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CO_2 REDUCTION AND REMOVAL: MEASURES FOR THE NEXT CENTURY

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Abstract—A workshop† on CO_2 reduction and removal measures for the next century was held at the International Institute for Applied Systems Analysis (IIASA)‡ and is briefly described. It was organized to assess carbon dioxide (CO_2) reduction and removal strategies worldwide and to review other studies and technological options being considered by leading research organizations in different countries. Policy measures for environmentally compatible development of energy systems encompass many different areas of human activities both in space and time. Accordingly, the workshop participants' affiliations and backgrounds reflected this diversity. The 48 participants represented more than 11 disciplines from academic, private and public organizations from 15 different countries both North and South. Five workshop sessions dealt with global and regional studies, national studies, efficiency improvements and cleaning (scrubbing), low and zero carbon options (including renewables), global issues and integration.

1. INTRODUCTION

Energy-related emissions of greenhouse gases (GHGs), especially of CO_2 are an important cause of increasing concerns over global environmental change, concerns that reflect the growing search for longer-term environmental security and sustainability of human development, both in the energy community, in policy circles and among the public at large. In 1987, global CO_2 emissions from fossil energy use were about 6 Gigatons (Gt) of carbon. The levels, structure and etiology of emissions vary greatly between countries and regions. Figure 1 illustrates the high degree of heterogeneity in the world today with respect to the level of energy-related CO_2 emissions. For example, both the U.S. and the area of the former G.D.R. have the highest per capita CO_2 emissions in the world, in excess of 5 t carbon (*per capita*)/yr, but for fundamentally different reasons. At comparable levels of affluence, some other West European countries and Japan emit much less carbon indicating that decarbonization and development are not mutually exclusive provided that an appropriate policy mix is found. Currently, about 75% of energy-related CO_2 emissions come from the highly-industrialized

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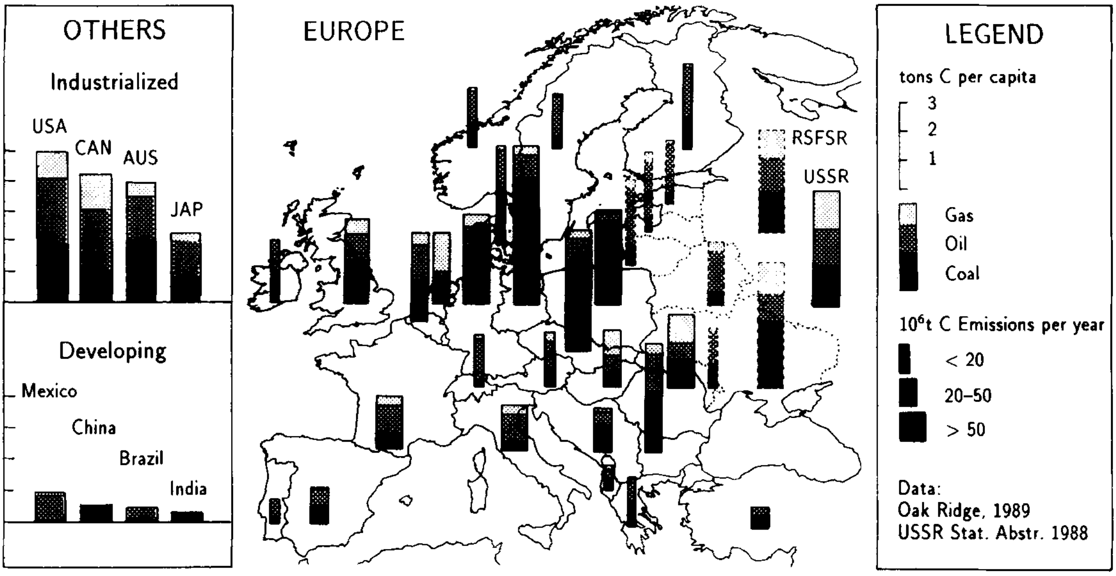


Fig. 1. *Per capita* CO_2 emissions from commercial energy use, by source and for selected countries (in tons of carbon/yr *per capita*).[1] A graphical representation of *per capita* carbon emissions from energy use reveals extreme disparities and heterogeneity. These are the result of differences in the degree of economic development, level and efficiency of energy consumption and the structure of the energy-supply system (i.e., its carbon intensity). The figure illustrates the significant North–South differences in energy-related CO_2 emissions. Also noticeable are the high *per capita* emission levels in Eastern Europe, most of which stem from coal use. Even in cases when the *per capita* emissions are of similar magnitude, they are often so for entirely different reasons. For example, both the U.S. and the former G.D.R. have *per capita* CO_2 emissions in excess of 5 tons carbon/yr. In the case of the U.S. this is due to high energy consumption and energy intensive lifestyles, like the high oil consumption for private transportation. In the former G.D.R. it is due to a different level and structure of consumption and supply of energy, stressing the basic material production sector and a high share of brown coal in the energy balance.

countries, but this will change dramatically with the increase of populations in the developing countries, the concomitant increase in *per capita* energy use, and further tropical deforestation. There is a prevailing belief in the scientific community today that something must be done. Some demand more research in the hope of increasing scientific certainty, while others insist on immediate reductions of CO_2 and other greenhouse gas (GHG) emissions.

Although a number of initiatives have been taken to stabilize and in some cases even to reduce further emissions, there is no agreement among industrialized countries on the timing and the extent of GHG reductions necessary or desirable. Developing countries, in particular, face severe constraints in attaining continued economic growth and thus have more limited possibilities for stabilizing their CO_2 and other GHGs [except chlorofluorocarbons (CFCs)] emissions. Indeed, the best that can be hoped for is a *reduction of the expected increase of CO_2 emissions*. On the other hand, there are views that global energy consumption could stabilize or even decrease due to enhanced energy conservation and economic restructuring.

From the point of view of possible climatic change and its global consequences, there is undoubtedly a need for action. The questions are: what, how much, when and by whom? The choices made will have economic, social and political implications far beyond the climatic effects, uncertain as they are.

The most prominent international effort to analyze global GHG emissions, atmospheric concentrations, impacts and response strategies has been undertaken by the Intergovernmental Panel on Climate Change (IPCC).[2] Within the IPCC *inter alia* possible future emissions scenarios[3] were formulated corresponding to an atmospheric concentration of GHGs equivalent to a doubling over pre-industrial levels during the next century. The group subsequently developed additional emission scenarios in which atmospheric concentrations of GHGs are stabilized at lower levels and then reduced further during the next century. Figure 2 illustrates

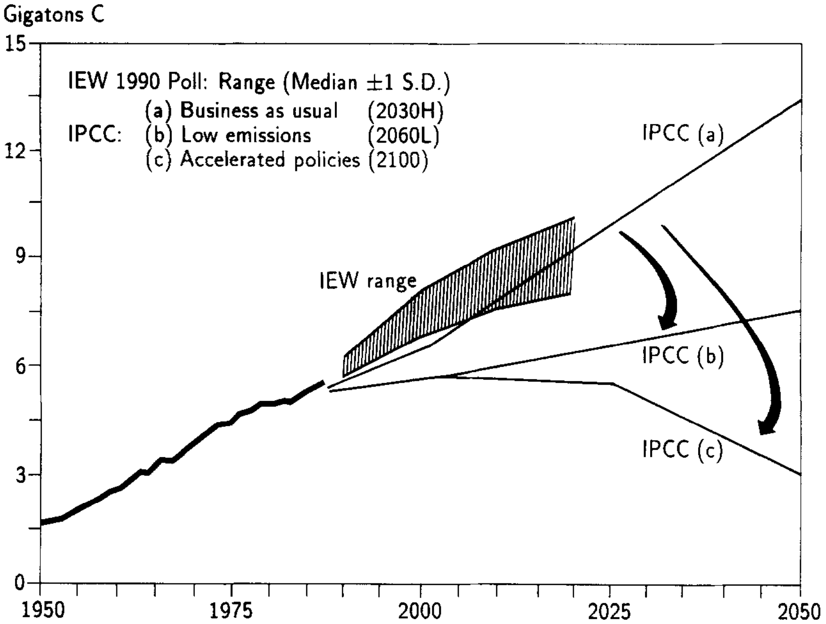


Fig. 2. Historical and future global energy-related CO_2 emissions.[1] From 1950 to present emissions have increased on average at about 2%/yr. Possible future global energy-related CO_2 emissions are indicated by the IEW poll-response range and by three IPCC scenarios.

three IPCC emission scenarios and compares them with the historical increase in global CO_2 emissions averaging about 2%/yr since 1950.

Since 1981, Manne and Schrattenholzer have jointly organized the International Energy Workshop (IEW) with the aim of comparing energy projections and analyzing their differences.[4] The IEW is a worldwide group of energy experts that meets annually. It conducts informal semi-annual polls to compare energy price, supply and economic growth projections. Average global primary energy consumption increased from 1850 to the present in the order of 2.2%/yr, and the IEW median anticipates similar growth rates for the next decades. The median of the global CO_2 emissions calculated from the IEW polls of global energy consumption or, in our interpretation, the current consensus view, corresponds to an annual growth rate of about 1.5%/yr, i.e., to an emissions increase from about 6 Gt today to some 9 Gt carbon by the year 2020, with a range between 8 and 10 Gt carbon. In Fig. 2, we compare this IEW range for future global CO_2 emissions with IPCC scenarios against the background of the historical increase since 1950. Although lower than the business-as-usual scenario of the IPCC for the same year, the IEW poll range gives rise to concerns as to how such a trend could be bent downwards, e.g., along the lines of the low emission and perhaps even the accelerated policy scenarios of the IPCC.

This all strongly suggests that, in the absence of appropriate counter-measures, global carbon emissions will perhaps rise beyond environmentally acceptable levels. Consequently, the workshop was organized in order to review and discuss technological and policy options for CO_2 reduction and removal. However, reduction and mitigation scenarios at the global level are scarce. Besides the work of the IPCC, few global studies have been performed, and those that have, have mainly focussed on a macroscopic top down approach in estimating CO_2 avoidance and reduction costs. However, noteworthy country studies were presented at the meeting describing the CO_2 reduction and mitigation measures and their costs including, e.g., those in The Netherlands, Germany, India, Japan, and the U.S. All the country studies reviewed at the meeting indicate that the CO_2 reduction potentials compared to a business-as-usual scenario (i.e., with no mitigation measures) are considerable, especially through energy efficiency improvements. Typical figures for highly developed countries indicate a possible CO_2 emission-reduction rate of between 50 and 70% under stringent control (tough or green) scenarios compared to a business-as-usual scenario.

Discussions at the meeting indicated the need for a long-term view in evaluating these options. This was best epitomized by "The New Earth 21" (NE 21) conceptual framework[5] presented by Kaya.[6] NE 21 is an example of an innovative approach to evaluate potentials of various energy technologies toward reducing future CO_2 emissions and other measures to enhance CO_2 sinks. The NE 21 action program devotes the next 100 yr to the recovery of this planet from 200 yr of the accumulation of carbon dioxide and other greenhouse gases. According to this action plan framework, the first 50 yr is the transition period devoted to development and introduction of environmentally friendly technologies, while the next 50 yr are devoted to full implementation and diffusion of these technologies leading to restoration of the green planet. The key technologies considered for reducing and controlling the CO_2 content in the atmosphere are illustrated in Fig. 3.

Richards presented findings of a very comprehensive study by the U.S. National Academies examining reductions of emissions of all GHGs.[7,8] This study concludes that the U.S. should continue the aggressive phase out of chlorofluorocarbons (CFCs) and other halocarbons, which would significantly reduce the national contribution to potential greenhouse warming. It also recommends the introduction of full social cost pricing of energy which can be expected to reduce GHG emissions by enhancing, for example, cogeneration and energy efficiency. Finally the study stresses the need to reduce global deforestation, and when appropriate also use reforestation as a carbon offset. It is particularly noteworthy that the study recommends several actions whose costs are justified mainly by countering GHG warming or adapting to it, but cautions against those actions are not considered cost effective.

Styrikovich and Chernavsky discussed current inefficiencies in energy use in the U.S.S.R. that have led to high emissions. Elimination of the most obvious inefficiencies alone would result in lower CO_2 emissions. Thus, the Soviet Union is probably in a position to reduce GHG emissions by efficiency improvements that are expected to offset further energy-demand increases. However, this would require a number of policy measures, all of which would be difficult to implement.

Authors at the Tata Energy Research Institute have examined the potential for reducing primary energy consumption in India without reducing end-use services.[9] As a collaborating institute under the aegis of the Asian Energy Institute, they participate in a project to investigate emissions of GHGs in the major countries of Asia and Brazil. As reported by Mathur,[10] the largest potential for mitigating CO_2 emissions in India is by afforestation, which carries the lowest specific cost of all of the options identified.

