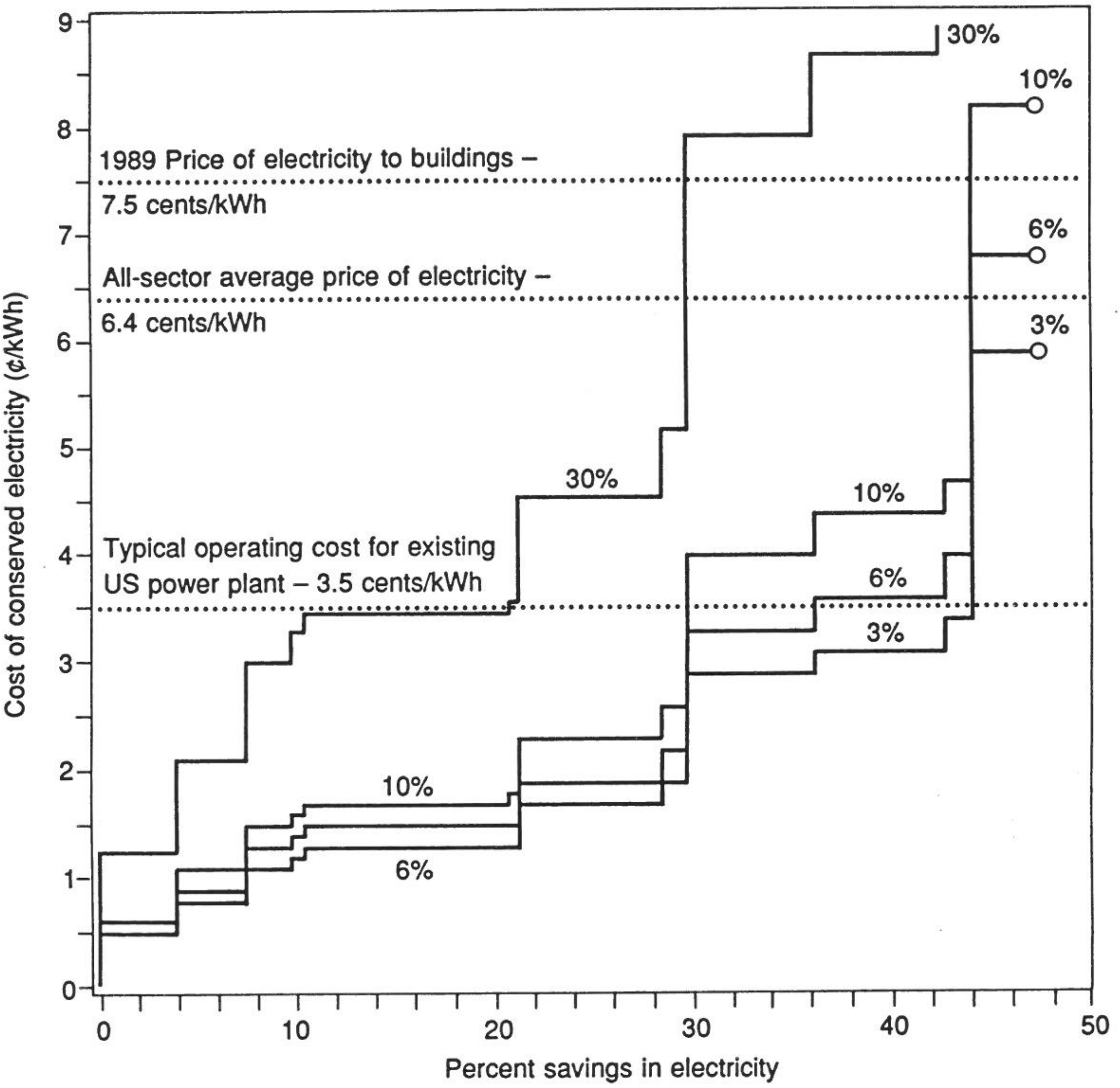


Figure 8-16. Electricity saving potential of buildings sector versus conservation costs for a range of real discount rates between 3% and 30% (Source: COSEPUP, 1991).

8.5.3 Carbon Emission Scenarios for 2020

Assuming business-as-usual conditions, carbon emissions from the households/services sector will follow the general upward trend. This is illustrated by the EPA's RCW (Rapidly Changing World) scenario (EPA, 1990), which includes high GDP and moderate population growth and rapid technological improvements. As shown in Table 8-8, a 65% increase in final energy consumption between 1990 and 2020 is accompanied by a 94% increase in carbon emissions during the same time interval. This more rapid increase in emissions (relative to energy consumption) prevails in all three world regions.

Table 8-4. Potential emission savings (%) from efficiency measures in the residential sector, worldwide (Source: Fisher, 1990).

	Potential savings from replacing:	
End use	Average existing unit with best new unit[a]	Average new unit with best new unit
Lighting (incandescent) (energy-saving lamps, tungsten-halogen lamps, compact fluorescent lamps)	75	75
Refrigeration (insulation, high-efficiency compressors, fan and motor efficiency)	40–50	25–35
Air conditioning (high-efficiency compressors, improved heat exchangers, fan and motor efficiency, alternate refrigerants, variable-speed drives)	40–50	30–40
Space heating/electric (heat pumps, integrated space and water heating appliances)	40–60	40–50
Space heating/gas (electronic pilot lights, flue dampers, improved combustion, flue gas condensation, integrated space and water heating appliances)	45–55	20
Water heating/electric (low-flow showerhead and faucets, water-conserving appliances, insulation, heat pumps, integrated space and water heating appliances)	50–65	40–50
Water heating/gas (low-flow showerheads and faucets, water-conserving appliances, insulation, heat pumps, integrated space and water heating appliances)	25–40	25
Cooking/electric (reflective pans, improved heating elements, microwave ovens, inductive heating)	30–40	20–30
Cooking/gas (electronic ignition, reflective pans, improved burners)	40	20
Cooking/wood (improved cook stoves)	75	75

[a] Includes savings from application of retrofit measures to average models in use.

Table 8-5. Potential emissions savings (%) from efficiency measures in the commercial/service sector, worldwide (Source: Fisher, 1990).

	Potential savings from replacing:	
End use	Average existing unit with best new unit[a]	Average new unit with best new unit
Lighting (incandescent) (energy-saving lamps, tungsten-halogen lamps, compact fluorescent lamps)	75	75
Lighting (fluorescent) (high-efficiency lamps, high-efficiency ballasts, reflector inserts, timers and occupancy sensors, daylighting systems, metal halide or sodium lamps)	70–85	60–85
Heating, ventilation and air conditioning (HVAC) (proper sizing, improved control systems, improved air handling systems, economizers, high-efficiency motors, fans, and pumps, high-efficiency air conditioners and chillers, heat pumps, variable-speed drives)	40–70	30–60

[a] Includes savings from application of retrofit measures to average models in use.

In contrast[13] to the EPA's RCW scenario, ECS '92 shows clear signs of decarbonization, i.e., a slower increase in carbon emissions than in final energy. Worldwide, ECS '92 has – for a 10% lower final energy demand – 30% less carbon emissions in the households/services sector than the "business-as-usual" RCW scenario.

As a third outlook, we present the EPA's RCWR (Rapidly Changing World with Rapid Emission Reductions) scenario as an example involving radical reductions of carbon emissions in the households/services sector. The RCWR scenario is based on the same socioeconomic assumptions as RCW. In addition, it includes aggressive policies for reducing emissions, among them a carbon fee/tax of \$100/tonne of coal (\$144/t C), \$19.20/barrel of oil (\$180/t C), and \$2.16/GJ for natural gas (\$153/t C). Together, these measures lead to a stagnation in final energy consumption between 1990 and 2020 and to emission reductions of 73% of current emissions and 86% relative to the business-as-usual scenario.

---

[13] A few remarks are in order: (i) Due to discrepancies between their 1990 values the (ECS energy consumption figures are some 30% higher than those of the EPA), the numbers for the developing countries are not readily comparable between ECS '92 and the two EPA scenarios. However, the average annual growth rates between 1990 and 2020 are almost identical for the EPA's RCW and ECS '92 scenarios – about 3%. (ii) For this comparison, only commercial energy was considered in ECS '92. (iii) Although the EPA scenarios are unusually well documented, deriving the numbers presented here involved making some assumptions. We attempted to make these in the original spirit of the scenarios, and we trust that the errors thereby introduced are within the limits of natural uncertainty.

Table 8-6. Emission reduction through the use of best available technologies in the tertiary sector in the EC (Source: Springmann, 1991), in million tonnes of carbon and ECU/tonne of carbon reduced.

Process	BAT number	Best available technology	From fuel (Mt)	From electricity (Mt)	Total savings (Mt)	Net costs/yr (million ECU)	Net costs/yr (ECU/t C)
Space heating	5201	Improved insulation	9.3	1.9	11.2	3101	275
	5202	Passive solar energy use	0.5	0	0.8	189	249
	5203	Active solar energy use	0.5	0	0.5	868	1610
	5204	Improved heating control	0.8	0	0.8	–416	–484
	5205	Gas-fired condensing boilers	1.4	0	1.4	–540	–418
	5206	Expansion of district heating heating with combined heat and power	0.3	0	0.3	–58	–143
	5207	Gas-driven heat pumps	1.4	0	1.4	268	198
Water heating	5208	Solar water heating	0.8	0.6	1.4	354	238
Lighting	5209	High-efficiency fluorescent lamps	0	11.7	11.7	–6022	–517
Total			15.3	14.2	29.5	–2256	–77
% of 1985			29.2	30.1	29.6		
Emissions 1985			52.4	47.2	99.6		

Table 8-7. Cost savings through the use of best available technologies (BATs) in private households in the EC (Source: Springmann, 1991).

Process	BAT number	Best available technology	Investment costs/a (ECU/GJ)	Investment costs/a (million ECU)	Fuel savings (million ECU)	Electricity savings (million ECU)	Energy savings (million ECU)	Payback time (years)
Space heating	5101	Improved insulation	14.3	28493	17061	2505	19566	13.2
	5102	Passive solar energy use	13.8	4168	2568	397	2965	12.8
	5103	Active solar energy use	37.8	8111	1837	270	2107	32.1
	5104	Gas-fired condensing boilers	2.5	388	1372	0	1372	2.4
	5105	Expansion of district heating with combined heat and power	7.8	484	654	0	654	6.7
Water heating	5106	Solar water heating	13.2	7498	2860	2436	5296	11.8
Cooking	5107	Improved gas and electric cookers	4.0	531	584	635	1219	3.6
Lighting	5108	Miniature flourescent bulbs	7.5	2111	0	2658	2658	5.0
Washing machine	5109	Improved washing machines	9.9	1216	0	1160	1160	8.7
Refrigerator	5110	Improved refrigerators	2.0	711	0	3359	3359	1.8
Freezer	5111	Improved freezers	2.7	709	0	2480	2480	2.4
Total			12.2	54420	26936	15901	42836	

Table 8-8. Energy consumption (GWyr) and carbon emissions (Mt C) in the households and services sector, 1990 and 2020 (ECS '92 and the EPA's RCW scenarios) (Sources: Chapter 8; EPA, 1990).

	Final energy (GWyr)			Carbon emissions (Mt C[a])		
	Fuels	Electricity	Total	Fuels	Electricity	Total
1990:						
Market economies	716	390	1105	356	458	815
Reforming economies	341	58	399	191	72	263
Developing countries	418	75	493	279	81	360
World	1475	523	1998	827	612	1438
EPA's RCW, 2020:						
Market economies	1013	584	1599	591	837	1428
Reforming economies	608	164	773	355	236	590
Developing countries	642	282	924	374	405	779
World	2263	1030	3295	1319	1477	2796
ECS '92, 2020:						
Market economies	579	583	1162	274	498	772
Reforming economies	382	104	486	205	97	302
Developing countries	977	327	1304	605	305	911
World	1938	1014	2952	1084	901	1985
EPA-RCWR, 2020:						
Market economies	518	336	857	113	47	161
Reforming economies	397	119	516	87	17	104
Developing countries	475	180	655	104	25	129
World	1391	636	2028	304	90	393

[a] Fossil fuels and electricity generation; for biomass assuming renewable exploitation, therefore no carbon emissions.

8.6 Energy Sector

In the previous sections we discussed options to lower carbon emissions from energy end-use. We have concluded that the emission reduction potentials are substantial, but that there are important informational, institutional, and financial constraints for realizing the potentials identified. Therefore measures in the energy sector proper will also have to be considered in any mitigation effort. The potential for renewable energies is discussed in detail in Chapter 3, and clean fossil technologies and carbon free sources of energy are dealt with in Chapter 4. Here we focus on the actual situation of carbon emissions from the energy sector, propose a hypothetical *Gedankenexperiment* on the impact of technological improvements, and conclude with a discussion of scenarios of the future evolution of energy supply.

8.6.1 Current Emissions from the Energy Sector

The conversion of final energy into secondary energy carriers and their transport and distribution to the final consumer results at present in some estimated 2.5 Gt of carbon emissions worldwide (Table 8-9). Thus, the supply of energy accounts for nearly half of all energy-related CO_2 emissions. With 1.8 Gt C the generation of electricity is the main source of these emissions, of which coal-fired power plants account for the largest share (about 1.3 Gt). Because of its higher degree of electrification and heavy reliance on fossil fuels, close to 80% of the electricity sector's carbon emissions originate in the Northern Hemisphere. Coking plants, oil refineries, district heating plants, and other conversion processes from primary into secondary and final energy currently result in close to 0.7 Gt of carbon, with the Northern Hemisphere accounting for nearly 70% of the emissions.