Germany's Parliamentary Enquete Commission[11] proposes a global reduction strategy for all anthropogenic sources of GHGs in order to encounter the risks of global warming and, in particular, recommends reduction of CO_2 emissions worldwide by 5% by the year 2005 and at

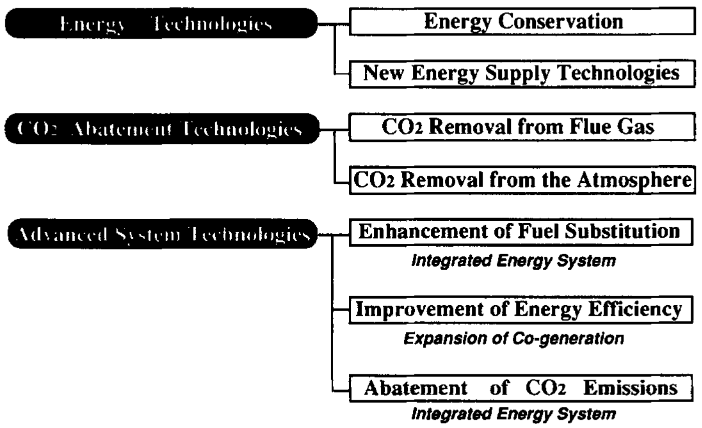


Fig. 3. Overview of technological options to reduce atmospheric CO_2 concentrations.[6] Improvements in energy efficiency, interfuel substitution, and CO_2 removal technologies can all contribute towards a common goal of an environmentally sustainable energy future. Their systemic evaluation is the objective of a number of research efforts presented.

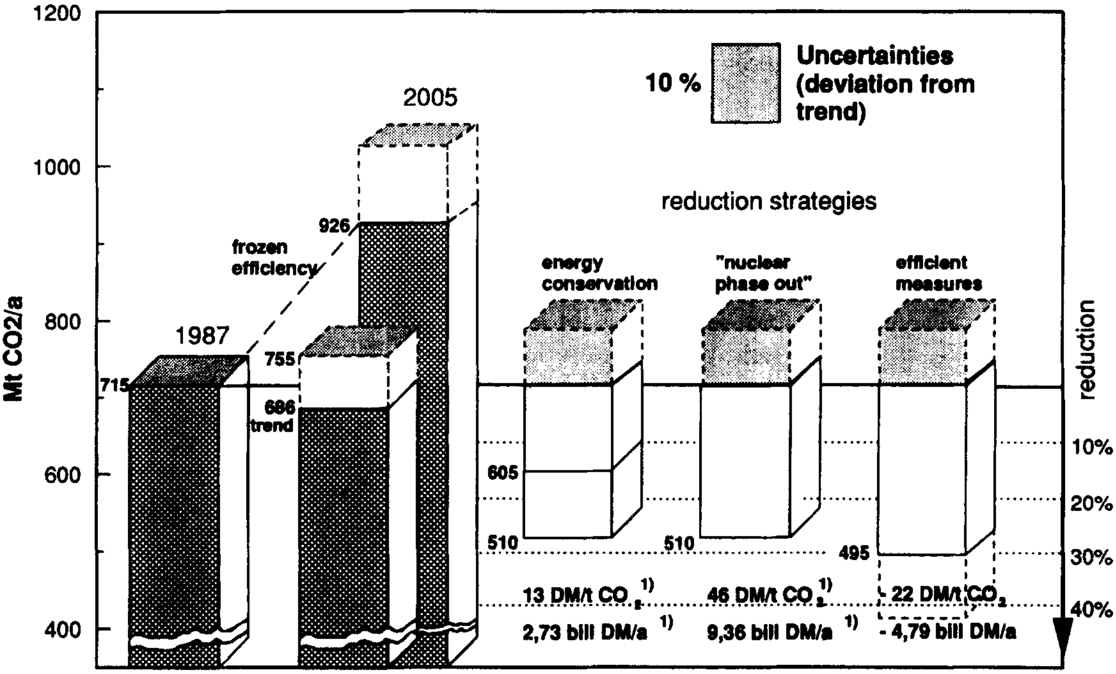
least 50% by 2050 compared to the year 1987. Germany's national target (including the territory of the former G.D.R.) in this global scenario is to reduce CO_2 emissions by 30 and 80% by 2005 and 2050 respectively, again with 1987 as the reference year. The Commission report also sets national emissions reduction targets for the other greenhouse gases; CH_4, NO_x, CO and non-methane volatile organic compounds. Schaumann presented a related study for Germany directed by Voss.[12] The IER calculated costs of various options to reach the target set by the Enquete Commission for 2005, which ranged from 46 DM/ton of carbon removed if nuclear power was phased out, to 13 DM/ton under a conservation scenario in conjunction with nuclear power. The results of this study are illustrated in Fig. 4.

The objective of the International Energy Agency's (IEA) Energy Technology Systems Analysis Program (ETSAP),[13] presented by Kram, is to identify cost-effective national options for reduction of emissions of GHGs, simultaneously dealing with other environmental problems such as emissions of SO_2 and NO_x. A further aim is to share its Markal model methodology internationally (including developing countries) in order to provide fora such as the IPCC with a consistent basis for comparison and evaluation of different countries.

Presenting plans to reduce GHG emissions in Poland, Lis spoke of activities which include modeling energy–economy–environment interactions.[14] In cooperation with the World Bank, Poland is assessing the development of other sources of energy, since at present its economy is highly dependent on hard coal for energy supply.

Gheorghe reported that Rumania sees no alternative to nuclear power and currently has five CANDU-type reactors under construction.[15] Rumania's oil reserves are depleted. Its *per capita* emissions of CO_2 are already among the highest in the world and expected to double by 2030.

There was an expected consensus that all immediate, low-cost options available should be



1) not all costs included

Fig. 4. CO_2 reduction scenarios for Fed. Rep. Germany as prepared for the German Parliamentary Enquete Commission were presented by Schaumann.[12] Three strategies were investigated for reducing energy-related CO_2 emissions by the year 2005 by 30% below present levels. The first relied mostly on energy-efficiency improvements and conservation measures. The second involved nuclear phase-out and consequently required even more conservation and increased use of renewables. The third scenario includes a portfolio of measures based on the least-cost criterion. Particularly costly are the results for the nuclear phase-out scenario; the CO_2 reduction target remains possible but costs more than three times the conservation scenario. Compared to the business-as-usual scenario, a 30% reduction of emissions could be reached without additional costs for CO_2 control under a scenario combining measures developed for the least-cost criterion as is indicated by the negative CO_2 reduction costs shown in the figure. The superscript (a) indicates that not all costs are included.

implemented, especially in the realm of efficiency improvements, where the potential for CO_2 reduction is seen to be large. The history of efficiency improvements shows strong heterogeneity among different countries. In an energy efficient economy like Japan the possibilities are different from those in a currently reforming economy like the U.S.S.R., or others with higher energy use like the U.S. For example, over the next few decades efficiency improvements, together with cogeneration, might account for up to one-half of the reduction in energy-related GHG emissions in the U.S.[16] The other half would be distributed among structural changes in the economy, changes in sources of energy and fuel mix, and forestry measures. Many developing countries face capital constraints, although in some, e.g., India, a relatively small additional investment in energy efficiency would lead to large emission reductions. The transforming economies of Eastern Europe have wide scope and several incentives to increase energy efficiency: reduced dependence on imports of oil and natural gas, with the additional benefit of less hard currency spent on energy, not to mention lower energy-related pollution and an improvement of their local environments.

2. EFFICIENCY IMPROVEMENT AND COSTS

Ever since the beginning of the Industrial Revolution energy efficiency increased along with the improvement of labor productivity and reduction of other factor inputs. For example, the energy intensity† has decreased in the U.S. at an average rate of 1%/yr since the middle of the last century. This decrease was sporadic rather than continuous.[17] The rate of improvement has been generally higher since the energy crisis of 1973, averaging more than 2%/yr. Nakićenović argued that there is strong evidence that historical experience does matter and that it has varied greatly among different countries as illustrated in Fig. 5. For example, France and Japan have always used energy more efficiently than the U.S., the U.K., or Germany, while at the same time the rates of efficiency improvement have been higher in both the U.K. and Germany than

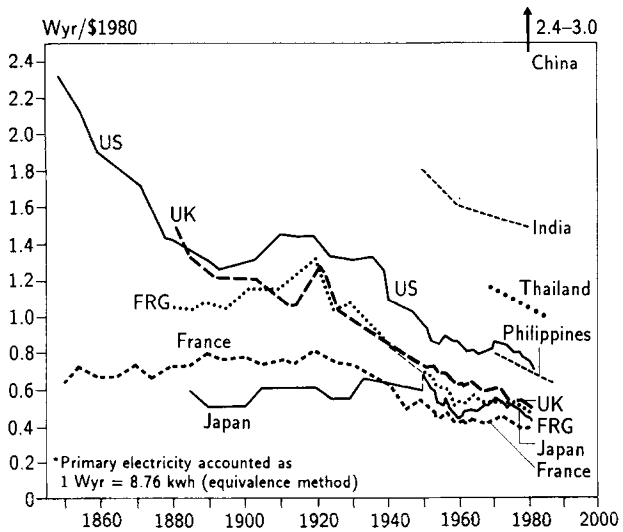


Fig. 5. The primary energy intensity (including biomass energy) in Wyr/U.S.$ 1980 is shown per unit of constant GDP.[17] Historically, the energy intensity has declined at an average rate of 1%/yr. Since the early 1970s, the energy intensity has decreased at rates of 2–3%/yr. The figure shows distinct differences in the industrialization paths of different countries. The present intensities, as well as future improvement potentials, are deeply rooted in the past, in the particular industrialization path followed, the settlement patterns that have developed, consumption habits of the population, etc. The fact that the U.S. consumes about twice as much energy/U.S.$ GDP than countries in Western Europe or Japan does not necessarily imply that improvements are easier to achieve there than in other countries. Developing countries have energy intensities similar to the industrialized countries at times of comparable levels of economic development and *per capita* income many decades ago.

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†Energy intensity denotes the ratio of total primary energy consumption divided by the gross domestic product.

in the U.S. Even more surprising is that Japan, which already by the early 1970s had one of the most energy efficient economies, has also achieved the highest improvement rates since. This should be contrasted with the opposite development in some of the rapidly industrializing countries where commercial energy intensity is still increasing, e.g., in Nigeria. The current energy intensity of Thailand resembles the U.S. situation in the late 1940s. The energy intensity of India and its present rates of improvement are similar to that of the U.S. about a century ago (Fig. 5).

Most efficiency improvements have occurred at two levels; conversion and end-use. Over the past 20 yr, aircraft manufacturers have managed to improve the energy efficiency of commercial jet transport by 3–4% annually.[17] Figure 6 illustrates this dramatic improvement of aircraft fuel efficiencies, but it also shows that new technologies may increase energy intensities due to lower energy efficiency that can result from improved performance, as in the case of supersonic aircraft. In electricity generation, efficiency improvements have averaged 2.5–3%/yr between 1930 and the 1970s.[17] An assessment of OECD countries shows that the efficiency of conversion from primary energy to the final forms required by the consumer is about 70%. In contrast the efficiency with which final energy forms are applied to provide useful energy and energy services is much lower, resulting in an overall conversion efficiency of primary energy to energy services of approximately 10%.[17] There is large scope therefore for more efficient energy use, particularly through the improvement of end use technologies.

The above shows that technical improvements and a change of consumption habits (increased service efficiency) are clear priorities for reducing CO_2 emissions through better energy use, especially in the near to medium term. 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. In areas like electricity production, improvements are leveling off, as if they were approaching some upper limit. Fortunately this is not the case for most energy use categories and the potential for improvement is still vast. Even in the case of thermal electricity generation we are actually not anywhere near the theoretical limit given by the Carnot Law, although the improvement potential is much higher in many other areas. An analysis of energy (or second law) efficiency, which allows to account for differing qualities of various energy carriers, indicates that the overall exergy efficiency of

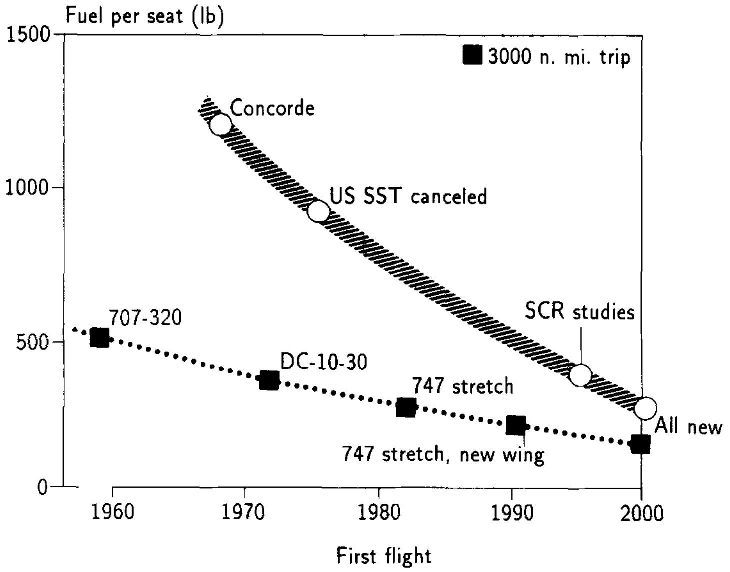

Fig. 6. Aircraft fuel efficiencies for 3000 nautical mile trips in lbs of fuel/seat.[18] Improvements in energy efficiency in the aircraft industry have been particularly dramatic. Improvement rates of 3–4% annually over the last 20 yr have been achieved, which means that the same transportation service can be provided now with as little as 40% of the energy requirements some 20 yr ago.[17] There are also counter-balancing trends, e.g., the introduction of new high-speed aircraft such as supersonic or hypersonic air transports. For these new technologies the specific energy requirements are significantly higher than for older aircraft but the loss in fuel efficiency is compensated for by time savings.

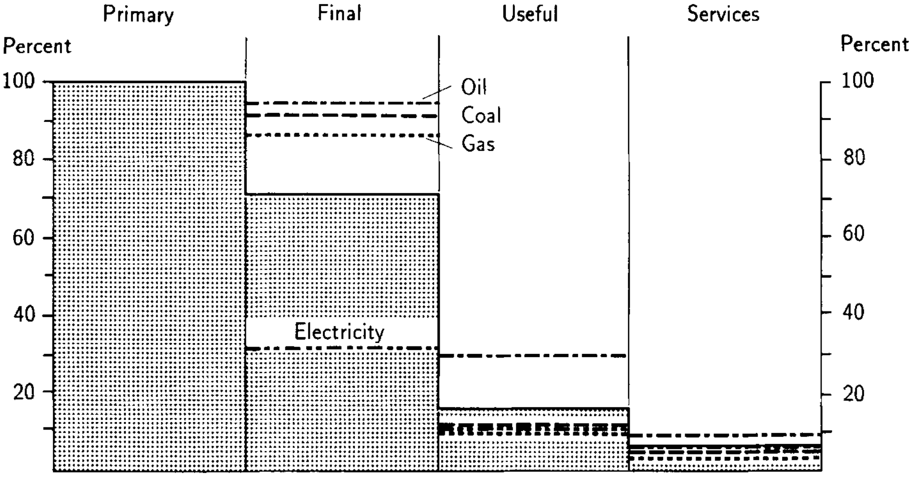

Fig. 7. Exergy balances for the OECD countries in 1986 in percent of primary exergy.[17] A second-law (exergy) analysis of the energy systems in the OECD countries shows that while the efficiency of conversion to final exergy is quite high, efficiencies at the end-use side and, in particular, in the provision of services are low. The overall exergetic efficiency of the OECD countries is estimated to amount only to a few percent. Figures for the U.S.S.R. and developing countries are probably even lower. Therefore, there remains large theoretical potential for efficiency improvements up to a factor of about 20. Realization of this potential depends on implementation of new technological options and organizational innovations. Tradeoffs and the costs and timing involved need detailed study.

current energy systems is very low.† Figure 7 illustrates that exergy efficiency in the OECD countries is not more than a few percent.[17] This is corroborated by similar results for most of the industrialized countries. In developing countries exergy efficiency is probably even lower, especially because noncommercial energy sources are used directly, resulting in very low overall efficiency. For example, open fires for cooking use up to four times more fuel than well-designed stoves. Steam locomotives have at best 7% efficiency compared to almost 30% for modern diesel-elecric locomotives. Commercial and industrial facilities themselves are often poorly designed and maintained. If an increase in service efficiency is added to this analysis, a reduction of primary energy input by up to a factor of about 20 appears feasible with energy services being maintained at current levels. Thus, the potential for efficiency improvement is indeed vast.

Turkenburg presented a comprehensive technological analysis with a listing of ways to improve efficiency in over 300 single technologies, broken down by industry and sector, ranging from greenhouse horticulture to production of aluminum to passenger transport.[19] The study concluded 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. Yamaji presented a similar study for Japan. This highlighted the need to compile such comprehensive assessments for other countries. Figure 8 compares the efficiency-improvement cost curves for The Netherlands and Japan.

Such a study also exists for a developing country. Mathur[8] presented a study of CO_2 mitigation prospects for developing countries and spoke of the scope for efficiency improvements in India. There is a large potential for the reduction of carbon emissions in the utilization of biomass. Current biomass use is often destructive, involving massive deforestation and adverse environmental impacts. A more sustainable use of this resource would recycle carbon, leading to a reduction of net emissions. Mathur also showed other potentials for efficiency improvements and their associated costs, ranging from installation of energy efficient equipment and better instrumentation in industry, to improved lighting in the domestic sector through the introduction of fluorescent tubes and compact lamps.

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†The balance 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%. In contrast the exergy of low temperature heat is very low resulting in very low transformation efficiency to other energy forms (for many processes governed by Carnot's cycle for heat engines).

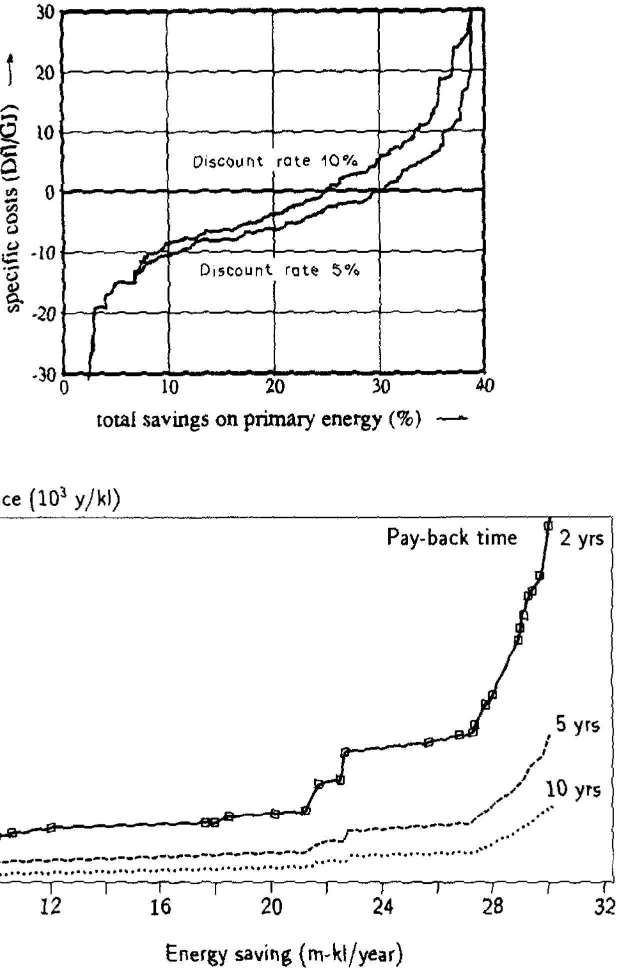

Fig. 8. National energy-conservation and efficiency-improvement cost curves for The Netherlands (top)[19] and Japan (bottom).[20] The costs of energy-conservation measures are based on discount rates of 10 and 5% for The Netherlands and indicate a maximum savings potential of close to 40% of the primary energy consumed. The specific costs range from net savings to costs of between Dfl 20 and 30/GJ. The energy-conservation costs estimated for Japan express the conservation potential as a function of energy prices for different payback times (2.5–10 yr). It is interesting to note the large efficiency improvements and conservation potentials for a range of relatively modest energy-price increases, even in a country with traditionally high energy prices and high overall energy efficiency.

Substantial improvements were also highlighted for the utilization of fuels with a lower specific carbon content such as natural gas. Combined-cycle power plants (CCPPs) achieve particularly high efficiencies.[21] For example, Eliasson described Asea Brown Boveri's (ABB) Pegus CCPP in operation in The Netherlands, with a gas–electricity conversion efficiency in excess of 50%.[22] The plant is also used in a dual mode during winter to cogenerate both electricity and heat, eliminating additional fuel demand for low temperature heat, thereby raising overall systems efficiency and dramatically lowering CO_2 emissions. CCPPs are seen to be one of the most important single technologies for the reduction of CO_2 emissions. However, CCPPs have not been introduced in many parts of the world as fast as could be expected considering their high efficiency and relatively low capital needs. Styrikovich pointed out that the Soviet Union uses natural gas for >50% of its primary energy supply. Efficiencies in conversion to electricity are very low, around 30%. This could be improved to almost 50% with wider application of CCPP technology. Unfortunately production capacity and financial resources are lacking to manufacture CCPPs in the number and quality needed. In greater numbers, such plants could potentially save 40% of the gas consumed by the electricity sector in the U.S.S.R. CCPPs can substantially increase efficiency and reduce emissions also in conjunction with other fossil sources of energy although the resulting carbon reduction would be lower than when powered with natural gas. Coal gasification is one such route to generate synthesis gas for clean combustion in turbines. The Coolwater power plant in California uses this process for generating electricity from coal without SO_2 and NO_x emissions and still achieves relatively high efficiency.

Other presentations highlighted the entire spectrum of energy cascades. Kashiwagi suggested tapping the broad temperature range of natural gas from the liquefied transportation stage (−155°C) to its highest post-combustion temperatures. Figure 9 illustrates this scheme. He advocated using the low temperature of LNG in successive stages, first to separate nitrogen from air and then for refrigeration, at higher temperatures. Further transformation stages would involve combustion of gaseous methane in CCPPs to produce electricity and supply high temperature heat for industrial processes. Alternatively, an advanced high temperature fuel cell, should it prove to be economical, could be used to convert gas into electricity and high temperature heat as well. The work available, in addition to electricity generated in a fuel cell

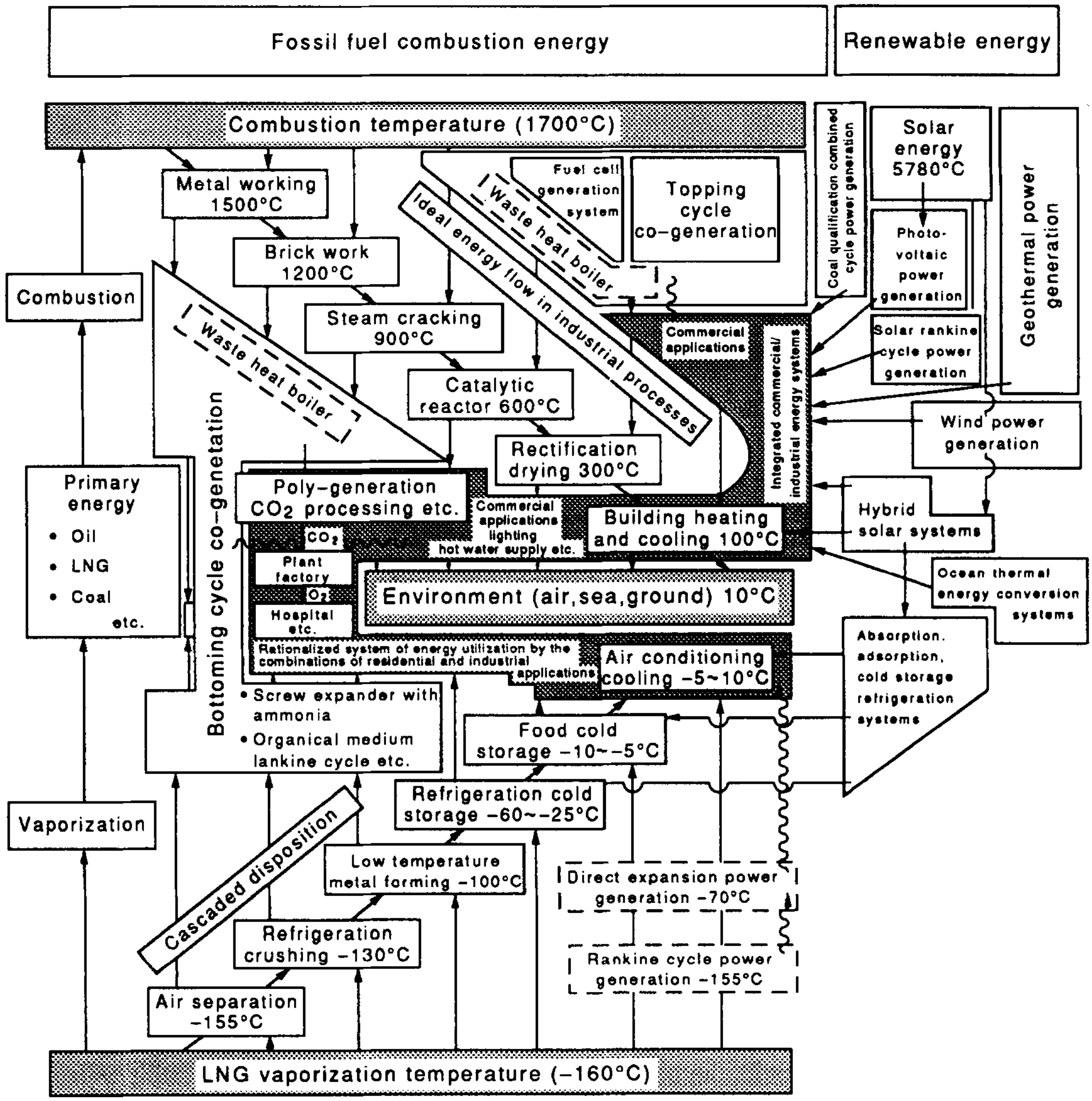

Fig. 9. Energy cascading, an innovative concept introduced at the conference to achieve improved efficiency and minimize exergy losses.[23] Full advantage is taken of both low temperatures (LNG at −155°C) and high combustion temperatures (~1700°C for NG). In order to minimize exergy losses, energy is passed on to successively lower (or higher in the case of cooling) temperature ranges. Implementation of such innovative concepts requires significant changes in the spatial and institutional organization of society.

or CCPP could be used in multiple stages all the way down the temperature cascade to the provision of low temperature heat for hot water supply and domestic space heating. A final stage would involve the application of heat pumps with river water as a lower temperature heat reservoir. The elegance of the system lies in its integration across temperature ranges, but the drawback is the need for extensive reform of institutional and spatial structures to efficiently distribute the power and heat from various conversion stages to multiple users, from a central complex to its peripheries.