It is interesting to compare the carbon emissions of different fossil fuels from direct end-uses versus the emissions originating in fuel transformation and conversion. Our estimates indicate that about 75% of emissions originating in the burning of natural gas occur in the energy sector and only 25% from end-use. Conversely, 70% of carbon emissions from the burning of oil (products) originate in industry, transport, and households, whereas only 30% stem from refineries, oil fired power stations, and other facilities of the energy sector. The ratio for coal is almost perfectly balanced: about half of emissions originate in the energy sector, the other half from direct uses of coal by final consumers. These relative ratios indicate the priority areas for mitigation measures. For oil, end-use demand management has a clear priority over measures in the energy sector, whereas efforts to limit emissions from natural gas use should first be geared toward the energy sector (e.g., wider diffusion of high-efficiency combined cycle power plants). For coal, clean technologies need to be developed both for energy conversion and for the direct use of coal, particularly in industry.

8.6.2 Reduction with Best Available Technologies

In Chapter 2 we reported on the results of a mind-experiment calculating the impact on energy efficiency if current energy conversion and end-use devices would be replaced by the most efficient ones presently available. Despite the hypothetical and static nature of this calculation for which we have assumed that both the structure of useful energy demand and of energy supply would remain unchanged, the results indicated a vast

Table 8.9. Current carbon emissions from the energy sector by fuel type and type of transformation (electric/nonelectric): World total and by region, in million tonnes of carbon.

Regions	Solids	Oil	Gas	Subtotal fuels	Electricity	Total
Market economies						
Fuel transformation[a]	60	67	61	188	–	1065
Electricity generation	690	108	79	–	877	
Reforming economies						
Fuel transformation[a]	120	54	94	268	–	820
Electricity	321	103	128	–	552	
Developing countries						
Fuel transformation[a]	64	55	78	197	–	596
Electricity	256	100	43	–	399	
World						
Fuel transformation[a]	244	176	233	653	–	2481
Electricity	1267	311	250	–	1828	
Total	1511	487	483	–	–	2481

[a] Including production of (district) heat.

potential for improvements, which would result in a decrease of current global primary demand from 12 to 7.2 TWyr.

This hypothetical scenario would result in a decrease of carbon emissions by some 2.2 Gt. About 1.3 Gt would stem from improvements in end-use efficiency (including electricity), and some additional 0.9 Gt from efficiency improvements in energy supply, transport, and distribution. Thus, best available technology could reduce the energy sectors carbon emissions by close to 40% (0.9 out of 2.5 Gt C).

In this calculation, the largest absolute reduction potential was in the supply and distribution of electricity (0.5 Gt), followed by improvements in the end-use efficiency of oil products, in particular transportation (0.46 Gt), and improvements in the end-use efficiency of electricity and coal (0.36 Gt each). All other measures per energy carrier in either the energy supply or demand side would yield a lower reduction potential: between 0.1 and 0.15 Gt.

Examples of the impact of technological improvements in the electricity sector include reductions of transport and distribution losses of electricity and improvements in thermal efficiency of existing power plants. For instance, Schramm (1991) has analyzed the public power utility total system losses[14] of 94 utilities mostly from developing countries. Eight had losses below 11%; 49 utilities had electricity losses amounting to between 11% and 18%; 31 had losses between 19% and 32%; and for 5 utilities electricity losses exceeded 32%. Estimates for Haiti and Bangladesh indicate total system losses of 39%. Other examples include the significant potential for improving the conversion efficiency of fossil fuel power plants. For instance, Omar and Hossain (1991) report that the average conversion efficiency of thermal power plants in Bangladesh does not exceed 25%. Individual plants can even have efficiencies as low as 16% (OTA, 1992). Even

---

[14] Defined as difference between net electricity generated and electricity billed to consumers. These losses entail both technical (losses in transport and distribution lines) and organizational/institutional (incorrect metering or even outright theft) dimensions. Total system losses in the order of 7% to 10% are generally considered an acceptable range.

natural gas-fired combined cycle power plants in the country operate at a 24% efficiency level, compared to 50% for state-of-the-art technology (see Chapter 4). These examples illustrate the potential for efficiency improvements in the power plant sector. Realization of this potential is, however, not only a question of technology alone. Institutions, price policies, operational practices and maintenance, availability of spare parts, and above all capital will govern the extent to which the efficiency improvement potentials may become realized.

The above calculation represents the currently perceived potential for technological improvements; however, it is a "static" viewpoint, as it does not consider any interfuel substitution, resource availability, or market penetration constraints. If for instance, electricity end-use efficiency improvements and the resulting decreasing demand were translated into a proportional decrease of coal-based electricity alone, the reduction potentials would be higher (by about 0.2 Gt).

For the future, the emission reduction potential in the energy sector may increase due to technological progress, cost reductions, and increased supply of low-carbon or zero-carbon energy options like renewables, nuclear, or the sustainable use of biomass. In Chapter 3, a practical potential of renewable energy of close to 4 TWyr/yr by the year 2030 was identified. The upper range of the polls collected by the International Energy Workshop (Schrattenholzer, 1992) indicates a potential contribution from nuclear energy of some 1.6 TWyr/yr by 2020. Yet, these potentials fall short of the projected primary energy demand in most scenarios over a similar time frame, which means that the energy system will continue to rely to a large extent on fossil fuels in the decades to come. Hence, enhanced uses of natural gas and other technological options for clean fossil energy and carbon scrubbing identified in Chapters 4 and 5 will have to be examined, if indeed substantial reductions of energy-related carbon emissions are to be realized. However, only detailed modeling exercises can determine an optimal policy and technology mix and resulting regional cost profiles for future CO_2 mitigation strategies in the energy sector.

8.6.3 Decarbonization Scenarios for the Energy Sector

Table 8-10 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) as well as the final energy carbon intensity (carbon emissions from direct fossil fuel use by end users divided by the total final energy demand). The first measure indicates the overall carbon intensity of the energy system, whereas the second measure indicates the carbon intensity of the energy carrier mix delivered by the energy sector to the final consumer. One of the advantages of delivering low- or zero-carbon energy carriers to the final consumer, even if the energy sector continues to rely on fossil fuels, is the possibility of sequestering and disposing carbon from a limited number of large energy conversion units (e.g., along the integrated energy system scheme, discussed in Chapter 4).

Two views of the future emerge from Table 8-10 (see also Figure 8-17). One view implies a discontinuity in the historically observed trend of decarbonization of energy systems. Instead, the fuel mix becomes more carbon intensive, for both primary and final energy. This is due to increased reliance on coal and synthetic fuel production

Table 8.10. Primary and final energy supply, carbon emissions and carbon intensity, 1990 and scenarios for the period 2020 to 2025, in TWyr and Gt carbon.

	1990	IPCC/EIS 2025	EPA-RCW 2025	WEC-reference 2020	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, Gt C							
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 (t C/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, thereofre, would be higher. This uncertainty also affects the primary energy carbon intensity.

in the scenarios. The EPA-RCW and (to a lesser degree) the IPCC/EIS scenario are examples. 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 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 Gt C by the year 2020.

We therefore consider a more unconventional scenario (Ausubel *et al.*, 1988) in which 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. Despite the drastic structural changes, the scenario is consistent with historically observed market penetration rates of primary energy carriers, i.e., the scenario does not assume more rapid structural change in the energy supply mix than has occurred over the last 150 years (Marchetti and Nakićenović, 1979). In addition, an aggressive energy efficiency improvement strategy results in a primary energy demand of only some 15 TWyr[15] by the year 2025. This, together with a drastic shift in the energy supply structure (natural gas accounts for 68% of primary energy supply by 2025), is reflected in carbon emissions of 6.2 Gt C, i.e., basically a stabilization of current emission levels.

A Renewables-Intensive Global Energy Scenario (RIGES) has been suggested by Johansson *et al.* (1992). Secondary/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% of primary/secondary[16] energy supply (>15.3 TWyr) by the year 2025. It must be emphasized, however, that such a rapid market penetration is without precedent in history. For comparison, it took about 80 years for the market share of oil to grow to 40% of the global primary energy supply. The carbon emissions in RIGES would amount to 5 Gt carbon, i.e., result in a stabilization (even slight reduction) of current energy-related CO_2 emissions.

An interesting parallel to the "methane economy" scenario discussed above is that the final energy mix of RIGES is characterized by a high share (44% of final energy) of high density, clean energy carriers such as electricity, natural gas and biogas, as well as hydrogen from biomass and intermittent renewables. This points to two important issues: (1) the potential of renewable energies and the importance of the sustainable use of biomass in conjunction with advanced energy conversion technologies; and (2) irrespective of the future primary energy mix, whether based on renewables or clean fossil energy such as natural gas and zero-carbon options, the provision of high-quality and clean final energy carriers to the consumers becomes a priority. Thus, the final energy mix is highly likely to move further toward clean and grid-oriented energy vectors: electricity, gas, and, in the long term, hydrogen.

---

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

[16] 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%). 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 8-17.

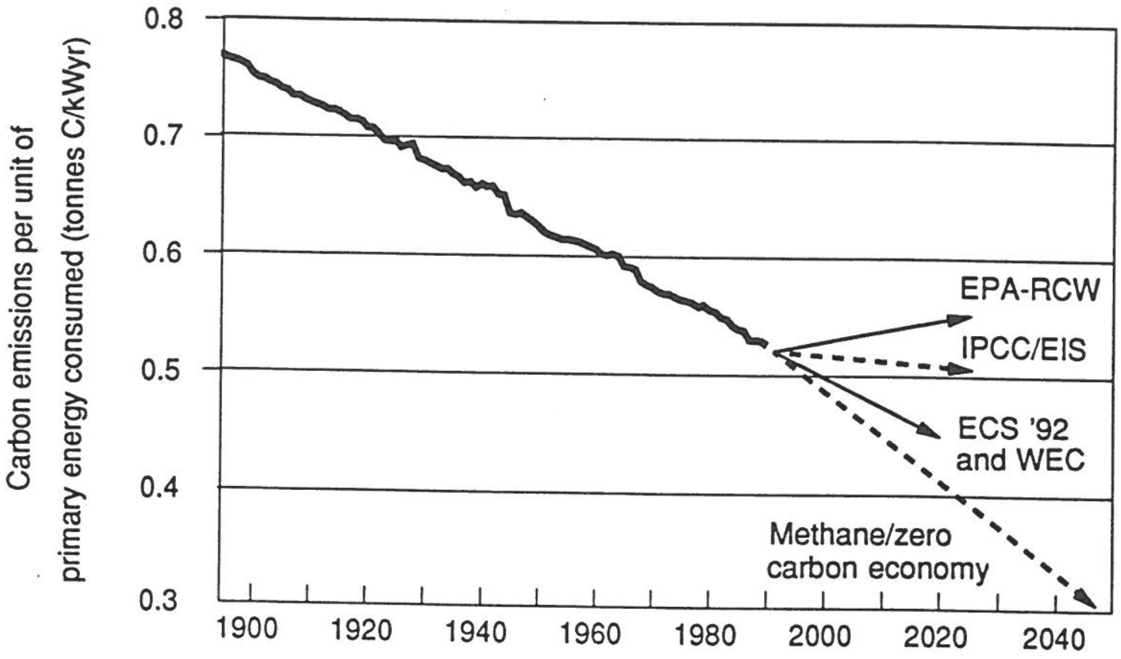


Figure 8-17. Carbon intensity of global primary energy consumption, 1900 to present, and scenarios for the future, in tonnes C/kWyr.

Figure 8-17 contrasts the historical perspective on the decarbonization[17] of the global energy system with the scenarios discussed above. The carbon intensity of primary energy supply in Figure 8-17 decreases at a rate of about 0.4%/yr (0.3%/yr over the period 1860–1990). To stabilize energy-related carbon emissions at current levels (5.5 Gt) for a primary energy demand between 15 and 18 TWyr by the year 2020, the rate of decarbonization would have to range between 0.8 and 1.4%/yr, i.e., two to four times the rates achieved in the past.

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.

---

[17] Fuelwood use in the 19th century and present fuelwood consumption in developing countries included as mostly exploited unsustainably, i.e., resulting in net additions of carbon to the atmosphere.

Energy Vol. 18, No. 5, pp. 583–595, 1993
Printed in Great Britain. All rights reserved

0360-5442/93 $6.00 + 0.00

Chapter 9

Conclusions†

The very nature of the greenhouse problematique indicates that mitigation strategies must indeed be comprehensive and pervasive if they are to arrest a further increase in the anthropogenic sources of greenhouse gases. In particular, CO_2 is so pervasive in most human activities that mitigation measures and strategies cannot be confined to any single individual measure, no matter how effective it might be, or to any single source of emission, no matter how large it might be. Therefore the complex nexus of economic *and* energy systems development has to be redirected from "business-as-usual" paths toward enhanced compatibility with natural energy flows and minimization of interference with natural geochemical cycles.

9.1 Global Decarbonization

Four types of technological strategies can be distinguished for stabilizing and eventually also reducing energy-related CO_2 emissions. The first is an incremental one, emphasizing energy efficiency improvements. 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. The other three strategies are more radical. They include changes in the design and operational practices of technologies with and without changes in the energy chains. We refer to these as changes in technological "trajectories". In the simplest case, the end-use technology is changed but keeps 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, 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. 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

---

†Arnulf Grübler and Nebojša Nakićenović with contributions by Leo Schrattenholzer.