Gilli discussed potential efficiency improvements along similar lines through the use of heat pumps. Although new, the technology is gaining substantial market shares in some end use categories both for domestic, district and industrial use. Table 1 shows that almost 300 GW thermal installed capacity is in use worldwide.

Many other efficiency improvement measures were discussed, ranging from power plants, transport and distribution systems to individual end-use devices such as vehicles, home heating and various industrial systems. However, after discussing energy efficiency, one needs to look at carbon efficiency. In other words, instead of only looking at the energy input and energy flow of a given conversion process, it is also useful to consider the carbon flow and resulting carbon releases. Kuyper presented an example of carbon efficiency accounting for petroleum refineries where impressive efficiency gains were reported.[25]

Participants noted, however, that despite these potential gains, energy efficiency will be only one criterion shaping future patterns of energy use. Nakićenović said other criteria might include product quality and the efficient utilization of time, capital and other factor inputs. The pace of improvement will also depend on the age distribution of the capital stock. For example about 60 and 80% of the capital stock of the F.R.G. and U.S.S.R., respectively, are <20 yr old. This means that during the next 20 yr in both these countries, these portions of the capital stock could in principle be replaced by vintages that are much more energy and carbon efficient. The bad news, given the current distribution of capital stock, is that 20–40% of the oldest vintages are infrastructures and similar forms of capital with extreme longevity, some of which might be used for another five decades or more.

Skea illustrated this persistence of capital stock in the U.K. where about one-half of the

Table 1. Present utilization of heat pumps in selected countries and sectors.[24] Utilization of heat pumps is considerable and contributes towards increased efficiency of energy end use for low-temperature heat applications. Nearly 300 GW of heat-pump capacity are estimated to be installed worldwide and supply about 300 TWh of heat annually.

Sector	Numbers	Power (Heat)		Utilization Factor hr/yr	Annual Heat Supply TWh/yr
		Per Unit kW	Total MW		
Residential					
Single Flats					
Japan	22×10^6	3.5	77000		
US	8	8	64000		
Others	5	4.0	20000		
Total	35	4.1	161000	1000	161
Commercial	8	15	120000	1000	120
Total Residental and Commercial	43	6.5	281000		281
(of which heating – only heat pumps)	(3)	(8.0)	(24000)	(1000)	(24)
Industry	$\simeq 5 \times 10^{-3}$	$\simeq$ 500	2500	4000	10
			(2000)		(8)
District Heat					
> 2 MW	155×10^{-6}	18000	2800		
Others	$\simeq 45 \times 10^{-6}$	4500	200		
Total	200×10^{-6}	15000	3000	5000	15
			(2900)	(5000)	(14.5)
Total			286500		306
(of which heating – only heat pumps contribute)			(28900)		(46.5)

Note: values in parentheses refer to heating-only heat pumps, i.e., units without cooling.

housing stock is of pre-1939 vintage.[26] Given this permanency and the very small annual turnover, efficiency improvements can only be introduced slowly based on normal replacement rates. This example highlights the considerable potential for retrofitting measures and difficulties encountered in improving the efficiency of older capital vintages without replacement.

Seen from a long term perspective, improvement in energy intensity of GDP has averaged about 1%/yr. However, this is a long-term historical average over 200 yr that contains periods of rapid improvement (2–3%/yr), stagnation and even reversal.[17] Improvement has been faster in certain areas than in others, e.g., air-conditioning equipment, aircraft engines, demonstrating that these are about the upper boundary values to be expected in efficiency improvements. With an improvement in energy intensity of 3%/yr, a dollar of GDP could be produced 50 yr from now with only 20% of current energy requirements. Figure 10 illustrates the combined effect of improved energy efficiency with changes in carbon intensity.

Cost considerations are a fundamental part of any CO_2 reduction and mitigation strategy, and are used to compare different options. Because the time range of models used in energy analysis is generally measured in years to decades, going much beyond that time frame makes cost analysis difficult because of the nonequilibrium and nonlinear nature of economic evolution and technological change. For example, as innovations become commercialized and applied on a large scale the price structure can change fundamentally and invalidate any *a priori* calculation. Despite all these caveats, it is important to estimate the cost of especially those measures that are now at least in principle available, such as CO_2 scrubbing, more efficient vehicles or power plants.

In addition to costs, there is a need to compute benefits. How are benefits to be quantified?

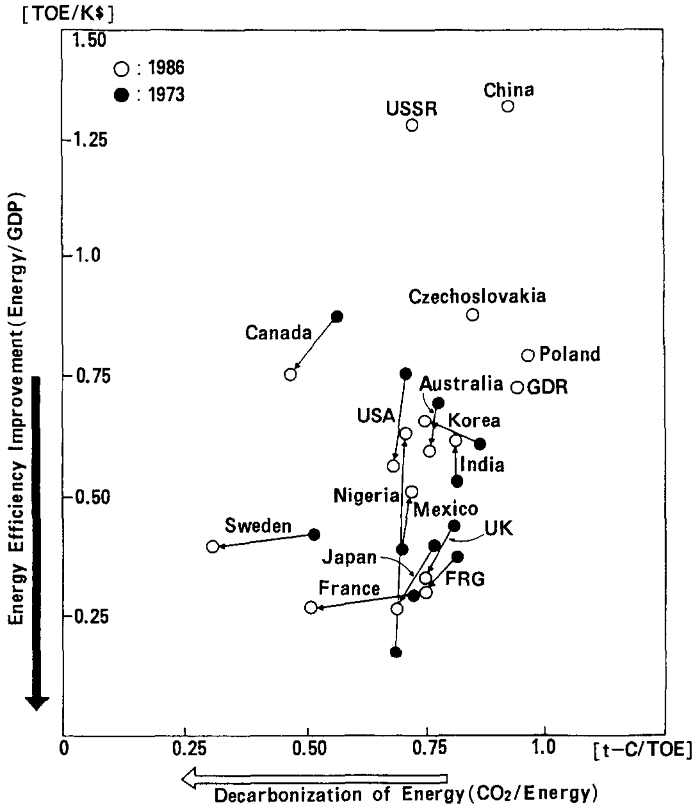

Fig. 10. 1973–1986 trends in energy and carbon intensity of various countries.[20] Reduced energy and interfuel substitution to lower the carbon intensity of energy use are two important options. The graph shows the diverse policies and strategies followed in different countries. Sweden and France have followed a decarbonization strategy, whereas the U.S. has mostly used an efficiency-improvement strategy. Canada, the F.R.G., Japan, and the U.K. have achieved improvements in both domains. Also noticeable are increasing commercial energy intensities of developing countries such as Nigeria.

We are still groping in the dark here. Few attempts have been made to tackle this problem, but benefits from the reduction in concentration of GHGs in the atmosphere are as difficult to compute as the likely impacts of global warming.

An examination of energy systems both at the macro and micro level is needed to study the potential for efficiency improvement. Analysis at the macro level involves aggregated energy–economy interactions and general descriptions of consumer behavior. At the micro level, it deals with individual technological measures and systems integration for efficiency improvement. Looking at costs from the micro viewpoint essentially involves ranking numerous technologies, usually resulting in an upward sloping cost curve as is shown in Fig. 11. This often means that much can be achieved initially in reducing emissions (improving efficiency) at relatively low cost but the cost rapidly increases with more substantial reductions.

Styrikovich and Sinyak pointed out that elimination of large inefficiencies in transforming economies and developing countries could enable emissions reduction at practically no cost. The recent OTA study also identifies significant CO_2 reduction potential with little or even negative cost as shown in Fig. 12. This is the case with many of the cost curves of mitigation measures; and while these low-cost efficiency improvement and emission reduction measures sometimes refer to loss of service (e.g., smaller vehicles), often, there is no loss of quality (e.g., more efficient cookers or aircraft). Sinyak presented an analysis of the possible negative costs of CO_2 emissions reduction for the U.S.S.R. (Fig. 12). It must be pointed out, however, that these figures are the result of a number of implicit assumptions. These analyses assume a set of conditions not now in existence, but which can reasonably be expected in the future. If the assumptions prove correct, then their far-reaching implication is that some CO_2 mitigation measures are economically beneficial on their own, in addition to their positive environmental effects.

Mathur presented an aggregate cost curve for CO_2 emission mitigation measures for India shown in Fig. 13. Despite a national savings rate >20%, the constraint here is shortage of capital, the available total being in the order of \$150 *per capita*/yr. There are many other

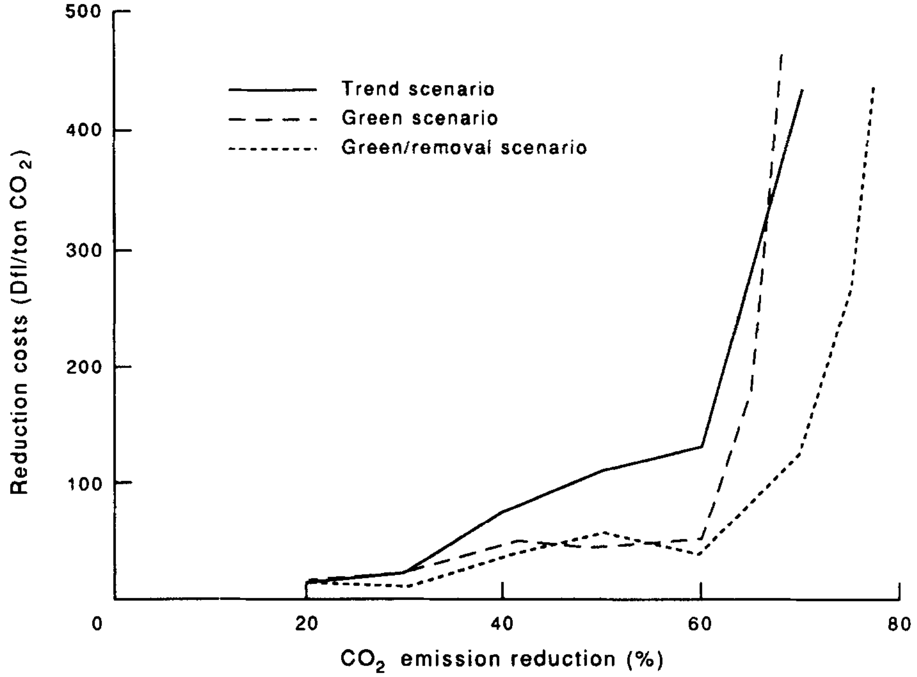

Fig. 11. Marginal CO_2 reduction cost curves for The Netherlands in Dfl/ton of CO_2.[27] Based on detailed energy models, the economic impact of various CO_2 reduction strategies can be assessed. The particular shape of the marginal cost curve gives an indication of economic boundary values for CO_2 reduction. In this particular study for The Netherlands, the marginal cost curves suggest that reductions up to 60% below present emission levels are possible before entering the steep exponential part of the marginal cost curves.