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 up: 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 and diluted the source of emissions, the more expensive are the carbon control measures. Again, demand-side measures such as improved efficiency (i.e., emission *avoidance* altogether) are cheaper than post-combustion scrubbing of stack gases which, in turn, is cheaper than carbon removal from the atmosphere (such as via micro-algae carbon fixation).

From this perspective, it is not surprising that this study has also confirmed that energy efficiency improvements (end-use demand management measures) generally are amongst the most cost-effective measures, followed by fuel substitution, in particular toward natural gas (where available). More traditional energy supply-side measures, or even extensive industrial and infrastructural restructuring measures, are generally more expensive.

Cost comparisons must consider the relative economic merits of alternative options not only from a static but also from a *dynamic* perspective. Hence, not only do the current relative economics matter, but also their future evolution. As regards current economics, most renewables are among the most expensive carbon-reducing energy carriers. Photovoltaic electricity, for example, with estimated carbon reduction costs of up to $2000/tonne C (in the OECD region), can be between ten to twenty times more expensive than the nuclear option. This extreme case illustrates the wide range of mitigation costs.

However, the study has concluded that the cost gap between these two options has been narrowing. Whereas solar and other new renewable options are expected to experience significant cost decreases as a result of learning-curve effects and future economies of scale, nuclear costs have been increasing due to the growing complexity of the regulatory environment and limited social acceptance. These trends are also likely to affect the future economics of nuclear power in the reforming and developing economies where nuclear energy costs are still about half of the prevailing level in the OECD region. From this dynamic cost perspective, the relative economic merits of alternative mitigation options will certainly change at some time in the future.

Another ranking of cost effectiveness also emerges from our analysis. The short- to medium-term mitigation costs are generally lower in developing and reforming economies than in the OECD countries. The inefficiency of current technological vintages, as well as low labor costs, are among the factors that explain this phenomenon. One of the drastic regional cost differences identified was for the afforestation option, where costs may differ by as much as a factor of 10 between some areas of the South compared to the North. This general tendency toward cheaper mitigation opportunities in developing countries was also confirmed for a large number of other options. Some of the illustrative examples include improving energy efficiency by simple housekeeping measures, better power plant availability factors, and fuel quality upgrading such as coal washing in India.

However, it must be emphasized that for developing countries the upfront capital requirements are *the* dominant constraint for implementing such options. Perennial capital shortages frequently do not even allow investments into energy efficiency improvements with a payback times of less than one year. In view of further population growth and economic development, carbon emissions are bound to increase in the developing world. Limiting carbon emissions clearly cannot be a major policy concern in these countries compared with the multitude of other urgent problems that need to be addressed. Although most of the historical responsibility and mitigation capability rests with the North, tragically it is the developing countries that are the most vulnerable to the risks of climate change and that have limited capabilities for adaptation.

Fortunately, economic development and reduction of emissions can be complementary efforts and not necessarily contradictory objectives. Many technological options serve both economic development and global environmental compatibility, such as by generating employment for growing populations. Examples include the improvement of energy efficiency in many end-use categories that are often labor-intensive, or the development of local renewable energy sources and afforestation programs. Thus, appropriate models will have to be developed at the international level to utilize more fully the low-cost carbon reduction potentials in developing countries.

In conclusion, there is a salient methodological issue connected with the objective of this study, i.e., to provide an overview of CO_2 emission reduction potentials and costs of a large number of individual options. An *aggregation* and synthesis of the results cannot be performed by simply adding individual mitigation measures. In particular, important interlinkages exist between energy end-use and supply measures, industrial restructuring and behavioral change, and energy and resource efficiency. The study recognizes some of these important linkages, especially those connected with the comparison of options that involve whole energy chains and not only single technologies. This means that multiple trade-offs and linkages must be included between end-use and supply measures in the energy system.

There are obvious limitations to this approach. A consistent comparison of many different constraints connected with single technologies and whole energy chains is required. Constraints include local and regional resource availability, access to capital, and maximal diffusion and build-up rates. Other consistency criteria must be fulfilled, such as the discrimination of mutually exclusive options links, centralized versus decentralized supply strategies, or avoidance of double-counting of reduction potentials. Such a synthesis requires a detailed, disaggregated *model*. The development of an appropriate model with the required fine grain of detail was not the objective for the present study. Rather, the objective was to provide an assessment of possible reduction potentials, costs and their possible trade-offs. As such it provides a first but necessary step toward more comprehensive global mitigation studies that might also involve the development of a new modeling tool. Such a tool would require a novel methodological approach since it would need to be both dynamic and have detailed regional and energy system disaggregation. In any case, a careful selection would have to be made of individual technologies and energy chains and their possible timing. Thus, the technologies and options analyzed in this report can provide inputs to any subsequent model development and to the selection of the most attractive options considering their theoretical "stand-alone" reduction potential and the combinations of their mutual potentials in the energy chains.

9.2 CO_2 Reduction Potentials and Costs

Carbon is the single largest volume of material handled by industrial metabolism. Anthropogenic activities result in some 8 Gt of carbon emissions each year. Out of this, 6 Gt stem from industrial activities, energy conversion, and end use. This quantity surpasses any other waste stream released into the environment. Considering the high level of emissions, their pervasiveness across a wide range of diverse activities and their close connection to material well-being and economic development, the reduction of CO_2 emissions is indeed a daunting task. Fortunately, human ingenuity has developed a wide range of technological options for reducing emissions while preserving the services rendered by energy conversion processes. It can be expected that further technological development would be stimulated by a concrete global policy to arrest and eventually reduce carbon emissions.

From a purely theoretical viewpoint, the ultimate asymptotic state of carbon emissions could be zero, illustrating that in principle there is a vast potential for emission reductions. However, whereas technologies available either now or in the future can define *opportunities* for emission reductions, i.e., *potentials*, the question of how many such theoretical options may be realized and over what time horizon is much more complex to answer.

Compared to current emission levels, the options analyzed indicate that emission reduction potentials are substantial across many sectors and regions. Typically, they are in the range of one-third to one-half of the emissions in a "no control" case. Such potentials were found for efficiency improvements in end-use sectors as diverse as industry, transportation and households. They range from industrial process technology change combined with enhanced recycling and fuel-efficient cars to energy-conserving appliances and lighting. On the supply side, reductions of similar orders of magnitude could be achieved from the replacement of conventional coal-fired by natural gas combined-cycle power plants to replacement by nuclear and renewable energy.

The carbon sequestering potential of a global afforestation program was calculated to be about 1.6 Gt C or about the mid range of estimates of current carbon releases by land-use changes and deforestation (1.6 ± 1 Gt C per year, IPCC, 1992). This confirms the attractiveness of the afforestation option as a CO_2 mitigation measure, but the result also identifies its limits. Even a massive global afforestation program would not be sufficient to offset continuing current trends in deforestation or ever increasing fossil fuel emissions. On the contrary, from the perspective of the respective global carbon reservoirs and fluxes, halting deforestation would be a much more effective CO_2 reduction strategy than the most vigorous afforestation program. Afforestation is also not a sufficient substitute for implementing a range of low-cost efficiency improvements and decarbonization strategies in the energy sector proper, because the current energy-related emissions are about four times greater than the identified ultimate afforestation potential to absorb 1.6 Gt of carbon per year in a few decades from now.

The largest *relative* mitigation potential compared with the current emission levels can be found in reforming and developing economies. This is due to the comparatively low energy efficiency of many end-use applications and also due to the importance of non-energy related carbon emissions in many of these countries. The largest *absolute* reduction potentials remain in the OECD countries, despite their comparatively higher energy efficiency. This is simply because of their high levels of affluence and energy consumption, and consequently high CO_2 emissions.

Many options were identified throughout the study that could achieve substantial carbon reductions at modest costs and sometimes even lead to overall savings, i.e., emission reductions at negative life-cycle costs. This was particularly the case with efficiency improvements in end-use, typically due to the avoided fuel costs. It must be emphasized that the identification of such cost-saving reduction *potentials* is the result of a comparative assessment of different technological alternatives. As such, it does not imply that these measures will indeed be implemented "automatically". Cost savings and emission reductions are often called "free lunch" options. In the case of improved energy efficiency they yield reduced operating costs, particularly fuel savings and sometimes also other cost reductions. The time horizon over which such cost savings are calculated is often the most important factor explaining the discrepancy between the results of bottom-up and top-down approaches. Bottom-up or engineering-type analyses consider cost over the entire (long) life cycle of an investment where accumulated fuel and cost savings can be substantial. Conversely, top-down or macroeconomic approaches include a (high) implicit discount rate, which puts more weight on up-front expenditures than on future fuel and cost savings, frequently resulting in smaller cost savings over the time horizon considered.

Carbon reduction potentials with cost savings could also be realized by eliminating price distortions between energy carriers and energy subsidies in general. Such reduction possibilities exist almost everywhere and are thus neither confined to reforming and developing economies nor to the energy sector alone. Many opportunities exist also within the OECD region. Examples include subsidized coal production in a number of European countries, subsidies of various primary commodities with low prices on international markets (e.g., steel), and institutional barriers that hinder the replacement of the existing capital stock by more energy-efficient equipment. Elimination of many such "market imperfections" would reduce emissions but it is notoriously difficult to achieve in practice.

All told, CO_2 mitigation costs span an extremely wide spectrum from actual savings or very low costs of just a few dollars per tonne of carbon release avoided all the way to very high costs ranging up to a few thousand dollars per tonne of carbon. In comparison, one tonne of carbon embodied in oil costs about $150 at current oil prices.

Some of the cheapest mitigation options for the world as a whole are those that are intended to offset the potential effect of global warming by changing the Earth's albedo. Sometimes they are called "geoengineering" options since they involve large-scale structures or mitigation operations. One of the cheapest is stratospheric sulfate spraying that could reduce solar radiation by about 1%, supposedly enough to offset almost a doubling of atmospheric CO_2 concentrations. These options are not only among the cheapest, but they are also among the most controversial and uncertain with respect to unanticipated side-effects. At the other extreme are the *indirect* mitigation options such as a shift from individual to mass transportation in urban areas. Such indirect measures can reduce CO_2 emissions by reducing energy consumption, but they are often very costly. For example, the improvement of public urban transport systems by the construction of metros is a very capital-intensive strategy for carbon reduction. Such measures therefore cannot be considered from the sole perspective of cost-effective global carbon mitigation strategies, although they might be attractive because they also improve the local environment and reduce traffic congestion.

There are obvious uncertainties and methodological problems inherent in any cost assessment of greenhouse gas mitigation strategies. Therefore, less emphasis should be given to the absolute levels of derived cost estimates, and instead be placed on the *relative ranking* of different (technological) options. Often the relative costs are comparable given the ranges of the uncertainties involved. In those cases emphasis should be placed on the possible cost-effectiveness of different mitigation options across regions. Reductions in carbon emissions should be effected where costs are the lowest. This is often the case in the developing countries where the implementation possibilities are usually minuscule due to capital shortages, lack of appropriate technologies and skills, and many other limitations. Therefore, appropriate institutional mechanisms and market incentives need to be developed to achieve globally cost-effective strategies.

9.3 Methodological Issues

Two major methodological issues were identified in this study. One deals with the question of how to define a reference scenario against which the potential of various mitigation strategies can be evaluated and the other deals with the question of whether to assess various mitigation potentials from a "bottom-up" or "top-down" approach. The first issue is perhaps more hypothetical because it deals with the anticipation of future developments in greenhouse gas emissions. In short, the question is how to specify the "reference" or "business-as-usual" scenario with which a possible mitigation scenario can be compared, e.g., differential costs of emission reduction. Although every scenario *per se* can illustrate some future development path, the likelihood that will actually occur is an entirely different matter. A scenario that postulates future developments simply as "more of the same" compared with the present situation is probably as unrealistic as anticipating the aggressive introduction of environmentally benign energy systems and drastic reductions in global CO_2 emissions. It would be also questionable to expect a shift to environmentally less benign energy systems such as a heavier reliance on coal.

There is a strong indication from the historical changes examined throughout the study that in the long run the energy system is already moving in the right direction toward improved energy efficiency and less carbon intensive supply structures. New data sets developed for the study indeed illustrate the substantial improvements in energy consumption per unit of GDP and in the specific carbon emissions per unit of energy consumed. These improvements have taken place throughout the industrialization process of the last two centuries. In the past, these powerful trends were fortunate "by-products" of the quest to improve the technical and economic performance of energy supply and end-use. Therefore, there is a strong reason to assume that similar trends, perhaps even at accelerated rates, could also persist in a more environmentally conscious future.

Human responsiveness toward environmental concerns can best be judged against the background of concrete policy actions taken to improve the environmental impacts of anthropogenic activities. Successful efforts to reduce local air pollution and recently also regional SO_2 and NO_x emissions and other acid rain precursors are all cases in point. These efforts illustrate the importance of social responsiveness to changes in knowledge and perceptions. Therefore, we have refrained from using as a reference case the "business-as-usual" type of scenarios with unabated or even more rapidly accelerating emission growth paths. Instead, we developed a different reference scenario: the ECS '92 scenario describes a "dynamics-as-usual" future development. The scenario envisages further development of energy efficiency and decarbonization – as experienced in the past prior to the wide awareness of the dangers of possible global warming. Consequently, the ECS '92 scenario leads to lower CO_2 emissions without any additional mitigation measures when compared with the "business-as-usual" type of global scenarios. The EPA's RCW scenario, for example, projects CO_2 emissions of 10 Gt and energy consumption of 18 TWyr in the year 2020. The IPCC/EIS business-as-usual scenario results in emissions of more than 9 Gt of carbon for the same year and the median of the IEW energy projections results in less than 9 Gt of carbon. In contrast, the ECS '92 scenario results in 8 Gt of carbon emissions, i.e., 1–2 Gt of carbon less than alternative "business-as-usual" projections. As the ECS '92 scenario was based on an energy model that minimizes energy systems costs, such differences in emission scenarios not only reflect different "modeling approaches" but are also a good indication of the importance of "no-regrets" policies in reducing future CO_2 emissions.

In the ECS '92 scenario, CO_2 emissions in the OECD countries remain stable, indicating that emission stabilization in this region is compatible with the objective of minimizing future energy system costs. However, even under the "no-regrets" policies of the ECS '92 scenario, global emissions do increase. Worldwide, they nearly double by the year 2020 compared with present levels, primarily due to the additional energy needs in the developing and reforming economies. Additional mitigation efforts (and costs) are required to achieve further emission reductions at the global level compared with the ECS '92 scenario.

The second methodological issue deals with two very different ways of determining mitigation potentials and costs. The top-down approach, usually taken in economic assessments, starts with the basic assumption that "there is no free lunch", i.e., that any additional mitigation measure is going to cost something no matter how low these costs might be. The bottom-up approach, often attributed to engineers, holds that the best available technology can at the same time be cheaper and emit smaller amounts of greenhouse gases than the equipment used at present. In the bottom-up assessments, negative costs reflect technological change and indicate that a shift might be cheaper because of energy savings and other potential benefits. This sometimes leads to the confusing situation where carbon emissions are reduced and large investments are avoided at the same time. In contrast, top-down assessments involve price mechanisms in allocating scarce resources. Therefore, prices are the driving variables. This usually means that technological change is exogenous to the analysis. It is treated at a phenomenological level considering rates of (non-price induced) "autonomous energy efficiency improvements" (AEEI). Today, AEEI has an established place in the field of macroeconomic modeling. It is acknowledged that there are other driving factors – such as potentials for improvement and technological change – that influence the path of energy consumption in addition to energy prices.

Another important difference between the two approaches is related to the assumptions about explicit and implicit discount rates. Different discount rates of future costs and benefits, and different time horizons adopted in the analyses influence the comparison of initial investments and subsequent operating costs (or savings) among options. For instance, empirical studies of household investment decisions about the purchase of energy-efficient equipment have found implicit discount rates of up to 90%. Such high discount rates may be regarded as economically irrational; at the same time, however, they express indirect costs not accounted for by mere observation of the market price of a given appliance. For example, indirect costs include the time and effort of obtaining sufficient information, risks due to the uncertainty of the exact amount of payback, and transaction costs.

Thus, one part of the explanation why engineering, "bottom-up" and economic "top-down" approaches arrive at different results is that the utilities of consumption can be very different from market prices. In economic studies it will be required to include technological change more explicitly and in engineering studies to acknowledge the complexity of criteria entering a consumer's and even an industry's investment decisions.

There is a long way to go before technological and economic opportunities for efficiency improvements are taken up by economic agents.

Another cause for misunderstanding can arise from the comparison of alternatives that are not completely substitutable. A typical case would be a cost-benefit analysis of alternative mitigation technologies based on a comparison of life-cycle costs. Strictly speaking, such a comparison is only valid if an investment decision is made for new equipment in both cases. It does not apply to a situation where existing equipment is still not obsolete. Thus, to evaluate realistic options for reducing greenhouse gas emissions, a *dynamic* rather than a *static* potential must be calculated, one that takes into account the age structure of a given capital stock. Potentials determine diffusion rates, but these can be quite slow due to rigidities such as a given capital vintage structure, especially for big systems such as energy infrastructures.

The potential for improvement has always driven reductions of energy intensities. Inasmuch as the potentials identified are large indeed, this gives rise to a cautious optimism that some might be realized provided appropriate policies to promote such improvements are implemented. However, only detailed modeling exercises can provide a quantitative answer to specific questions concerning future mitigation potentials, including "how much, by when, at what costs, and where" can be realistically achieved. To fulfill these goals, the models would need to endogenize both the heterogeneity of consumer preferences as reflected in implicit discount rates, as well as the heterogeneity of possible rates of technological change as reflected in the age structure and efficiency of the capital stock.

The critical question today is whether the threat of a changing climate can add enough force toward the reduction of greenhouse gas emissions to accelerate the historical rates of technological progress. This seems to be the key uncertainty surrounding the future development of greenhouse gas emissions. Resolution of this uncertainty is largely a judgmental process, and it is the aim of this report to educate the reader's judgment by quantifying CO_2 reduction potentials and the costs of different options in different parts of the world.

9.4 Trade-Offs and Constraints

The conclusions of the study would not be complete without mentioning the most important trade-offs in the analysis of CO_2 reduction options. We illustrate below three potential trade-offs.

9.4.1 Efficiency

The finding that the efficiencies of energy conversion and end-use devices in developing and reforming economies are generally lower than those in market economies could lead to the impression that efficiency improvements would result automatically from economic liberalization and the introduction of market mechanisms throughout the world. However, energy efficiency improvements can have two opposing effects: they reduce energy requirements for a given unit energy service, but they can also alter the structure of the energy system and end-use patterns. For example, in the reforming economies of Eastern Europe almost all energy technologies are less efficient in comparison with Western Europe, but the overall energy system efficiency is higher due to structural characteristics (e.g., the importance of public transportation systems). Thus, although cars are more efficient in Western than in Eastern Europe, buses are more efficient in Eastern Europe than the private automobile in Western Europe. Furthermore, Eastern Europe has a high share of cogeneration and district heat as well as a structure of demand favoring less energy-intensive ways of providing services. Many of these structural features evolved within a centralized planning system. In a move toward a market structure some of the more energy-efficient equipment will be either imported from the West or developed indigenously, yielding important efficiency gains. However, it is equally likely that some (if not a majority) of the structural characteristics of the existing energy supply and end-use systems will deteriorate, implying higher energy consumption per unit of service and thus higher energy demand and carbon emissions.

9.4.2 Renewables

There are two crucial issues concerning the future role of renewable options in the context of greenhouse gas mitigation strategies. One has to do with relatively high costs and the other with generally low conversion efficiency. Costs are usually so high that it is often cheaper to avoid additional energy demands. In other words: *the strongest competitor of renewable energies like solar is energy conservation.* This might lead to a situation where necessary investments, which could achieve cost reductions along the learning curve for renewable technologies, compare unfavorably with investments in energy efficiency improvements. Low energy efficiency *per se* is not a direct issue for technologies harnessing natural energy flows. Nevertheless, it is important because lower efficiency results in higher material, labor and land requirements that have to be mobilized to implement and operate renewable options. Thus, the lower the efficiency, the higher the costs. At present, most of the renewable options, whether they are based on photosynthesis or other natural flows, portray minuscule efficiencies compared with fossil or nuclear energy conversion systems. There is a danger that renewables could remain a comparatively high-cost option for CO_2 reduction, unless significant technological improvements enable drastic increases in conversion efficiencies or result in lower non-energy resource requirements.

Trade-offs among different renewable options have been also illustrated in the study. For instance, it was shown that some hydropower projects in Brazil may not be too attractive because the area to be flooded could produce more energy with sugarcane plantations and ethanol production than by hydroelectricity. Therefore, renewable options also have to be carefully assessed within the comprehensive analysis of many alternatives, including comparisons with efficiency improvement measures, other renewables and also more traditional energy options.

9.4.3 Work-Pleasure

Affluence leads to spare time. Increasing life expectancy, the reduction of working hours and shortening of active work careers are pervasive phenomena in all industrialized countries. Changes in the structure of goods and services consumed accompany these shifts in time budgets and allocation. For energy services, this implies a progressive shift in consumption away from the productive to the service sphere. However, it is precisely in the growing area of energy service demands that the end-use efficiencies are the lowest. This includes residential energy end-use, leisure activities and transportation. Additionally, individual reactions to economic signals are different from those in the productive sphere. This is perhaps best illustrated by the development of energy consumption in the

OECD countries since 1973. Whereas technology-stimulated energy efficiency improvements have progressively decoupled industrial from energy demand growth, the growth in energy demand by the households/services and transportation sectors has continued even during periods of high energy prices. Economic (even if bounded) rationality in industrial activities resulted in a substantial reduction of energy requirements per unit value added. Leisure and private activities, on the other hand, are frequently associated with less concern for (economic) efficiency in general and energy use in particular. Further shifts in service demand toward free-time and leisure activities can be expected. In the absence of a new consumer ethic and changing preferences for personal investment and consumption decisions, energy efficiency gains could lose momentum or could be offset by drastic service demand increases. This would all make the identified mitigating potentials more difficult to achieve and more remote.

9.5 Implementation Strategies

The multitude of options discussed in the study can be regrouped together in a number of implementation strategies that might lead toward further improvements in energy efficiency and decarbonization.

First of all, emission avoidance is a clear priority over emission abatement. For example, minimizing carbon releases from deforestation will have a more significant short- to medium-term effect than even the most ambitious global afforestation strategy. Stopping the flaring of natural gas which produces CO_2 emissions, without any energy service delivered, is another (though more limited) example. Improvement of energy efficiency and delivery of required energy services (referred to as "service efficiency") is another priority area for achieving large gains in CO_2 reductions.

In the short term, improved energy end-use efficiency and the use of conversion systems with higher efficiency, such as cogeneration or combined-cycle power plants, should be deployed wherever possible. Priority should be given to all measures that can be deployed under "no-regrets" policies or that yield multiple benefits in addition to reduced carbon emissions. Reduced local air pollution, less acidic precipitation, reduced dependence on imports, and overall lower systems costs are examples of multiple objectives that could be fulfilled by a number of options discussed here.

In the case of fossil fuels, the "least of all evils" is natural gas because it results in the lowest CO_2 emissions. There are many efforts to translate the pervasive geological occurrences of natural gas into economically recoverable reserves. Among such policy measures are new transport and distribution infrastructures in a large number of countries and the abandonment of restrictive regulations that impair more widespread use of natural gas. Marginal, yet globally still important, improvements can also be realized by a number of improved coal preparation and combustion technologies to be promoted in those countries where no cleaner fossil or non-fossil options are available. In contrast, "dirty fossil fuel technologies" like autothermal synfuels production from coal should be treated cautiously as a possible longer-term energy strategy. The fact that an ample oil and natural gas resource base is at our disposal relieves the urgency and pressure to prematurely go to these carbon-intensive alternatives.

The study identifies a number of research and development priorities concerning second- and third-generation technologies. Emphasis should be given to the further development of energy systems that deliver carbon-free energy carriers to end-uses. In particular, the combination of electricity and hydrogen offers multiple advantages. Both are "blind" to the primary energy sources upstream and are easily mutually convertible. In particular, the electrochemical conversion routes offer the promise of very high efficiencies. Both are well suited for use in conjunction with very different possible structures of future energy systems from small and decentralized renewable sources all the way to the largest nuclear plants. What is most important is that they are both *de facto* pollution free and zero-carbon energy carriers. All of these developments would lead to a further decarbonization of the world economy and ultimately also to zero-carbon emissions. A further research and development priority in conjunction with zero-carbon energy carriers is to close the carbon cycle also upstream. This means that carbon is removed from all fossil energy sources still in use before or immediately after the carbon-free energy carriers are generated.

Although electricity generation is rapidly expanding worldwide, the production of hydrogen is very limited and most processes are too costly and restricted for energy purposes. Hydrogen production by steam reforming of natural gas or synthesis gas is associated with high costs. Steam reforming with CO_2 separation and storage would be even more expensive. Electrolysis is a more mature technology but by no means much less expensive. Significant research and development efforts are therefore still required to identify the most promising and economic routes that might lead toward a hydrogen and electricity economy. The potential marriage of electricity and hydrogen is perhaps best symbolized by fuel-cell technology. It holds the promise of achieving environmentally compatible future energy systems even in those areas where population and energy consumption densities are too high to easily harness natural energy flows. At present, this is already the case in the majority of urban and metropolitan areas. Hydrogen and electricity are in the best position to bridge the gap between the low density of renewable energy generation and the high density of consumption. Hydrogen can also provide an appropriate storage medium for meshing the discrepancies between the availability of renewable (intermittent) energy and varying demand loads.

Should these more futuristic concepts fail to become available at a scale sufficient to close the carbon cycle prior to fossil energy combustion, CO_2 removal and scrubbing technologies would provide an adequate handle for reducing CO_2 emissions. These technologies are still rather expensive and further development will be required to reduce their costs. Nevertheless, the largest uncertainties surrounding scrubbing technologies and carbon removal in general concern carbon storage. Carbon could be stored by enhancing its natural sinks, such as those in the deep ocean, or by depositing it in appropriate natural reservoirs such as depleted oil and natural gas fields. The deep ocean is the largest natural sink and reservoir of carbon and would in principle provide unlimited storage capacity. The costs of carbon injection and subduction into the deep ocean are an unresolved issue but even more critical are the possible adverse effects on marine environments. Storage in depleted oil and natural gas fields seems more attractive and associated with fewer unknowns. The use of CO_2 for enhanced oil recovery appears to be the most promising storage option because enhanced recovery yields significant economic benefits from additions to the petroleum resource base. When extracted, each additional barrel of oil can cover some of the CO_2 deposition costs.

The introduction and diffusion of completely new energy systems and carriers is a lengthy process on the global scale. It might take decades before new energy systems with higher environmental compatibility and reduced or eliminated carbon emissions become pervasive worldwide. Therefore, evolutionary strategies for incremental adjustments and responses to environmental concerns deserve particular attention. For example, the introduction of hydrogen-powered aircraft would offer a high-value and relatively small-scale application area for the initial market penetration of carbon-free energy carriers. The experience gained in such a quasi-protected *in vitro* environment could pave the way to exploit the learning curve for subsequent cost reductions as a prerequisite for large-scale applications.