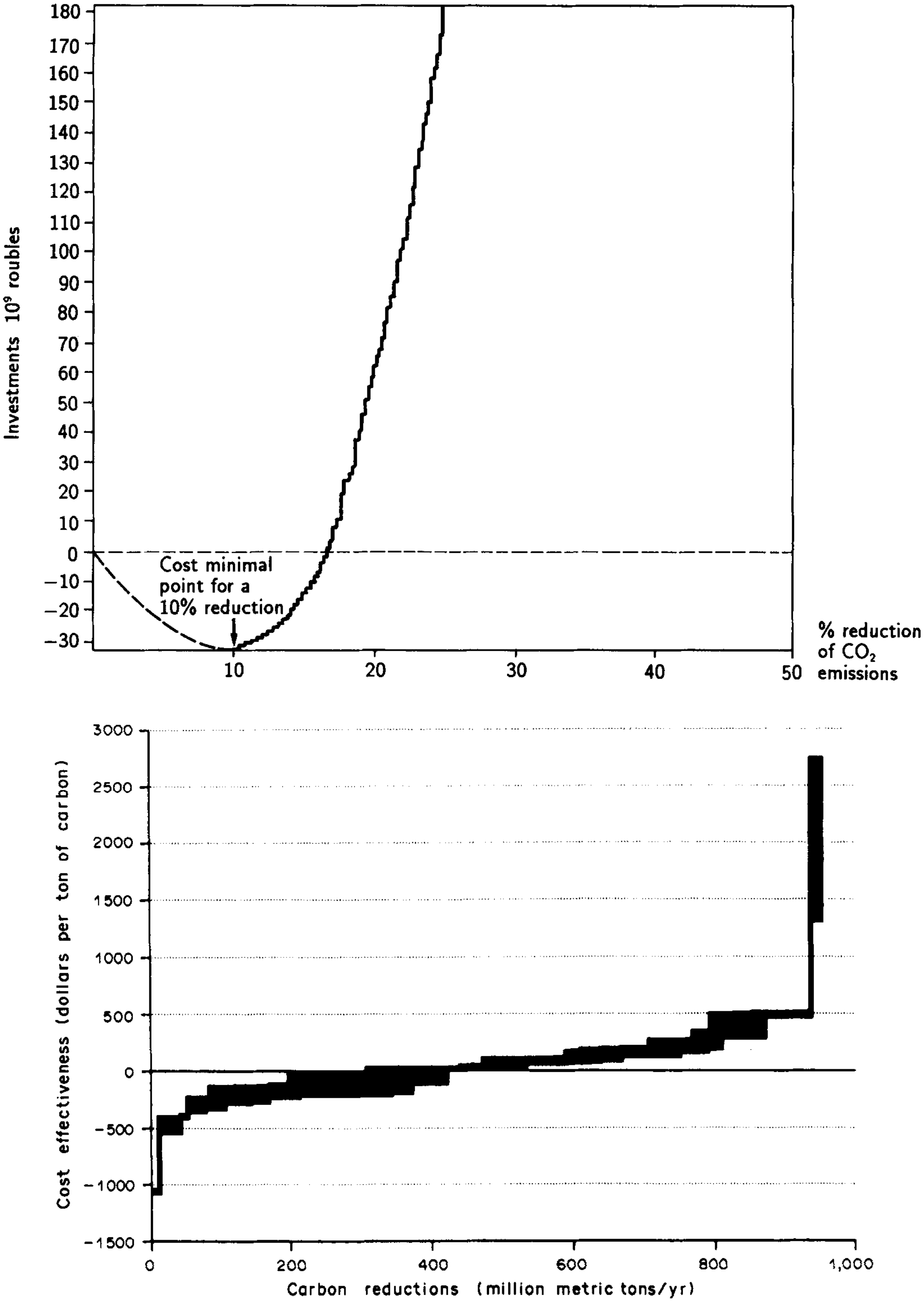

Fig. 12. CO_2 emission reduction and avoidance-costs estimates for the U.S.S.R. (top)[28] and the U.S. (bottom).[16] Emission-reduction costs are compared to a base-case scenario without any reduction measures. The time frames for the reference scenario are the year 2000 for the U.S.S.R. and the year 2015 for the U.S. Costs in the U.S.S.R. refer to investments only. Negative investments indicate investments saved by energy-conservation measures compared to capacity expansion. Maximum investment savings may be achieved by using a mix of policy measures resulting in a reduction of the reference CO_2 emissions by 10%. Emission-reduction costs in the U.S. refer to a reduction scenario with 0.9 Gt of C emissions in 2015 as compared to a business-as-usual scenario with 1.9 Gt of C emissions in 2015. Fuel savings are not included in the cost figures. Between one-third and one-half of the reductions in emissions between the two U.S. scenarios either save money or are of very low costs.

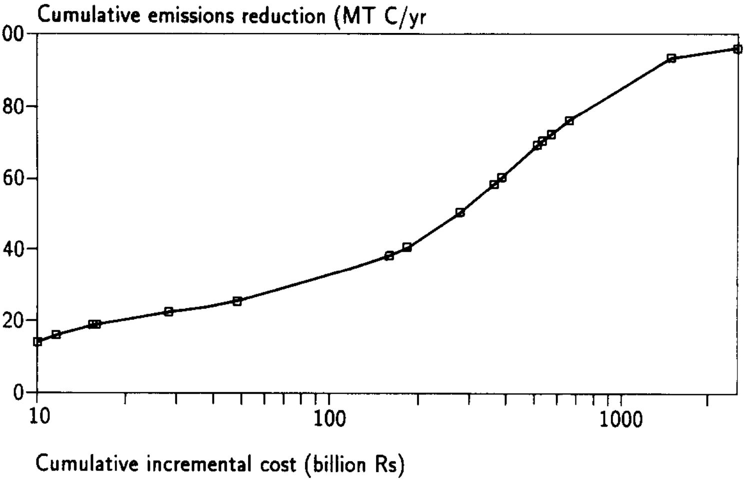

Fig. 13. Cost curve for reduction of energy-related CO_2 emissions in India in billion of Rs.[21] Each symbol represents the complete exploitation of a particular emission-reduction option. Recent work has dealt with the potential of CO_2 reduction from the perspective of a developing country. The cost curve shown is the first elaborated for a developing country and is based on a detailed assessment of various measures which highlight its innovative character. Mathur stated that in view of population growth and necessary economic development, absolute emission reductions would be both infeasible and inequitable for the developing countries. Instead, the concept of pursuing social and economic development with low emissions was suggested. The curve illustrates the costs of lowering CO_2 emissions in India by the year 2000 as compared to a base case without mitigating measures. A number of very cost-effective options exist, particularly in the area of sustainable exploitation of biomass. However, capital shortages remain the most serious bottleneck for CO_2 avoidance measures in developing countries.

urgent needs such as creation of new jobs for the burgeoning population. For this reason, efficiency improvements possible in theory are difficult to implement in practice. In India's case therefore, and probably also true of other developing countries, it is more important to consider efficiency of capital use rather than efficiency of energy use. Beyond that, it would be also desirable to improve the efficiency of other economic activities as well, so that the two policies really lead to the same end, namely, sustainable development.

Strubegger and Messner reported on an effort to develop an inventory of CO_2 mitigation measures and the related technology data base that will allow assessment and comparison of a large number of GHG reduction options worldwide. Individual technologies and processes are currently being compiled to provide global coverage. This will enable derivation of global CO_2 reduction cost and efficiency improvement curves by 1992.

As mentioned earlier, it is possible to view the various mitigation strategies also from the perspective of aggregated energy–economy interactions. Often this approach involves macroeconomic models that can describe economic consequences of reducing GHG emissions through carbon taxes and other regulatory mechanisms. Accounting for various price responses in an economy resulting from mitigation measures enables derivation of aggregate supply curves. The basic approach is to assess the overall economic cost of various CO_2 emission reduction strategies and the reduction potential. This is often implemented by levying a carbon tax or some other regulatory mechanism in a macroeconomic model. The effects of a carbon tax and the reduction potential that could be achieved by such measures were discussed at the meeting. The best known of these models were developed by Edmonds and Reilly, Manne and Richels, and Nordhaus and Yohe. At the workshop, Yamaji presented a model for Japan that estimates the effects of a carbon tax on both emissions and GDP.

The questions of implied equity and distributional effects are at the core of the debate over GHG regulatory mechanisms. For example, should tradeable permits imply permanent ownership? Could they lead to excessive drainage of emission rights from developing to rich countries, although this would generate a reverse flow of capital? Might it not be prudent to think of leaseable permits for limited periods of time that would conserve emission rights of future generations in the developing world? In addition to trading issues, other equity considerations are of fundamental importance, e.g., should emission quotas be determined *per capita,* by land area, or per unit of economic activity? The temporal question is whether only current emissions or also past emissions should be considered? If yes, how far back in time? The same is true for measurement of *per capita* or GDP criteria. Does one consider only the current or also past human generations and vintages of economic output? Would one measure just adult populations of countries or their entire populations? The last question is important because choice of the former course might be perceived as an asymmetry in favor of industrial countries, while past vintages of economic output represent accumulated wealth and therefore presumably also the social and economic capacity to adopt and respond to climate change and variability.

3. LOW CARBON AND CARBON FREE OPTIONS

Efficiency improvements are a fundamental measure for reducing carbon emissions especially in the near to medium term, but in the long run there is a clear need to achieve greater reductions by shifting to energy sources with low carbon content, such as natural gas; and ultimately to those without carbon whatsoever, such as solar, nuclear and fusion. Concurrent technological and economic structural change will be important for improving end-use efficiencies and lowering carbon emissions. Much of the discussion at the meeting was devoted to the change from carbon rich fossil fuels to less carbon intensive sources and energy carriers.

Of all fossil energy sources, coal has the highest and natural gas the lowest carbon content. Conversely, gas has the highest hydrogen to carbon atomic ratio and coal the lowest. Carbon free energy sources include geothermal and hydro, solar and nuclear energy, and the sustainable use of biomass.† The only carbon free energy carrier is electricity in addition to some district heat. All other energy carriers are carbon based. In principle, carbon emissions can be reduced by either shifting to low-carbon content fuels, to carbon-free sources of energy, or by removing carbon from energy carriers, resulting in carbon-free end-use as achieved by electricity today and possibly also by hydrogen in the future. In fact the historical trend has been toward the transition from one primary fuel to another, from wood to coal to oil, resulting in an increasing hydrogen to carbon ratio. Consequently, some participants identified a methane age as the logical interim possibility to reduce CO_2 emissions beyond those achievable only by efficiency improvements.[29]

Marchetti referred to central place theory and suggested another evolutionary imperative in the choice of energy vectors. In addition to an increasing hydrogen carbon ratio in the average fuel consumed since the beginning of the industrial revolution, successive sources of primary energy have another salient characteristic: increasing distribution range.[30] For example, the share of electricity in total final energy consumed has increased and with it the size of the electricity distribution grids. Structural change in the energy system, including the shift to new sources of energy and energy carriers, has also to be seen from this perspective. Following this logic, the next primary energy of choice probably ought to have a higher degree of integration and a wider range of effective distribution. It would need to be truly global and also more pervasive (i.e., used in more places and activities) than oil. Natural gas might be a possible intermediary before the eventual shift to truly carbon free sources of energy is achieved during the next century.[31]

Some saw resource shortages and leakage of methane as limiting factors to enhanced use of natural gas. Kuyper and Turkenburg pointed out that economic reserves might not be adequate for natural gas to play a substantive role in reducing carbon emissions. Grübler insisted on a perspective of natural gas abundance rather than of shortage and held out the promise of further discoveries. His argument was based on potential occurrences and speculative resources being so large that new discoveries are unavoidable if prospecting efforts throughout the world

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†For every carbon atom, biomass contains about 1.4 hydrogen atoms and about 0.6 oxygen, but when dried as a fuel source the hydrogen to carbon ratio is much lower. The fossil fuels have the following ratios. Coal has one hydrogen atom per carbon, oil about two hydrogen atoms per carbon and methane four. Therefore, CO_2 emissions are lowest for methane and highest for coal.

Table 2. Natural gas reserves, resources and occurrences (in 10^{12} m^3).[32] A summary contrasting the present estimates of identified and technically and economically recoverable reserves to resources, as well as exotic methane occurrences locked in clathrates, shows the large geological abundance of methane in the Earth's crust. If only a small fraction of this resource base becomes recoverable, gas supplies will last for centuries rather than for decades.

Types of Reserves and Resources	Low	High
Reserves in 1988	111	-
Conventional, recoverable resources	280	800
Unconventional, recoverable resources (present day technology)	20	50
Subtotal	300	850
Unconventional resources		
Identified	280	340
Inferred (speculative)	2,000	?
Subtotal	2,600	3,200
Clathrates	21,000	?
Deep gas	??	??