All of these results indicate that future energy systems need to be much more integrated than their current counterparts. Integration will be required both along technological and institutional domains. Institutionally, many different operations would need to be consolidated, including such presently quite distinct organizations as electric utilities, chemical and automotive industries. New institutional interfaces between consumers and end-use providers will have to be organized. For example, comprehensive demand-side management appears to be almost the only realistic option capable of closing the large gap between social and individual discount rates. Utilities will have to provide energy services rather than energy itself to assure that end-use efficiency improvement potentials are realized to their maximum possible levels. The increased grid-orientation of energy systems also points in the direction of further integrating those components presently distant from one another. Grid-orientation could eventually lead to integration on a global scale as is already the case for gas and electricity grids at the international level. Energy systems will also have to be integrated horizontally to link different primary energy sources to many possible end-use categories. This could be achieved by using multiple processes along the lines of the novel integrated energy system that first decomposes fossil energy into hydrogen and carbon monoxide, and combines them stoichiometrically with each other and with oxygen from the air. The process is possible with or without a zero-carbon external heat source such as nuclear or solar energy. Such an integrated system could eliminate most of the emissions in addition to closing the carbon cycle.

Another aspect of systems integration in general is the closing of the whole industrial metabolism and energy flows, thus eliminating most of the waste streams. The objective is to achieve almost complete recycling of material and chemical flows. This would include the energy-carbon cycle. For instance, extracted fossil fuels should preferably be used to produce zero-carbon energy carriers with the removed CO_2 then being returned to the original reservoir for permanent disposal. From such a perspective, natural gas and petroleum are the fuels of choice from such a perspective because they have a more favorable hydrogen to carbon ratio and thus lead to lower carbon flows. In contrast, hydrogen production with elementary carbon separation from coal or even biomass appears to be a less attractive option simply because of the (costly) carbon and other material handling operations. To supply the current global energy requirements of about 12 TWyr with hydrogen from biomass would require gigantic carbon handling capabilities and storage capacities. The carbon black obtained as a "by-product" of such a separation process would represent a material handling problem to the tune of 300 Gt per year! In contrast, no other commodity (steel, cement, etc.) exceeds 1 Gt per year. The same concept of removal of pollutants and storage in the original fuel reservoir could also be extended from carbon to other elementary constituents such as sulfur or nitrogen. Ultimately, this could completely close the metabolism of the energy system.

9.6 Environmentally Compatible Energy Strategies

Any long-term strategy to arrest CO_2 emissions implies important trade-offs among many complex issues. There are demographic developments, economic priorities, human preferences and aspirations and precautionary principles to hedge against the risks of undesired changes in the global carrying capacity. The scales of human activities have changed so dramatically that we can no longer neglect and be negligent toward our interference with natural processes on Earth such as the geochemical cycle. Perceptions about possible energy futures are thus also changing.

What is changing in the energy area is the increasing recognition that fossil energy is more abundant on Earth than was believed only a decade ago and that the ultimate limits to energy consumption may not be the resources but rather the environment. What is perhaps even more important is the recognition that the ultimate goal of energy systems is to provide adequate services for whatever level of population will inhabit the Earth during the twenty-first century. Human ingenuity and its expression in the form of technologies to provide the required services are now challenged to make even more "prudent use of the carbon atom" (Häfele *et al.*, 1981) and to minimize our interference with natural cycles, at least as long as it is needed to acquire sufficient scientific certainty about the possible consequences.

Energy Vol. 18, No. 5, pp. 597–609, 1993
Printed in Great Britain. All rights reserved

0360-5442/93 $6.00 + 0.00

References

Abele, A.R., Kindt, G.S., Clark, W.D., Payne, R., and Chen, S.L., 1987, *An Experimental Program to Test the Feasibility of Obtaining Normal Performance from Combustors Using Oxygen and Recycled Gas Instead of Air*, ANL/CNSV-TM-204, Argonne National Laboratory, Argonne, USA.

Allan, T. and Lanly, J.P., 1991, *Overview of Status and Trends of World's Forests*, Proceedings of the Technical Workshop to Explore Options for Global Forestry Management, 24–29 April 1991, Bangkok, Thailand, International Institute for Environment and Development, UK.

Alves, D.S., 1991, *Remote Sensing and Deforestation Rates in Brazil*, Presented at the 1991 Global Change Institute, Snowmass, Colorado, Office for Interdisciplinary Earth Studies, NCAR, Boulder, Colorado, USA.

American Institute of Physics (AIP), 1975, *Efficient Use of Energy*, Conference Proceedings No. 25, AIP, New York, USA.

Andrasko, K., 1990, *Climate Change and Global Forests: Current Knowledge of Potential Effects, Adaption and Mitigation Options*, FAO:MISC/90/7, Forestry Department, Food and Agriculture Organization, Rome, Italy.

Andrasko, K., Heaton, K., and Winnett, S., 1991, *Evaluating the Costs and Efficiency of Options to Manage Global Forests: A Cost Curve Approach*, Proceedings of the Technical Workshop to Explore Options for Global Forestry Management, 24–29 April 1991, Bangkok, Thailand, International Institute for Environment and Development, UK.

Anonymous, 1989, *The Noordwijk Declaration on Climate Change: Atmospheric Pollution and Climate Change*, Ministerial Conference held at Noordwijk, The Netherlands, 6–7 November 1989.

Arthur, W.B., 1988, Competing technologies: An overview, in G. Dosi, C. Freeman, R. Nelson, G. Silverberg, and L. Soete, eds., *Technical Change and Economic Theory*, Pinter, London, UK, pp. 590–607.

Asea Brown Boveri (ABB), 1982, *Electric Power from Pressurized Fluidized Bed Combustion*, ABB, Fingspong, Sweden.

Asian Energy Institute (AEI), 1991, *Collaborative Study on Strategies to Limit CO_2 Emissions in Asia and Brazil*, AEI, New Delhi, India.

Austvik, T. and Løken, K.-P., 1992, CO_2 *Hydrate Deposition on the Sea-Bed*, Paper presented at the 1st International Conference on Carbon Dioxide Removal, 4–6 March 1992, Amsterdam, The Netherlands.

Ausubel, J.H., 1980, *Climatic Change and the Carbon Wealth of Nations*, WP-80-75, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Ausubel, J.H., Grübler, A., and Nakićenović, N., 1988, Carbon dioxide emissions in a methane economy, *Climatic Change* 12:245–263.

Ayres, R.U., 1988, *Energy Inefficiency in the US Economy: A New Case for Conservation*, Carnegie-Mellon University, Pittsburgh, USA.

Baes C., Beall, S., Lee, D., and Marland, G., 1980, *Options for the Collection and Disposal of Carbon Dioxide*, ORNL-5657, Oak Ridge National Laboratory, Oak Ridge, TN, USA.

Bajura, R.A. and Webb, H.A., 1991, The marriage of gas turbines and coal, *Mechanical Engineering Journal*, September, pp. 58ff.

Baker, C., 1991, Tidal power, *Energy Policy* 19(8):792–798.

Baldwin, S.F., 1986, *Biomass Stoves: Engineering Design, Development, and Dissemination*, VITA, Arlington, VA, USA.

Blok, K., Hendriks, C., and Turkenburg, W., 1989, *The Role of Carbon Dioxide Removal in the Reduction of the Greenhouse Effect: Energy Technologies for Reducing Emissions of Greenhouse Gases*, Proceedings of the Experts' Seminar, April 1989, OECD, Paris, France.

Blok K., Farla, J., Hendriks, C., and Turkenburg, W., 1991, *Carbon Dioxide Removal: A Review*, Paper presented at the International Symposium on Environmentally Sound Energy Technologies and their Transfer to Developing Countries and European Economies in Transition (ESETT '91), October 1991, ENI - San Donato Milanese, Italy.

British Petroleum (BP), 1991, *BP Statistical Review of World Energy*, BP, London, UK.

Brown, S., Lugo, A.E., and Chapmen, J., 1986, Biomass of tropical tree plantations and its implications for the global carbon budget, *Canadian Journal of Forest Research* **16**.

Budyko, M., 1982, *The Earth's Climate: Past and Future*, Academic Press, New York, USA.

Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), 1989, *Reserven, Resourcen und Verfügbarkeit von Energierohstoffen*, BGR, Hannover, Germany.

Bureau of National Affairs (BNA), 1991, *Discussion Paper to be Issued on CO_2 Rather than Formal Commission Proposal*, International Environment Reporter Current Report, Vol. 24, p. 501 (available on Lexis), USA.

Burtraw, D. and Toman, M.A., 1991, *Equity and International Agreements for CO_2 Containment*, ENR91-07, Energy and Natural Resources Division, Resources for the Future, Washington, DC, USA.

Cameron, D.S., 1990, World developments of fuel cells, *International Journal of Hydrogen Energy* **15**(9).

Carnegie Commission, 1992, *International Environmental Research and Assessment: Proposals for Better Organization and Decision Making*, Report of the Carnegie Commission on Science, Technology and Government, USA, April.

Cavallo, A., Hock, S., and Smith, D., 1992, Wind energy: Technology and economics, in T.B. Johansson, H. Kelly, A.K.N. Reddy, and R.H. Williams, eds., *Renewables for Fuels and Electricity*, Island Press, Washington, DC, USA.

Chandler, W.U., ed., 1990, *Carbon Emissions Control Strategies: Case Studies in International Cooperation*, World Wildlife Fund, Washington, DC, USA.

Chapman, J.N. and Johanson, N.R., 1991, MHD Generators in Power Production, *Mechanical Engineering Journal*, September, pp. 64ff.

Chayes, A., 1991, Managing the transition to a global warming regime, or what to do 'til the treaty comes, in J.T. Mathews, ed., *Greenhouse Warming: Negotiating a Global Regime*, World Resources Institute, Washington, DC, USA.

Cheng Chun, H. and Wei Du, L., 1991, The development of new and renewable sources of energy in China, in *Global Collaboration on a Sustainable Energy Development*, Technical University of Denmark.

Commission of the European Communities (CEC), Directorate-General for Economic and Financial Affairs, 1992, *The Economics of Limiting CO_2 Emissions*, European Economy Special Edition No. 1, CEC, Brussels, Belgium.

Committee on Science, Engineering and Public Policy (COSEPUP), 1991, *Policy Implications of Greenhouse Warming: Report of the Mitigation Panel*, U.S. National Academy of Sciences, U.S. National Academy of Engineering and Institute of Medicine, U.S. National Academy Press, Washington, DC, USA.

Cooper, C.F., 1983, Carbon storage in managed forests, *Canadian Journal of Forestry Research* **13**:155–166.

Cottie, L.E., Schreuder, G.F., and de Barros, A.A.A., 1990, *Brazil: A Country Profile of the Forests and Forest Industries*, Working Paper 27, CINTRAFOR, University of Washington, Seattle, USA.

Culp, A.W., 1991, *Principles of Energy Conversion*, McGraw-Hill Inc., New York, USA.

Dacey, J., Golomb, D., Michael, A., and Zemba, S., 1992, *The Fate of CO_2 Sequestered in the Deep Ocean*, Paper presented at the 1st International Conference on Carbon Dioxide Removal, 4–6 March 1992, Amsterdam, The Netherlands.

Dafter, R., 1980, *Scraping the Barrel, The Worldwide Potential for Enhanced Oil Recovery*, Financial Times Business Information Ltd., London, UK.

Department of Energy (DOE), 1988, *Five Year Research Plan (1988–1992): Biofuels and Municipal Waste Program*, DOE/CH10093-25, Office of Renewable Energy Technologies, U.S. Department of Energy, Washington, DC, USA.

Dessus, B., Devin, B., and Pharabod, F., 1992, *World Potential of Renewable Energies*, Extraits de la Houille Blanche, Paris, France.

Dixon, R.K., Winjum, J.K., and Krankina, O.N., 1991, *Afforestation and Forest Management Options and Their Costs at the Site Level*, Proceedings of the Technical Workshop to Explore Options for Global Forestry Management, 24–29 April 1991, Bangkok, Thailand, International Institute for Environment and Development, UK.

Dornbusch, R. and Poterba, J.M., eds., 1991, *Global Warming: Economic Policy Responses*, MIT Press, Cambridge, MA, USA.

Dosi, G., 1991, The research on innovation diffusion: An assessment, in N. Nakićenović and A. Grübler, eds., *Diffusion of Technologies and Social Behavior*, Springer-Verlag, Germany.

Dosi, G., Freeman, C., Nelson, R., Silverberg, G., and Soete, L., eds., 1988, *Technical Change and Economic Theory*, Pinter, London, UK.

Eden, R., Posner, M., Bending, R., Crouch, E., and Stanislaw, J., 1981, *Energy Economics*, Cambridge University Press, MA, USA.

Electric Power Research Institute (EPRI), 1990, New push for energy efficiency, *EPRI Journal* **15**(3):4–17; and Barakat and Chamberlin Inc., 1990, *Efficient Electricity Use: Estimates of Maximum Energy Savings*, EPRI Report CU-6746, EPRI, Palo Alto, CA, USA.

Elliot, D.L., Wendell, L.L., and Gower, G.L., 1991, *An Assessment of the Available Windy Land Area and Wind Energy Potential in the Contiguous U.S.*, PNL-7789, Pacific Northwest Laboratories, Richland, WA, USA.

Energy and Industry Subgroup (EIS) of Intergovernmental Panel on Climate Change (IPCC), 1991, *Enery and Industry Subgroup Report*, IPCC, Geneva, Switzerland.

Enquête-Kommission "Vorsorge zum Schutz der Erdatmosphäre" Deutscher Bundestag, 1990, *Vol. 4 Fossile Energieträger*, Economica-Verlag, Bonn, Germany.

Environmental Protection Agency (EPA), 1990, *Policy Options for Stabilizing Global Climate*, EPA, Washington, DC, USA.

Esser, G., 1991, Osnabrück biosphere model: Structure, construction, results, in G. Esser and D. Overdieck, eds. *Modern Ecology, Basic and Applied Aspects*, Elsevier, Amsterdam, The Netherlands.

Fearnside, P.M., Tardin, A.T., and Meira Filho, L.G., 1990, *Deforestation Rate in Brazilian Amazonia*, SCT/PR INPA, National Secretariat of Science and Technology, Brasilia, Brazil.

Feron, P., Jansen, A., and Klaassen, R., 1992, *Membrane Technology in Carbon Dioxide Removal*, Paper presented at the 1st International Conference on Carbon Dioxide Removal, 4–6 March 1992, Amsterdam, The Netherlands.

Ferreira, M.C. and Marcondes, M.E., 1991, Global deforestation and CO_2 emissions, Past and present: A comprehensive review, *Energy and Environment* **2**(3):235–282.

Financial Times Business Information (FTBI), 1991, Energy/carbon tax concept detailed by Commission paper, *EC Energy Monthly* **30**:4–6.

Fisher, D., ed., 1990, *Options for Reducing Greenhouse Gas Emissions*, Stockholm Environment Institute, Stockholm, Sweden.

Food and Agriculture Organization (FAO), 1991a, FAO's 1990 reassessment of tropical forest cover, *Nature and Resources* **27**(2):21–26.

Food and Agriculture Organization (FAO), 1991b, *Wood and Wood Products 1961–1989 ... 2010*, Food and Agriculture Organization of the United Nations, Rome, Italy.

Food and Agriculture Organization (FAO), 1991c, *FAO Yearbook 1989. Forest Products*, FAO, Rome, Italy.

Food and Agriculture Organization (FAO), 1991d, *Climate Change and Global Forests: Current Knowledge of Potential Effects, Adaption and Mitigation*, Proceedings of the Technical Workshop to Explore Options for Global Forestry Management, 24–29 April 1991, Bangkok, Thailand, International Institute for Environment and Development, UK.

Frankena, F., 1987, Rethinking the scale of biomass energy conversion facilities: The case of wood-electric power, *Biomass* **14**:149–171.

Freeman, C. and Perez, C., 1988, Structural crises of adjustment, business cycles and investment behavior, in G. Dosi, C. Freeman, R. Nelson, G. Silverberg, and L. Soete, eds., *Technical Change and Economic Theory*, Pinter, London, UK, pp. 38–66.

Fujii, Y., 1990, *An Assessment of the Responsibility for the Increase in the CO_2 Concentration and Inter-generational Carbon Accounts*, WP-90-55, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Fujii, Y., 1992, *Assessment of CO_2 Emission Reduction Technologies and Building of a Global Energy Balance Model*, Kaya Laboratory, Department of Electrical Engineering, University of Tokyo, Japan.

Giovannini, B. and Pain, D., 1990, *Scientific and Technical Arguments for the Optimal Use of Energy*, Université de Genève, Geneva, Switzerland.

Gipe, P., 1991, Wind Energy Comes of Age, *Energy Policy*, August, pp. 756–767.

Gold, T., 1987, *Power from the Earth*, J.M. Dent, London, UK.

Goldemberg, J., Macedo, I., Monaco, L., 1992, The Brazilian fuel-alcohol program, in T.B. Johansson, H. Kelly, A.K.N. Reddy, and R.H. Williams, eds., *Renewables for Fuels and Electricity*, Island Press, Washington, C, USA.

Goldemberg, J., Johansson, T.B., Reddy, A.K.N., and Williams, R.H., 1988, *Energy for a Sustainable World*, Wiley Eastern Limited, New Delhi, India.

Golomb, D., Herzog, H., Tester, J., White, D., and Zemba, S., 1989, *Feasibility, Modeling and Economics of Sequestering Power Plant CO_2 Emissions in the Deep Ocean*, MIT-EL 89-003, MA Institute of Technology, Cambridge, MA, USA.

Goudrian, J., 1991, *Is the Biosphere a Buffer for Increasing Atmospheric CO_2?* Department of Theoretical Production-Ecology, Agricultural University of Wageningen, The Netherlands (draft).

Grainger, A., 1988, Estimating areas of degraded tropical lands requiring replenishment of forest cover, *The International Tree Crops Journal* **5**.

Grainger, A., 1990, *Modeling the Impact of Alternative Afforestation Strategies to Reduce Carbon Dioxide Emissions*, Proceedings of the Conference on Tropical Forestry Response Options to Global Climate Change, São Paulo, Brazil, pp. 93–104.

Grainger, A., 1991, Constraints on Increasing Tropical Forest Area to Combat Global Climate Change, *Proceedings of the Technical Workshop to Explore Options for Global Forestry Management*, 24–29 April 1991, Bangkok, Thailand, International Institute for Environment and Development, UK.

Grubb, M., 1989, *The Greenhouse Effect: Negotiating Targets*, Royal Institute of International Affairs, London, UK.

Grubb, M. and Meyer, N., 1992, Wind energy: Resources, systems and regional strategies, in T.B. Johansson, H. Kelly, A.K.N. Amulya, and R.H. Williams, eds., *Renewables for Fuels and Electricity*, Island Press, Washington, DC, USA.

Grübler, A., 1990, *The Rise and Fall of Infrastructures: Dynamics of Evolution and Technological Change in Transport*, Physica-Verlag, Heidelberg, Germany.

Grübler, A., 1991a, Introduction to diffusion theory, in R.U. Ayres, W. Haywood and I. Tchijov, eds., *Computer Integrated Manufacturing Vol. 3: Models, Case Studies and Forecasts of Diffusion*, Chapman and Hall, London, UK, pp. 3–52.

Grübler, A., 1991b, Energy in the 21st century: From resource to environmental and lifestyle constraints, *Entropie* **164/165**:29–34.

Grübler, A. and Fujii, Y., 1991, Inter-generational and spatial equity issues of carbon accounts, *Energy* **16**(11–12):1397–1416.

Grübler, A. and Nakićenović, N., 1991a, *Long Waves, Technology Diffusion, and Substitution*, RR-91-17, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Grübler, A. and Nakićenović, N., 1991b, *Evolution of Transport Systems: Past and Future*, RR-91-8, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Grübler, A. and Nowotny, H., 1990, *Towards the Fifth Kondratiev Upswing: Elements of an Emerging New Growth Phase and Possible Development Trajectories*, RR-90-7, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Grübler, A., Nakićenović, N., and Schäfer, A., 1992, Dynamics of Transport and Energy Systems: History of Development and a Scenario for the Future, *Proceedings of the World Energy Council 15th Congress*, T3.3, 20–25 September 1992, Madrid, Spain.

Gupta, S. and Khanna, N., 1991, India country paper, in Ghosh, P., Achanta, A., Bhandari, P., Damodaran, M., and Khanna, N., eds., *Collaborative Study on Strategies to Limit CO_2 Emissions in Asia and Brazil*, Asian Energy Institute, New Delhi, India.

Häfele, W. *et al.*, 1981, *Energy in a Finite World*, Ballinger, Cambridge, MA, USA.

Häfele, W. and Nakićenović, N., 1984, *The Contribution of Oil and Gas for the Transition to Long-range Novel Energy Systems*, Proceedings of the 11th World Petroleum Congress, 28 August–2 September 1983, John Wiley, Chichester, UK.

Häfele, W., Barnert, H., Messner, S., and Strubegger, M., with Anderer, J., 1986, Novel integrated energy systems: The case of zero emissions, in W.C. Clark and R.E. Munn, eds., *Sustainable Development of the Biosphere*, Cambridge University Press, Cambridge, UK.

Hall, D.O., 1991, Biomass energy, *Energy Policy* **19**(8):711–737.

Hall, D.O., Mynick, H.E., and Williams, R.H., 1990, *Carbon Sequestration vs. Fossil Fuel Subscription: Alternative Roles for Biomass in Coping with Greenhouse Warming PU/CEES Report No. 255*, Center for Energy and Environmental Studies, Princeton University, Princeton, NJ, USA.

Hall, D.O., Mynick, H.E., and Williams, R.H., 1991a, Cooling the Greenhouse with Bioenergy, *Nature* **353**, 5 September.

Hall, D.O., Mynick, H.E., and Williams, R.H., 1991b, Alternative roles for biomass in coping with greenhouse warming, *Science and Global Security* **2**(2–3):131–151.

Hall, D.O., Woods, J., Senelwa, A.K., and Rosillo-Calle, D., 1992, Biomass for energy: Future supply prospects, in T.B. Johansson, H. Kelly, A.K.N. Reddy and R.H. Williams, eds., *Renewables for Fuels and Electricity*, Island Press, Washington, DC, USA.

Harvey, L.D.D., 1989, Managing atmospheric CO_2, *Climatic Change* **15**:343.

Haugland, T., Lunde, A.T., and Roland, K., 1992, *A Review and Comparison of CO_2 Taxes in the Nordic Countries*, Paper presented at the OECD Workshop on Fee and Charge Systems for Reducing GHG Emissions, 5–6 November 1991, OECD, Paris, France.

Hausman, J.A., 1979, Individual discount rates and the purchase and utilization of energy-using durables, *Bell Journal of Economics* **10**:33–54.

Hendriks, C., Blok, K., and Turkenburg, W.C., 1991, Technology and cost of recovering and storing carbon dioxide from an integrated-gasifier, combined cycle plant, *Energy* **16**:1277.

Herman, R., Ardekani, S.A., and Ausubel, J.H., 1989, Dematerialization, in J.H. Ausubel and H.S. Sladovich, eds., *Technology and Environment*, U.S. National Academy Press, Washington, DC, USA.

Holt, J.A. and Spain, A.V., 1986, Some biological and chemical changes in a North Queensland Soil following replacement of rainforest with *Araucaria cunninghammii*, *Journal of Applied Ecology* **23**.

Horn, F. and Steinberg, M., 1982, *Possible Storage Sites for Disposal and Environmental Control of Atmospheric Carbon Dioxide*, Department of Energy and Environment, Brookhaven National Laboratory, Upton, USA.

Houghton, R.A., 1990, The global effects of tropical deforestation, *Environmental Science and Technology* **24**(4):414–422.

Houghton, R.A., 1991, Tropical deforestation and atmospheric carbon dioxide, *Climatic Change* **19**:99–118.

Houghton, R.A., Boone, R.D., Fruci, J.R., Hobbie, J.E., Melillo, J.M., Palm, C.A., Peterson, B.J., Shaver, G.R., Woodwell, G.M., Moore, B., Skole, D.L., and Meyers, N., 1987, The flux of carbon from terrestrial ecosystems to the atmosphere in 1980 due to changes in land use: Geographical distribution of the global flux, *Tellus* 39(B):122–139.

Houghton, R.A. and Skole, D.L., 1990, Carbon, in B.L. Turner II, W.C. Clark, R.W. Kates, J.F. Richards, J.T. Mathews, and W.B. Meyer, eds., *The Earth as Transformed by Human Action*, Cambridge University Press, Cambridge, UK.

Houghton, R.A., Unruh, J., and Lefèbre, P.A., 1991, Current Land Use in the Tropics and Its Potential for Sequestering Carbon, *Proceedings of the Technical Workshop to Explore Options for Global Forestry Management*, 24–29 April 1991, Bangkok, Thailand, International Institute for Environment and Development, UK.

International Energy Agency (IEA), 1991, *Energy Efficiency and the Environment*, OECD/IEA, Paris, France.

Institut d'Estudis Metropolitans (IEM) de Barcelona, 1988, *Cities: Statistical, Administrative and Geographical Information on the Major Urban Areas of the World*, Vols. 1–5, IEM, Barcelona, Spain.

Intergovernmental Negotiating Committee (INC), 1991, *Consolidated Working Document*, A/AC.237/Misc.17, Fourth Session, United Nations General Assembly, 9–20 December 1991, Geneva, Switzerland.

Intergovernmental Negotiating Committee (INC), 1992, Annex I to the Report of the Intergovernmental Negotiating Committee for a Framwork Convention on Climate Change: United Nations Framework Convention on Climate Change, Document A/AC.237/18 (Part II)/Add.1, 15 May 1992, UN, New York, USA.

Intergovernmental Panel on Climate Change (IPCC), 1990, *Climate Change, The IPCC Scientific Assessment*, Cambridge University Press, Cambridge, UK.

Intergovernmental Panel on Climate Change (IPCC), 1991, *Climate Change, The IPCC Response Strategies*, Island Press, Washington, DC, USA.

Intergovernmental Panel on Climate Change (IPCC), 1992, *1992 IPCC Supplement*, February, Geneva, Switzerland.

International Atomic Energy Agency (IAEA), 1991, *Advanced Technologies for Water Cooled Reactors 1990*, International Working Group on Advanced Technologies for Water Cooled Reactors, IAEA, Vienna, Austria.

International Atomic Energy Agency (IAEA), 1992, *Nuclear Power Reactors in the World*, IAEA, Vienna, Austria.

International Labor Organization (ILO), 1991, *Yearbook of Labor Statistics*, International Labor Office, Geneva, Switzerland.