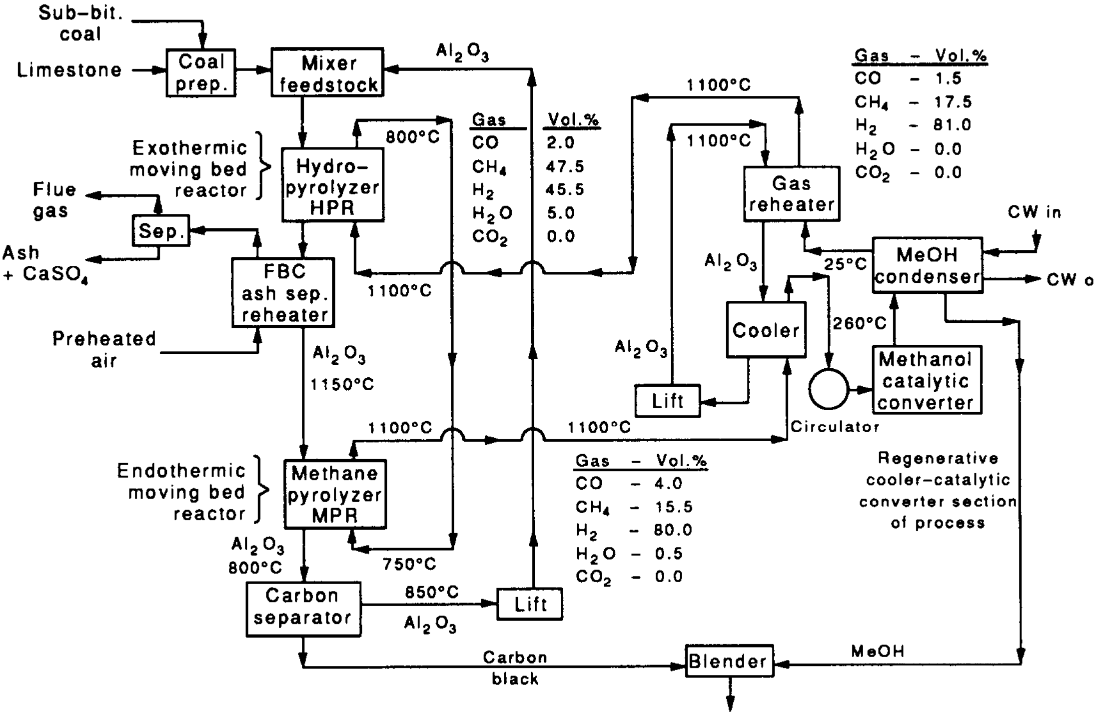
come even close to the American experience. Table 2 shows Grübler's comparison of global natural gas reserves, resources and potential occurrences. In a similar vein, Marchetti compared oil drilling finding rates (tons per meter of exploratory well) to show that apart from North America, other potential oil and gas bearing structures of the world have been barely explored. Styrikovich also cited the example of the Soviet Union where new natural gas fields containing the equivalent of 15 TWyr of energy have been discovered during the last 3 yr alone, sufficient to provide more than 6 yr supply at the current global gas consumption level. These findings only indicate that we are very far from conclusive evidence on how much oil and natural gas might be available to future generations. In all probability, the actual size of the resource base will increase with technological advances and improved theories of hydrocarbon formation.

In addition to wide-ranging discussions over resources, concern was expressed about possible leaks that might offset any carbon reductions gained by methane use. Since natural gas is a GHG with a radiative forcing around 30 times that of CO_2, its short term global warming potential is of major concern. Leakage rates of all energy-related sources of methane, in addition to natural gas use, are not well known. Sources include such activities as coal mining, oil and gas production, and gas transport and distribution. Other anthropogenic sources of methane are rice paddies, ruminants and waste disposal sites. Methane seepage from waste disposal sites was mentioned by Hackl who stated that waste avoidance and reduction should be considered a priority. A number of participants said it would be better to extract methane from waste disposal sites and burn it as a clean fuel, in addition to the methane from some coal mines. This is practised now in the U.S. and offers a potential source of energy to countries with large coal deposits (such as China). At the same time it would provide two additional bonuses; reducing methane seepage to the atmosphere and the danger of explosions. Lis had mentioned Poland's need to acquire expensive gas from abroad in addition to current imports from the Soviet Union if its CO_2 emissions were to be substantially reduced. Some of this requirement could actually be supplied from methane in Polish coal beds.

Fortunately methane has a short atmospheric residence time of around 10 yr, thus the contribution of a given amount emitted over longer periods to the greenhouse effect is relatively small compared to its radiative forcing. From a global perspective, for substitution of coal by natural gas, Victor calculated the break-even point of methane leakages to be between 4 and 6%, a figure far above that probable for high pressure gas pipelines.[33] The figures mentioned for The Netherlands and the U.S. were <1%. Some concern was voiced by a number of participants about high leakage rates in the gas distribution grid in the U.S.S.R. Official figures of 0.5% were questioned. Soviet participants emphasized that in no case was the true figure above 3%, since the majority of gas in the U.S.S.R. was consumed by industry, power plants and district heating plants, all with high pressure gas pipeline systems where leakage rates are indeed low.

Inaba underscored these points in his discussion of emissions reduction potential in electricity generation, stressing the transition from oil to coal and gas worlds. In doing so he also considered the effect of efficiency improvements in reducing emissions, limiting the analysis to incremental changes such as high temperature turbine blades, and improved coal gasification and liquefaction schemes. His analysis clearly shows that electricity production from fossil energy will not lead to fundamental reductions in CO_2 emissions by only applying incremental technological change. The widespread use of current best technologies could lead to reductions between 5 and 14%. All this points to the need to introduce radical, fundamentally new technologies to reduce emissions; to either remove carbon from fuels or after combustion, or to shift to carbon free sources of energy. It is likely that all of these measures will be needed.

A number of longer term options for the introduction of entirely carbon free fuels were presented. These involve production of carbon free vectors such as electricity and hydrogen, with carbon removed during the conversion process. Carbon removal and scrubbing will be discussed in detail in the next section. It is sufficient to mention here that carbon free vectors can make a large contribution to meeting energy demand. For example, electricity today supplies 30% of global final energy used. Steinberg advocated a no-regrets policy, using the hydrocarb process to separate hydrogen from carbon in coal, store the carbon generated and



Process conditions	Conversion	Carboline-MTH
P = 50 ATM	90% of coal C to CH_4	C - 60%
HPR = 800°→1100°C	65% of CH_4 to C	MeOH - 40%
MPR = 1100°C→750°C	20% of coal C to CH_3OH	Btu value - 120,000 Btu/gal
H/O ratio = 42-50 in gas	80% of coal C to C	

Fig. 14. The hydrocarb process as suggested by Steinberg and under study at the Brookhaven National Laboratory in the U.S.[34] In this particular flow scheme, carbon black produced from subbituminous coal is blended with methanol to produce carboline, a 60% carbon and 40% methanol mix of liquid fuel. Although originally conceived to produce a clean pure carbon fuel from coal, the hydrocarb process lends itself also to CO_2 reduction. Hydrogen contained in fossil fuels such as coals is used for energy purposes, whereas the carbon black is deposited for future use as a fuel or else to be in permanent storage as in coal mines.

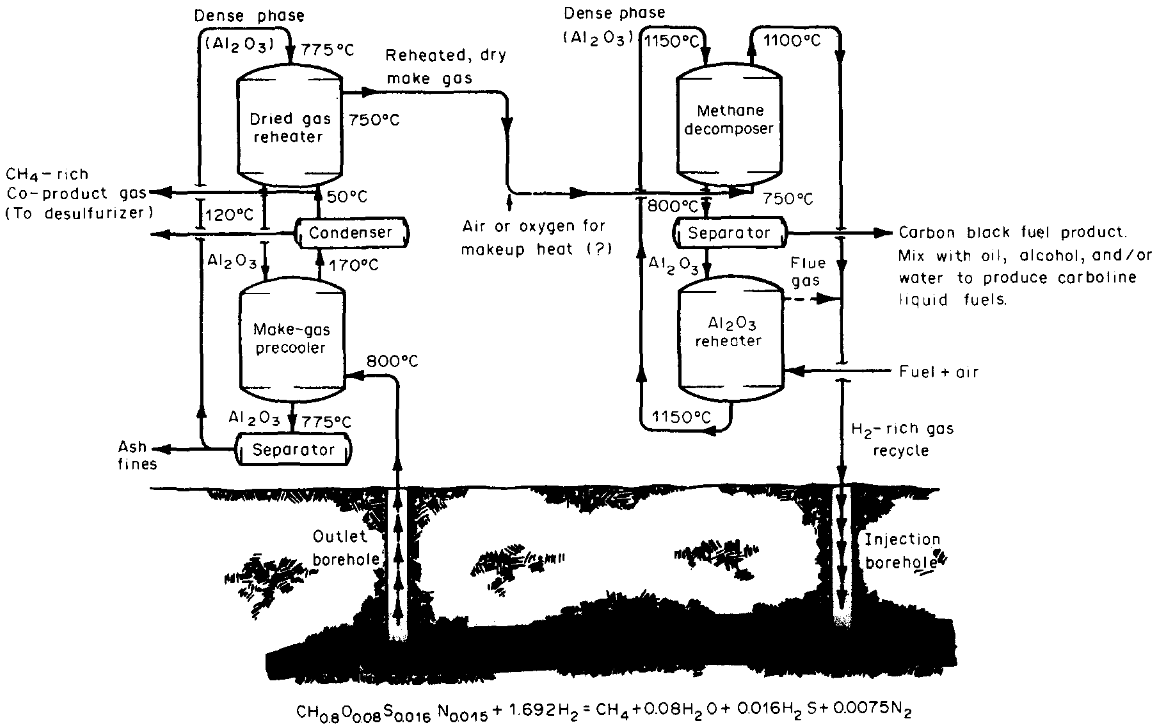


Fig. 15. The hydrocarb process applied to underground coal gasification.[35] Due to the abundance of coal resources in many countries, safe and clean production of energy carriers from resources located underground is an attractive option. The process could be used in a CO_2 reduction strategy by using only methane and hydrogen-rich gases for energy purposes while storing elementary carbon for later use or final disposal.

use hydrogen as a clean fuel.[34] Figures 14 and 15 illustrate the hydrocarb processes and give two applications based on coal. An intermediate stage between fuels with low carbon content and those entirely free of carbon entails the production of oxygenated fuels such as methanol from fossil fuels or biomass. Coal would be the most likely choice for production of liquid synthetic fuels since, as Steinberg pointed out, of all carbon based energy sources, coal is, and will continue to be, the most abundant.

Marchetti proposed steam reforming of natural gas into H_2 with CO_2 removal.[36] In conjunction with nuclear or solar energy as a source of heat this would further reduce the quantities of CO_2 generated in the process. This strategy of using natural gas with or without an external source of heat is becoming one of the preferred processes for carbon removal prior to combustion. The same process can also be used for coal provided it is gasified, followed by a shift reaction. In both cases the resulting mixture of gases includes CO_2 and hydrogen, making it possible to extract CO_2 by an adsorption or separation process. Variations of this process are being pursued in many countries and the results of some of these efforts were presented at the meeting by Steinberg, Hendriks and Matsuhashi. Hendriks described the advantages of an integrated gasifier combined cycle (IGCC) plant in which coal is converted to an intermediate synthesis gas. Subsequently, the carbon is recovered from this synthesis gas in three steps: conversion of CO to CO_2, extraction of CO_2 by a physical absorption process, and compression of CO_2 after drying.

Biomass offers another potential intermediate stage. Although it contains carbon, this carbon is recycled by plants. Today, extensive biomass use throughout the world is often associated with heavy deforestation or with considerable expenditure of fossil fuels for its production and harvesting. However, it can in principle be a source of very low carbon fuel, provided harvesting is done on a sustainable basis. Steinberg proposed the use of biomass in conjunction with the hydrocarb process to produce a hydrogen-rich fuel such as methanol, sequestering all or part of the carbon (Table 3). The major advantage of co-processing biomass with fossil fuel

Table 3. The CO_2 generated or removed from the atmosphere is shown for various methanol syntheses and co-processing systems using fossil-fuel feedstocks.[37] An overview is provided of processes for methanol synthesis and co-processing systems using fossil-fuel feedstocks, including combinations with biomass. The table shows different processes in terms of their overall energy-utilization efficiency and their CO_2 generation or removal per unit of energy delivered. The combined use of biomass and fossil fuels via the hydrocarb process offers interesting possibilities for carbon removal from the feedstock and its subsequent storage. The overall carbon balance could thus become negative, i.e., involve effective carbon sequestering via photosynthesis and subsequent processing and storage of elementary carbon.