International Road Federation (IRF), 1990, *World Road Statistics*, IRF, Geneva, Switzerland.

Johansson, T.B., Kelly, H., Reddy, A.K.N., and Williams, R.H., 1992, Renewable fuels and electricity for a growing world economy, in T.B. Johansson, H. Kelly, A.K.N. Reddy, and R.H. Williams, eds., *Renewables for Fuels and Electricity*, Island Press, Washington, DC. USA.

Kallio, M., Dykstra, D.P., and Binkley, C.S., 1987, *The Global Forest Sector. An Analytical Perspective*, John Wiley and Sons, New York, USA.

Kaya, Y., Fujii, Y., Matsuhashi, R., Yamaji, K., Shindo, Y., Saiki, H., Furugaki, I., and Kobayashi, O., 1991, *Assessment of Technological Options for Mitigating Global Warming*, Paper presented at the IPCC EIS Group Meeting, 6–7 August 1991, Geneva, Switzerland.

Kearney, D., Price, H., Repogle, I., Manes, T., Constanzo, J., Gilon, Y., and Walzer, S., 1991, Status of the SEGS Plants, *Proceedings of the International Solar Energy Society*, Denver, CO, USA, August.

Kearney, D., Cavallo, A., Hock, S., and Smith, D., 1992, Wind Energy: Technology and Economics, in T.B. Johansson, H. Kelly, A.K.N. Reddy, and R.H. Williams *Renewables for Fuels and Electricity*, Island Press (in press).

Kemi, W., 1987, Industrial uses of carbon dioxide, in M. Aresta and G. Forti, eds., *Carbon Dioxide as a Source of Carbon*, NATO ASI Series C, Vol. 206, Reidel, Dordrecht, The Netherlands.

Koide, H., Noguchi, Y., Iijima, M., Ito, K., Tazaki, Y., and Shindo, Y., 1992, *Subterranean Disposal and Long-term Storage of Carbon Dioxide in Unused Aquifers and in Depleted Natural Gas Reservoirs*, Paper presented at the 1st International Conference on Carbon Dioxide Removal, 4–6 March 1992, Amsterdam, The Netherlands.

Lanly, J.P., Singh, K., and Janz, K., 1991, FAO's 1990 reassessment of tropical forest cover, *Nature and Resources* **27**(2):21–26.

Larson, E., 1992, Personal communication, 5 March.

Larson, E.D., Svenningsson, P., and Bjerle, I., 1989, Biomass gasification for gas turbine power generation, in T.B. Johansson, B. Bodlund, and R.H. Williams, eds., *Electricity: Efficient End-use and New Generation Technologies and Their Planning Implications*, Lund University Press, Lund, Sweden.

Ledbetter, M. and Ross, M., 1989, *Supply Curves of Conserved Energy for Automobiles*, American Council for an Energy Efficient Economy, Washington, DC, USA.

Lee, T.H., Linden, M.R., Dreyfus, D.A., and Vasko, T., eds., 1988, *The Methane Age*, Kluwer Academic Press, Dordrecht, The Netherlands.

Lee, T.H., Ball, B.C., and Tabors, R.D., eds., 1990, *Energy Aftermath: How We Can Learn from the Blunders of the Past to Create a Hopeful Energy Future*, Harvard Business School Press, Boston, MA, USA.

Levine, M.D., Geller, H., Koomey, J., Nadel, S., and Price, L., 1992, *Electricity End-Use Efficiency: Experience with Technologies, Markets, and Policies Throughout the World*, Lawrence Berkeley Laboratory, Berkeley, Ca, USA.

Libäck, K., 1992, *Is Wood Needed in the Knowledge Society?* (in Swedish), Paper Presented at the Swedish Academy of Engineering Sciences, February 1991, Stockholm, Sweden.

Lunnan, A., Navrud, S., Rörstad, P.K., Simensen, K., and Solberg, B., 1991, *Forestry and Forest Production in Norway for CO_2 Sequestration* (in Norwegian), Norwegian Institute for Forestry Research, Skogforsk Report 6/1991, ÅS Norway.

Lynd, L.R., Cushman, J.H., Nichols, R.J., and Wyman, C.E., 1991, Fuel ethanol from cellulosic biomass, *Science* **251**:1318–1323.

MacDonald, G.J., 1990, The future of methane as an energy resource, *Annual Review of Energy* **15**:53–83.

Manne, A.S. and Schrattenholzer, L., with the assistance of T.F. Minkoff, 1992, *International Energy Workshop: Overview of Poll Responses*, January edition, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Marchetti, C., 1976, *On Geoengineering and the CO_2 Problem*, RM-76-17, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Marchetti, C. and Nakićenović, N., 1979, *The Dynamics of Energy Systems and the Logistic Substitution Model*, RR-79-13, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Marchetti, C., 1991, *How to Solve the CO_2 Problem Without Tears*, RR-91-6, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Marchetti, C., 1992a, *Trying to Help the Environment – More on the West Ukraine Case*, RR-92-2, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Marchetti, C., 1992b, Personal communication.

Marland, G., 1988, *The Prospect of Solving the CO_2 Problem Through Global Reforestation*, Office of Energy Research, Office of Basic Energy Sciences, Carbon Dioxide Research Division, U.S. Department of Energy, Washington, DC, USA.

Marland, G. and Marland, S., 1992, Should We Store Carbon in Trees? *Water, Air and Soil Pollution* **64**:181–195.

Martin, J., 1990, Glacial-interglacial CO_2 change: The iron hypothesis, *Paleoceanography* **5**:1–13.

Martin, J.H., Gordon, R.M., and Fitzwater, S.E., 1990, Iron in antarctic waters, *Nature* **345**:156–159.

Masseron, J., 1990, *Petroleum Economics*, Editions Technic, Paris, France.

Masters, C.D. *et al.*, 1987, *World Resources of Crude Oil, Natural Gas, Natural Bitumen and Shale Oil, Proceedings of the 12th World Petroleum Congress*, 5:3–27, John Wiley, Chichester, UK.

Masters, C.D., Root, D.H., and Attanasi, E.D., 1991, World resources of crude oil and natural gas, *Preprints of the 13th World Petroleum Congress* 25:1–14, John Wiley, Chichester, UK.

Mather, A.S., 1990, *Global Forest Resources*, Belhaven Press, London, UK.

Mathur, A., 1991, *Energy and CO_2 Scenarios Developed Within Asian Energy Institute's Collaborative Study*, Paper presented at the Workshop on CO_2 Reduction and Removal: Measures for the Next Century, 19–21 March 1991, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Matsuhashi, R., 1991, *Assessment of CO_2 Removal and Disposal Technologies*, Presentation at the Workshop on CO_2 Reduction and Removal: Measures for the Next Century, 19–21 March 1991, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Matsuo, N., 1991, Japan country paper, in Asian Energy Institute (AEI), *Collaborative Study on Strategies to Limit CO_2 Emissions in Asia and Brazil*, AEI, New Delhi, India.

McKelvey, V.E., 1972, Mineral resource estimates and public policy, *American Scientist* 60:32–40.

Meier, A., 1991, *Supply Curves of Conserved Energy*, in Proceedings of the IEA International Conference on Technology Responses to Global Environmental Challenges: Energy Collaboration for the 21st Century, 6–8 November 1991, Vol. 1, Inter Group Corporation, Kyoto, Japan.

Messner, S. and Strubegger, M., 1991, *User's Guide to CO2DB: The IIASA CO_2 Technology Database Version 1.0*, WP-91-31a, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Meyers, N., 1989, Tropical forests, in J. Leggett, ed., *Global Warming: The Greenpeace Report*, Oxford University Press, Oxford, UK.

Nakićenović, N., 1984, *Growth to Limits, Long Waves and the Dynamics of Technology*, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Nakićenović, N., 1986, The automobile road to technological change, diffusion of the automobile as a process of technological substitution, *Technological Forecasting and Social Change* 29:309–340.

Nakićenović, N., 1990, Dynamics of change and long waves, in T. Vasko, R. Ayres, and L. Fontvielle, eds., *Life Cycles and Long Waves*, Springer-Verlag, Berlin.

Nakićenović, N., 1992, *Energy Strategies for Mitigating Global Change*, WP-92-1, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Nakićenović, N., Bodda, L., Grübler, A., and Gilli, P.-V., 1990, *Technological Progress, Structural Change and Efficient Energy Use: Trends Worldwide and in Austria*, International part of a study supported by the Österreichische Elektrizitätswirtschaft AG, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Nakićenović, N. and John, A., 1991, CO_2 mitigation and removal: Measures for the next century, *Energy* 16(11–12):1347–1377.

Newman, P. and Kenworthy, J., 1989, *Cities and Automobile Dependence: A Sourcebook*, Gower Technical, Aldershot, UK.

Nichols, J.K. and Crawford, P.J., 1983, *Managing Chemicals in the 1980s*, OECD, Paris, France.

Nilsson, N.-E., 1982, An alley model for forest resources planning, in B. Ranneby, ed., *Statistics in Theory and Practice. Essays in Honour of Bertil Matrn*, Section of Forest Biometry, Swedish University of Agricultural Sciences, Umeå, Sweden.

Nilsson, N.-E., 1992, *The International Forestry Cooperation. Overview, Retrospects and Prospects* (in Swedish), Royal Swedish Academy of Agriculture and Forestry, February.

Nilsson, S., 1992, *Carbon Sequestering Potential by Global Afforestation*, Unpublished Manuscript, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Nilsson, S., Sallnäs, O., and Duinker, P., 1992a, *Future Forest Resources of Western and Eastern Europe*, Parthenon Publishing Group, Carnforth, UK.

Nilsson, S., Sallnäs, O., Hugosson, M., and Shvidenko, A., 1992b, *The Forest Resources of the Former European USSR*, Parthenon Publishing Group, Carnforth, UK.

Nishikawa, N., Morishita, M., Uchiyama, M., Yamaguchi, F., Otsubo, K., Kimuro, H., and Hiraoka, R., 1992, *Carbon Dioxide Clathrate Formation and its Properties in the Simulated Deep Ocean*, Paper presented at the 1st International Conference on Carbon Dioxide Removal, 4–6 March 1992, Amsterdam, The Netherlands.

Nishimura, F., 1991, *Technology Assessment for the Reduction of Carbon Emissions in the Electricity Sector*, International Institute for Applied Systems Analysis, Laxenburg, Austria (draft).

Nordhaus, W.D., 1975, *Can We Control Carbon Dioxide?* Unpublished internal paper, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Nordhaus, W.D., 1991, The cost of slowing climate change: A survey, *Energy* **12**(1):37–65.

Office of Technology Assessment (OTA), 1991a, *Changing by Degrees: Steps to Reduce Greenhouse Gases*, OTA-0-842, Congress of the United Sates, U.S. Government Printing Office, Washington, DC, USA.

Office of Technology Assessment (OTA), 1991b, *Energy Technology Choices Shaping our Future*, OTA, Washington, DC, USA.

Office of Technology Assessment (OTA), 1992, *Fueling Development: Energy Technologies for Developing Countries*, OTA-E-516, OTA, Washington, DC, USA.

Ogawa, Y., 1991, *Global Warming Problem and Developing Countries*, Energy and Environment Research Section, The Institute of Energy Economics, Tokyo, Japan.

Ogden, J.M., Williams, R.H., and Fulmer, M.E., 1990, *Cogeneration Applications of Biomass Gasifier/Gas Turbine Technologies in the Cane Sugar and Alcohol Industries: Getting Started With Bioenergy Strategies for Reducing Greenhouse Gas Emissions*, Paper presented at the Conference on Global Warming and Climatic Change: Perspectives from Africa, Nairobi, Kenya.

Olivier, D. and Miall, H., 1983, *Energy Efficient Futures: Opening the Solar Option*, Earth Resources Research Limited, London, UK.

Omar, K.I. and Hossain, I., 1991, Bangladesh Country Paer, in Asian Energy Institute (AEI), *Collaborative Study on Strategies to Limit CO_2 Emissions in Asia and Brazil*, AEI, New Delhi, India.

Organisation for Economic Co-operation and Development (OECD), 1989, *OECD Environmental Data: Compendium 1989*, Paris, France.

Organisation for Economic Co-operation and Development (OECD), 1991, *Estimation of GHG Emissions and Sinks*, Experts' Meeting, 18–21 February 1991, OECD, Paris, France.

Pachauri, R.K., 1991, *GHG Emissions and Mitigation Potential in India*, Paper presented at the International Energy Workshop, 18–20 June 1991, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Peng, T.-H. and Broecker, W.S., 1991, Dynamical limitations on the Antarctic iron fertilization, *Nature* **349**(6306):227.

Penner, S., Schneider, A., and Kennedy, E., 1984, Active measures for reducing the global climatic impacts of escalating CO_2 concentrations, *Acta Astronautica* **11**(6):345–348.

Postel, S. and Heise, L., 1988, *Reforesting the Earth*, Paper 83, Worldwatch Institute, Washington, DC, USA.

Ramanathan, V., 1988, The greenhouse theory of climate change: A test by an inadvertent experiment, *Science* **243**:293–299.

Ramaswamy, V. and Kiehl, J., 1985, Sensitivities of the radiative forcing due to large loadings of smoke and dust aerosols, *Journal of Geophysical Research* **90**(D3):5597–5613.

Richards, J.F., 1990, Land transformation, in B.L. Turner II, W.C. Clark, R.W. Kates, J.F. Richards, J.T. Mathews, and W.B. Meyer, eds., *The Earth as Transformed by Human Action*, Cambridge University Press, Cambridge, UK.

Rogner, H.-H., 1990, *Analyse der Förderpotentiale und Langfristige Verfügbarkeit von Kohle, Erdgas und Erdöl*, Studie A.3.1., Enquête-Kommission "Vorsorge zum Schutz der Erdatmosphäre" Deutscher Bundestag, Economica-Verlag, Bonn, Germany.

Rogner, H.-H. and Grübler, A., 1992, *Fossil Fuel Resources: From Supply Scarcity to Carbon Abundance?* International Institute for Applied Systems Analysis, Laxenburg, Austria, forthcoming.

Rosenfeld, A., Atkinson, C., Koomey, J., Meier, A., Mowris, R., and Price, L., 1992, *A Compilation of Supply Curves of Conserved Energy*, Center for Building Science, Lawrence Berkeley Laboratory, CA, USA.

Rossi, C., 1984, *Energy Aspects of Road Transportation, Future Development in Technology: The Year 2000*, The Open University, Milton Keynes, UK.

Row, C., 1990, *Tracing the Flow of Carbon Through U.S. Forest Product Sector*, Paper presented at the IUFRO 19th World Congress, 5–11 August, Montreal, Canada.

Row, C. and Phelps, R.B., 1990, *Determining the Flows and Disposition of Carbon in Timber Harvests and In Wood-in-Use*, American Forestry Association.

Russell, J., 1990, Plantation forestry and the Australian landscape, in J. Dargavel and N. Semple, eds., *Prospects for Australian Forest Plantations*, Centre for Resource and Environmental Studies, Australian National University, Canberra, Australia.

Saha, S. and Chakma, A., 1992, *Separation of CO_2 for Gas Mixtures with Liquid Membranes*, Paper presented at the 1st International Conference on Carbon Dioxide Removal, 4–6 March 1992, Amsterdam, The Netherlands.

Saji, A., Yoshida, H., Sakai, M., Tani, T., Kitamura H., and Kamata, T., 1992, *Fixation of Carbon Dioxide by Clathrate Hydrate*, Paper presented at the 1st International Conference on Carbon Dioxide Removal, 4–6 March 1992, Amsterdam, The Netherlands.

Salam, A., 1988, *Science, High Technology and Development*, Paper presented at the Conference of Nobel Laureates, January 1988, Paris, France, The Third World Academy of Sciences, Trieste, Italy.

Sathaye, J. and Ketoff, A., 1991, CO_2 emissions from major developing countries: Better understanding the role of energy in the long term, *Energy* **12**(1):161–196.

Sathaye, J. and Gadgil, A., 1992, Aggressive cost-effective electricity conservation, *Energy Policy*:163–170, February.

Schäfer, A., 1992, *Carbon Emissions in the Passenger Transport Sector: Technology and Alternative Fuels*, WP-92-04, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Schipper, L., 1976, Raising the productivity of energy utilization, *Annual Review of Energy* **1**:455–517.

Schopfhauser, W., 1992, *Carbon Sequestering Potential by Global Afforestation – The Role of Below-Ground Biomass, Litter and Soil*, Unpublished Manuscript, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Schramm, G., 1991, *Issues and Problems in the Power Sectors of Developing Countries*, Stockholm Initiative on Energy, Environment and Sustainable Development (SEED), Stockholm, Sweden.

Schrattenholzer, L., 1992, The IIASA scenarios of 1981 in comparison with 1992 IEW results, *International Journal of Global Energy Issues*, forthcoming.

Schumpeter, J., 1939, *Business Cycles: A Theoretical, Historical and Statistical Analysis of the Capitalist Process*, Vols. I and II, McGraw-Hill, New York, USA.

Schüßler, U. and Kümmel, R., 1989, *Carbon Dioxide Removal from Fossil Fuel Power Plants by Refrigeration Under Pressure*, in W.D. Jackson and D.A. Hull, eds., Proceedings of the 24th Intersociety Energy Conversion Engineering Conference, Washington, DC, USA.

Sedjo, R.A. and Lyon, K.S., 1990, *The Long-Term Adequacy of World Timber Supply*, Resources for the Future, Washington, DC, USA.

Sedjo, R.A. and Solomon, A.M., 1989, Climate and forests, in N.J. Rosenberg, W.E. Easterling III, P.R. Crosson, and J. Darmstadter, eds., *Greenhouse Warming: Abatement and Adaptation*, Resources for the Future, Washington, DC, USA.

Seifritz, W., 1991, *Der Treibhaus-effekt: Technische Maßnahmen zur CO_2-Entsorgung*, Carl Hanser-Verlag, Munich, Germany.

Shea, C., 1990, *Renewable Energy: Today's Contribution, Tomorrow's Promise*, Worldwatch Paper 81, Worldwatch Institute, Washington, DC, USA.

Shell Briefing Service (SBS), 1991, *Coal and the Environment*, SBS No. 1, London, UK.

Sinyak, Y. and Nagano, K., 1992, *Global Energy and Climate Change*, Draft Status Report 92-04, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Skea, J., 1990, *United Kingdom: A Case Study of the Potential for Reducing Carbon Dioxide Emissions*, PNL-SA-18216, Pacific Northwest Laboratory, Richland, WA, USA.

Socolow, R.H., 1991, *Concluding Remarks*, Paper presented at the Conference on Technologies for a Greenhouse-Constrained Society, 11–13 June 1991, Oak Ridge, TN, USA.

Solar Energy Research Institute (SERI), 1990, *The Potential of Renewable Energy*, SERI/TP-260-3674.

Sorenson, B., 1982, An American energy future, *Energy* **7**(9):783.

Spears, J., 1983, Replenishing the world's forests: Tropical reforestation: An achievable goal? *Commonwealth Forestry Review* **62**(3).

Springmann, F., 1991, *Analysis of the Ecological Impact of Demonstration Projects in the Field of Rational Use of Energy: Development of Evaluation Criteria*, Study on behalf of the Commission of the European Communities, Directorate General for Energy (DG XVII), Regio–Tec GmbH, Starnberg, Germany.

Steinberg, M., 1983, *An Analysis of Concepts for Controlling Atmospheric Carbon Dioxide*, DOE/CH/00016-1, U.S. Department of Energy, Washington, DC, USA.

Steinberg, M., 1990, *Biomass and Hydrocarb Technology for Removal of Atmospheric CO_2*, Prepared for Presentation at the World Hydrogen Energy Conference No. 3, Honolulu, Hawaii, BNL-44410, Brookhaven National Laboratory, Upton, USA.

Steinberg, M., 1991, *CO_2 Mitigation Technologies to Reduce CO_2 Emissions from the Utilization of Fossil Fuel: Executive Summary*, Paper presented at the Workshop on CO_2 Reduction and Removal: Measures for the Next Century, 19–21 March 1991, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Steinberg, M., Cheng, H., and Horn, F., 1984, *A System Study for the Removal, Recovery and Disposal of Carbon Dioxide from Fossil Fuel Power Plants in the United States*, DOE/CH/00016-2, U.S. Department of Energy, Washington, DC, USA.

Steinberg, M. and Grohse, E., 1989, *Hydrocarb-M^{SM} Process for Conversion of Coals to a Carbon-Methanol Liquid Fuel (Carboline-M^{TM})*, BNL-43569, Brookhaven National Laboratory, Upton, USA.

Subak, S. and Clark, W.C., 1991, Accounts for greenhouse gases: Towards a design of fair assessments, in W.C. Clark, ed., *Usable Knowledge for Managing Global Climatic Change*, Report, Stockholm Environment Institute, Sweden.

Subak, S., Raskin, P., and von Hippel, D., 1991, *Current Greenhouse Gas Accounts: Anthropogenic Sources and Sinks*, Stockholm Environment Institute - Tellus Institute, Boston, MA, USA.

Summers, 1971, The conversion of energy, in *Energy and Power*, Scientific American Freeman, San Francisco, CA, USA.

Svensk Energi Utveckling AB, 1991, Press Release, Stockholm, Sweden.

Swisher, J.N., 1992, Cost and Performance of CO_2 Storage in Forestry Projects, *J. of Biomass and Bioenergy* **2**(6):317–328.

Swedish Environmental Protection Agency (SEPA), 1991, *The Carbon Dioxide Tax and Energy Taxes - the Swedish Experience*, Ministry of the Environment, Stockholm, Sweden.

Thompson, D.A. and Matthews, R.W., 1989, *The Storage of Carbon in Trees and Timber*, Research Report 160, Forest Research Station, Alice Holt, Surrey, UK.

Train, K., 1985, Discount rates in consumers' energy-related decisions: a review of the literature, *Energy* **16**(12):1243–1253.

Trexler, M.C., 1991a, Estimating Tropical Biomass Futures: A Tentative Scenario, *Proceedings of the Technical Workshop to Explore Options for Global Forestry Management*, 24–29 April 1991, Bangkok, Thailand, International Institute for Environment and Development, UK.

Trexler, M.C., 1991b, *Minding the Carbon Store: Weighing U.S. Forestry Strategies to Slow Global Warming*, World Resources Institute, Washington DC, USA.

Turkenburg, W.M., 1991, *CO_2 Storage in Depleted Natural Gas Reservoirs*, Paper presented at the Workshop on CO_2 Reduction and Removal: Measures for the Next Century, 19–21 March 1991, International Institute for Applied Systems Analysis, Laxenburg, Austria.

United Nations (UN), 1989, *World Population Prospects 1988*, Population Studies No. 106, Department of International Economic and Social Affairs, UN, New York, USA.

United Nations (UN), 1991a, *1989 Energy Statistics Yearbook*, UN, New York, USA.

United Nations (UN), 1991b, *World Population Prospects 1990*, Population Studies No. 120, UN, New York, USA.

United Nations Conference on Environment and Development (UNCED), 1992a, *Structure of Agenda 21*, A/CONF.151/PC/100 (see also Addenda 1-27), Preparatory Committee, Fourth Session, 2 March–3 April, United Nations General Assembly.

United Nations Conference on Environment and Development (UNCED), 1992b, *Financial Resources and Mechanisms*, A/CONF.151/PC/101, Preparatory Committee, Fourth Session, 2 March–3 April, United Nations General Assembly.

U.S. Agency for International Development (USAID), 1990, *Greenhouse Gas Emissions and the Developing Countries: Strategic Options and the USAID Response*, USAID, Washington, DC, USA.

U.S. Department of Commerce (US DOC), 1991, *Statistical Abstract of the United States 1991*, 111th edn, Washington, DC, USA.

Valenti, M., 1991, Combined cycle plants: Burning cleaner and saving fuel, *Mechanical Engineering Journal*, pp. 46ff, September.

Van de Meer, L., 1992, *Carbon Dioxide Storage in Aquifers*, Paper presented at the First International Conference on Carbon Dioxide Removal, 4–6 March 1992, Amsterdam, The Netherlands.

Van der Harst, A.C. and van Nieuwland, A.J.F.M., 1989, Disposal of carbon dioxide in depleted natural gas reservoirs, in *Climate and Energy*, Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 178–188.

Van Engelenburg, B.C.W. and Blok, K., 1992, *Prospects for Disposal of Carbon Dioxide in Aquifers*, Paper presented at the First International Conference on Carbon Dioxide Removal, 4–6 March 1992, Amsterdam, The Netherlands.

Victor, D.G., Chayes, A., and Skolnikoff, E.B., 1992, Pragmatic approaches to regime building for complex international problems, in N. Choucri, ed., *Global Change: Environmental Challenges and International Responses*, MIT Press, Cambridge, MA, USA.

Williams, R.H. and Larson, E., 1992, Advanced gasification-based biomass power generation and cogeneration, in T.B. Johansson, H. Kelly, A.K.N. Reddy, and R.H. Williams, eds., *Renewables for Fuels and Electricity*, Island Press, Washington, DC, USA.

Winjum, J.K., Dixon, R.K. and Schroeder, P.E., 1992, Estimation the Global Potential of Forest and Agroforest Management Practices to Sequester Carbon, *Water, Air, and Soil Pollution* 62:2131–227.

World Energy Council (WEC), 1989, *Survey of Energy Resources 1989*, WEC, London, UK.

World Energy Council (WEC), 1992, *Energy for Tomorrow's World*, draft summary of the WEC commission global report, WEC, London, UK.

World Resources Institute (WRI), 1990, *World Resources 1990-91. A Guide to the Global Environment*, WRI, Oxford University Press, New York, USA.

Worrell, E., Cuelenaere, R.F.A., and Blok, K., 1992, *Energy Consumption of Industrial Processes in the EC*, University of Utrecht, The Netherlands.

Wyman, C.E., Bain, R.L., Hinman, N.D., and Stevens, D.J., 1992, Ethanol and methanol from cellulosic biomass, in T.B. Johansson, H. Kelly, A.K.N. Reddy, and R.H. Williams, eds., *Renewables for Fuels and Electricity*, Island Press, Washington, DC, USA.

Yamaji, K., 1991, *Lifestyle Factors in Japan's Energy Demands*, Paper presented at the International Workshop on Social Behavior, Lifestyles and Energy Use, 24–26 June 1991, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Yamaji, K., Matsuhashi, R., Nagata, Y., and Kaya, Y., 1991, *An Integrated Systems for CO_2/Energy/GNP Analysis: Case Studies on Economic Measures for CO_2 Reduction in Japan*, Paper presented at the Workshop on CO_2 Reduction and Removal: Measures for the Next Century, 19–21 March 1991, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Young, H.P., 1991, *Sharing the Burden of Global Warming*, Equity and Global Climate Change Discussion Paper, School of Public Affairs, University of Maryland at College Park, USA.

Zylbersztajn, D., 1992, Personal communication.