Feedstock	Methanol Process	Carbon Utilization Efficiency Methanol Based on Fossil Fuel Feedstock %	Energy Utilization Efficiency Methanol Based on Fossil Fuel Feedstock %	CO_2 Generated (+) CO_2 Removed (-) lb CO_2/MMBtu of Methanol Generated Energy
Conventional – Produces CO_2				
Natural Gas	Steam Reforming	82	68	+170
Oil	Partial Oxidation	50	64	+280
Coal – Bit.	Steam-Oxygen Reforming	42	64	+330
Hydrocarb – Store Carbon				
Bit. Coal (added H_2O)	Hydrocarb	27	40	+130
Lignite	Hydrocarb	18	30	+130
Hydrocarb Co-processing with Biomass and Storage of Carbon				
Biomass + Nat. Gas	Photosynthesis + Hydrocarb	200	166	−78
Biomass + Oil	Photosynthesis + Hydrocarb	85	115	−78
Biomass + Bit. Coal	Photosynthesis + Hydrocarb	30	50	0

Note: combustion of natural gas generates 110 lb CO_2/MMBtu, oil 160 lb/MMBtu and bituminous coal 215 lb CO_2/MMBtu; assumes 90% conversion feedstock to methanol in hydrocarb processes.

is that CO_2 is removed from the atmosphere by the biomass. When the hydrocarb process uses natural gas or oil as feedstock to produce carbon and methanol, utilizing only the methanol as fuel, an actual removal of CO_2 from the atmosphere per unit of energy generated is realized (−78 lb/MMB.t.u.). Co-processing biomass with coal and sequestering the carbon, yields a net zero emission of CO_2 per million B.t.u. of methanol fuel energy. Biomass assists fossil fuels to obtain a substantial reduction in CO_2 to either negative or zero values, thus allowing the continued use of fossil fuel.

Several other biomass schemes were discussed at the meeting. Unfortunately they are usually associated with low energy yield such as oxygenated fuels based on alcohols and bio oils. The economics of biomass as a carbon offset are far from being demonstrated. For example, Pollak's presentation of bio-fuel economics in Austria showed the difficulty of reaching the break-even point in energy yield and raised questions about the feasibility of an economy with large biomass subsidies. Although farmers have been extensively using bio-fuel for their agricultural equipment, subsidies have to be high in order to encourage its use. Currently the subsidy on a kilogram of bio-fuel in Austria amounts to almost the entire fuel consumption tax per kilogram of fossil fuels. Furthermore, production is limited and efficiency is low in energy terms as illustrated in Fig. 16. The total share of biomass in primary energy consumption is in the order of 11% worldwide, including fuelwood, agricultural waste and all other categories. Bio-alcohol is important as a fuel only in a few regions, notably Brazil, but there again the resulting inefficiencies and subsidies required to sustain the program are of questionable economic benefit. On the positive side, this option does decrease energy-related CO_2 emissions when the biomass production for the alcohol program is cultivated on a renewable basis.

In the long run the only genuinely carbon-free sources of energy available in potentially vast amounts are solar and nuclear. Currently, the largest sources of carbon free energy are hydro and nuclear power plants. Hydropower, though renewable, is unfortunately often associated with environmental problems and up to half its ultimate potential might already be exploited. Modest amounts of other renewable and carbon-free sources of energy are also being used; solar, geothermal and wind energy. All of them have and will continue to make important local contributions to energy supply, but unfortunately their contributions to global CO_2 reduction is very limited. There was full agreement that their potential should be used to the economic maximum available.

Currently, solar energy is produced at a 10-yr old solar thermal electric plant run by Luz

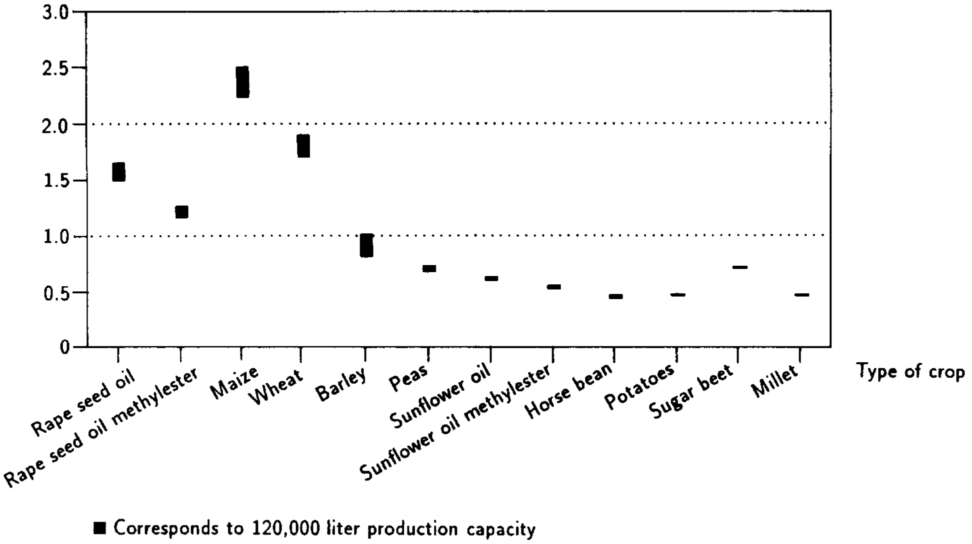


Fig. 16. Energy yield ratios for different biomass fuels given as energy output divided by energy input.[38] The overall energy balance for the use of many biomass fuels appears to be rather unfavorable and may be negative in many cases. For these cases, more (fossil) energy is spent on the production and processing of biomass fuels than corresponds to the energy content of the fuel produced. A recent Austrian study suggests that the potential of biomass use for transport-fuel (e.g., rape seed oil or bio-alcohols) as a CO_2-reduction measure is limited to a few percent of the CO_2 emissions in the transport sector.

International in California at a cost of 30 c/kWh. The price of energy from wind farms has fallen to around 6 c/kWh and electricity from solar-generated steam is estimated to cost around 10 c/kWh. The current lack of large investment in solar technologies is due to the absence of new demonstration plants and the questionable economic viability of large-scale plants given current low fossil fuel prices. Ullmann and Eliasson described the types of collectors currently in use. Technological change will undoubtedly decrease the cost of solar energy in the future, making greater energy generation possible. This not only includes solar thermal and photo-voltaic plants, but also systems in the more distant future (e.g., extraterrestrial facilities, like solar power satellites).

There was wide consensus among the participants that the future of nuclear power will depend on safety issues, namely, technical questions about the second generation of nuclear technologies and public perceptions of their safety. Marchetti's study on public attitudes to nuclear safety led him to conclude that systems considerations behind future energy systems (rather than public opinion) would be the primary deciding factor in a possible increase of nuclear power use.[39] Presenting the other side of the argument, Turkenburg insisted that nuclear power will prosper or die according to the whims of public opinion. In this context Steinberg pointed out that even in some countries where current nuclear prospects are bleak, in practice, as opposed to popular perception, usage is very wide. An example is the U.S. where, despite the Three Mile Island accident and the strong anti-nuclear movement, 112 nuclear power plants are still in operation today.[40] Styrikovich went so far as to cite Three Mile Island as a telling example of *nuclear safety* in contrast to Chernobyl, which was indeed an accident of catastrophic proportions. However there have been no new orders in the U.S. since Three Mile Island, so the domestic market for new nuclear plants is practically dead.

The basic idea behind most of the inherently safe reactors is that all the heat generated after emergency shutdown should be able to dissipate from the reactor vessel through thermal conduction.† Such a reactor would therefore not need active emergency cooling after

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†This means that the reactor vessel should be small enough to provide a sufficient cooling surface in relation to the volume of the reactor vessel and its power density. This is so because the surface of the vessel increases basically with the square of the dimension of the reactor while the volume increases with the cube. Therefore, beyond a certain size, reactors need active cooling systems even after shutdown to remove the after-heat and latent heat of fission products. Current designs all need such cooling systems.[41]

shutdown, eliminating one of the major single failure mode possibilities of power reactors. These reactors would of course also need other important safety features such as advanced containment design, flooding of the reactor vessels and so on. Eliasson mentioned the PIUS (process inherent ultimate safety) reactor and the walkaway safety features currently available in modern reactor designs.[22] 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, even without human intervention. This particular reactor design is illustrated in Fig. 17.

Commercial nuclear power is almost exclusively used for electricity generation, except for some amounts of district heat supplied in the U.S.S.R. Should nuclear energy with inherently safe second generation reactors be able to make a significant contribution to the reduction of GHGs in the future, then it will undoubtedly also have to expand its niche beyond electricity generation alone. This presumes that safety and reliability issues will have been resolved satisfactorily to the point of public acceptance of nuclear power. In addition to safety, there are three other major hurdles to acceptability of nuclear energy. The costs of the long regulatory

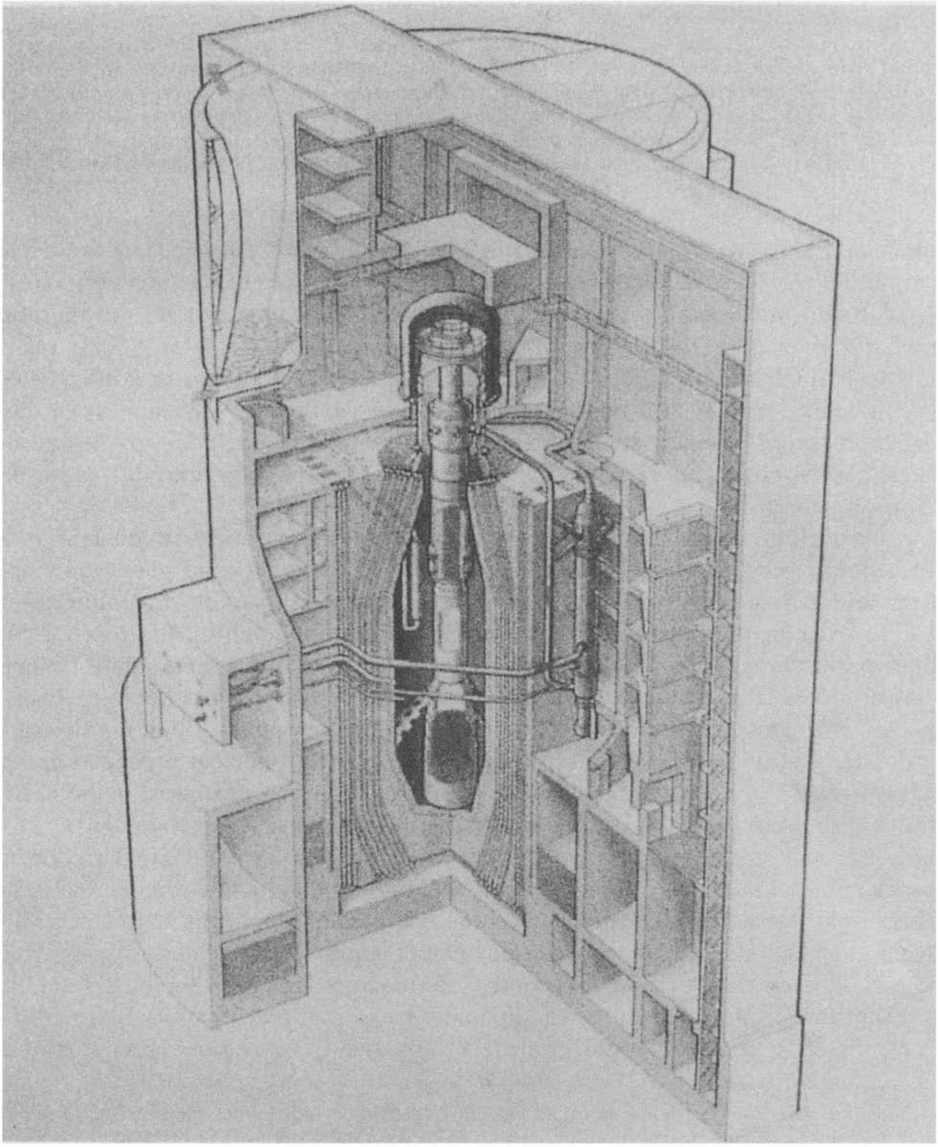


Fig. 17. PIUS reactor design, combining autonomous emergency-cooling features with flat economies of scale.[22] New inherently safe reactor designs could be a first step in overcoming public opposition and enhancing the contribution of carbon-free nuclear energy sources.

process and risk of liabilities from accidents; the lack of permanent waste disposal sites in many countries; and proliferation of nuclear technologies for military purposes. In addition to electricity, nuclear energy could provide heat. In particular, advanced high temperature reactors could provide process heat for industrial processes and other services along the temperature cascades. This is an attractive option but its difficulty lies in the colocation of nuclear plants with industry and commercial areas. This most probably will not be accepted for safety reasons for decades to come. The so-called "Adam and Eva" system has been studied in Germany where a high temperature reactor is used to reform methane into CO and hydrogen in a closed cycle that, when combined with the help of catalysts, provides high temperature heat at practically any desired distance from the power plant itself, returning methane and water to the plant.[42] Marchetti's suggestion to marry nuclear and natural gas is to open the cycle, whereby nuclear would provide the heat to steam reform natural gas into hydrogen and CO_2, the latter being removed from the system and hydrogen being provided to consumers.[36] Depending on future development, solar thermal could be introduced as an alternative source of heat for reforming the natural gas.

Marchetti then discussed the contribution of nuclear and solar in the long run to generate hydrogen in large conversion facilities on what he called energy islands.[43] He envisions a nuclear system on a remote location to produce power that feeds a hydrogen economy with clean, easily transportable fuel. The concept involves nuclear plants on barges that produce large quantities of hydrogen from seawater. This hydrogen is then shipped on large tankers for worldwide distribution. The energy island scheme is illustrated in Fig. 18.

Ullmann nudged Marchetti's futuristic vision closer to reality with a report on efforts underway to evaluate the use of hydrogen in practice, in conjunction with remote sources of energy. The Euro–Québec hydro–hydrogen pilot project uses the abundant hydropower of Québec to produce hydrogen that is then shipped on cryogenic tankers in liquid form.[44] Other possible transport systems could be lithium hydride or hydrogenated toluene. The carrier is shipped back to Québec for rehydrogenation while the hydrogen received is then available for

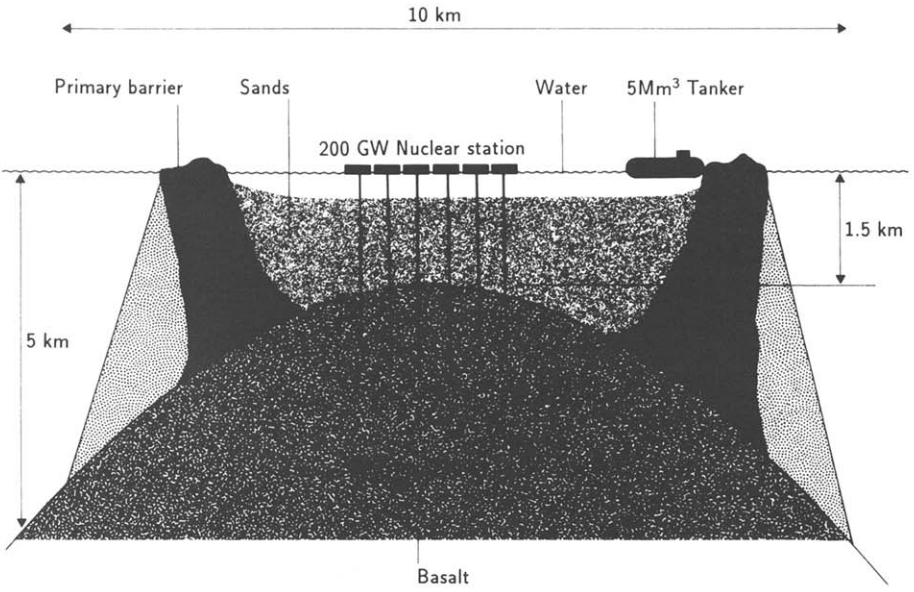


Fig. 18. Futuristic sketch of an energy island, the ultimate carbon-free energy-supply system.[43] Located far away from the human sociosphere on a Pacific island, the concept provides for full integration of uranium supply, the fuel-cycle facilities and waste disposal, nuclear reactors, hydrogen production from seawater and facilities for shipping liquid hydrogen to consumers. Each energy island would produce the energy equivalent of the present Persian Gulf with no CO_2 emissions at either the point of energy production or consumption. Instead of nuclear power, large-scale photovoltaic facilities could also provide the needed primary energy. In order to minimize albedo changes that would arise from the location of large solar farms in desert areas, the use of large floating platforms on the oceans has been suggested.

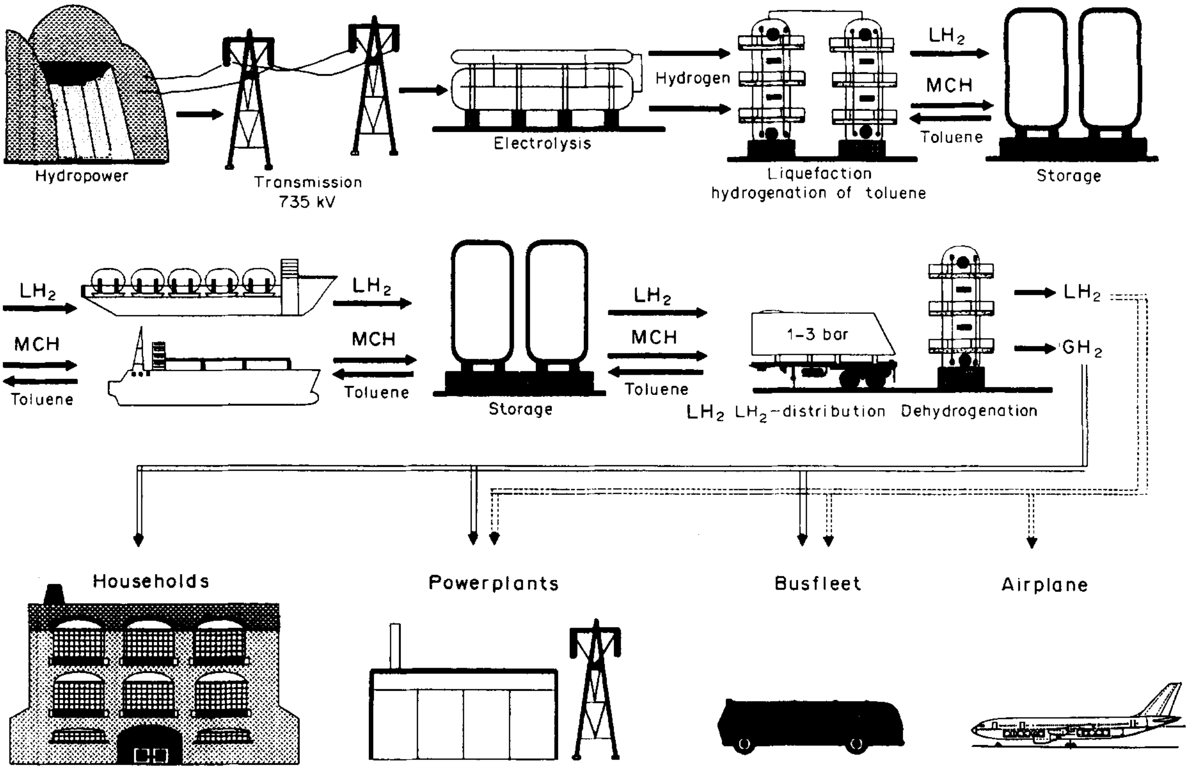


Fig. 19. Overview of the Euro–Québec hydro–hydrogen pilot project energy chain.[44] 100 MWe of hydropower are used to produce hydrogen via electrolysis, which is then liquefied (the toluene route was excluded during the feasibility study) and transported from Canada to Europe for use in stationary and mobile applications. The overall energy balance indicates a conversion efficiency from primary to final energy of around 52%. The economics of the hydrogen delivered is, at 148 ECU cents/l of gasoline equivalent, rather unfavorable, being between two and three times higher than European gasoline prices including taxes. Estimates indicate that the delivered hydrogen costs could ultimately be brought down to about 73 ECU cents/l, assuming large-scale implementation of the order of 1 TW.

distribution to a number of end users: households, power plants, or transportation. This project is illustrated schematically in Fig. 19.

It is also conceivable that aircraft could transport liquid hydrogen or liquefied natural gas (LNG). This is another promising long-term option because methane and hydrogen are ideal propulsion fuels for aircraft. They would not only reduce carbon emissions but other adverse by-products of aircraft propulsion by current jet fuels. Should supersonic or hypersonic air travel become practical in the future, then methane and hydrogen would be the only fuels of choice. In fact, Airbus Industries plans to build an experimental passenger aircraft with hydrogen propulsion. A few years ago Tupolev flew a modified version of its TU-154 airliner with a hydrogen powered engine. Even more promising from the point of view of reducing GHG emissions are other potential end-use applications of hydrogen such as in motor vehicles or even in households, either simply as a replacement for current energy carriers or in conjunction with fuel cells and other new end-use technologies. Apart from electricity, hydrogen is also the only other carbon free energy vector for transporting not only nuclear but solar energy from remote generation points (e.g., the Sahara or offshore facilities) to consumption sites.

4. REMOVAL AND SCRUBBING

Since carbon-free energy sources, such as nuclear and solar, are still some distance in the future, carbon removal from energy carriers prior to combustion and scrubbing after combustion are important interim priorities. Scrubbing has been identified as a promising solution for the near term.[45] The advantage of removing CO_2 from a large, concentrated source such as the flue gas of a power plant, compared to direct removal from the atmosphere, is obvious. CO_2 is about 500 times more concentrated in flue gases compared to its dilution in the ambient atmosphere to about 350 ppm. In 1985, nearly 2 Gt of carbon (and proportionately three-and-a-half times this weight of CO_2) was released into the atmosphere as a result of fossil fuel use worldwide to generate electricity. Steinberg, one of the pioneers in the study of the feasibility of scrubbing, showed that all processes based on removal of CO_2 from the atmosphere with fossil energy have a negative carbon balance. If energy expenditure is not a concern, only carbon free sources such as nuclear and solar come into question as sources of energy. Of all known processes for sequestering carbon from the atmosphere the best is photosynthesis, a removal strategy that nature has practised for several billion years. This question will be revisited in the next section on afforestation.

All the systems originally proposed by Steinberg for CO_2 removal from flue gases have in the meantime become standard procedure and some, such as the chemical absorption process, have already been used on a number of scrubbing facilities now in operation. Hendriks presented three different scrubbing technologies to remove CO_2 from flue gases. These are: cryogenic distillation of CO_2 from flue gases, separation by membrane, and chemical absorption.[45] Each of the alternatives proposed has inherent limitations; for example, in membrane separation, there is a tradeoff between permeability of the polymer membranes used and purity of CO_2 separated. Similarly, chemical absorption is an energy intensive process. Hendriks and Turkenburg also showed the study's calculations of the costs of various options. The cost estimates of the options ranged from \$25 to \$45/ton of CO_2 removed.[45]

A few plants in existence today produce CO_2 for use as a raw material. Eliasson mentioned that only two processes are currently being used for scrubbing on a large scale, the monoethanolamine (MEA) and econamine (DGA) processes, both of which involve chemical absorption of the CO_2 and subsequent stripping to the desired degree of purity. The largest plant in operation, the Trona chemical plant in California, separates 860 tons of CO_2/day and converts it to soda ash for subsequent use by the glass-making and chemicals industry. The 300 MW Shady Point power plant in Oklahoma separates 200 tons of foodgrade CO_2 daily for use by the beverage industry. Both the above plants use the MEA process. The only plant in operation using the DGA process, at Bellingham in Massachusetts, produces 350 tons of foodgrade CO_2 every day. The major problems associated with scrubbing are to reduce the costs and minimize losses in plant efficiency due to the energy spent separating CO_2 from flue gases. The efficiency reductions of power plants amount to a few percent. Typically a power plant with an efficiency of 40% might operate at a total net efficiency of 35% with CO_2 scrubbing.

Unfortunately, the amount of carbon generated by scrubbing alone would be truly gigantic. For example, a single automobile produces its own weight in carbon per year and total emissions from energy use worldwide amount to almost 6 Gt/yr. As already mentioned, the share of electricity is about 2 Gt/yr.

Eliasson indicated commercial opportunities for the use of CO_2 as a raw material, citing the example of its being piped from a plant in Colorado to a Texas oilfield for use in enhanced oil recovery. Marchetti suggested use of CO_2 obtained from steam reforming of natural gas by the U.S.S.R. for enhanced oil recovery in some of its depleted fields. Other possible users include the beverage and chemical industries, but all these requirements of CO_2 are minuscule in comparison to the amounts that would be generated.

Steinberg advocated using the hydrocarb process to remove elementary carbon from fossil fuels.[34] This carbon can then be either used as a basic raw material (e.g., for plastics, construction, etc.) or sequestered. Again potential demand is seen to be very limited compared to almost 6 Gt that would be available. For example, steel and concrete production worldwide was only about 680 and 960 million tons, respectively, in 1985 (i.e., <1 Gt each). In view of the volume involved, the hydrocarb process makes eminent sense. The solid carbon that is not used industrially can be compactly stored in depleted mines. Should the greenhouse problem cease to be a major concern in the future, this carbon can then be consumed as fuel.

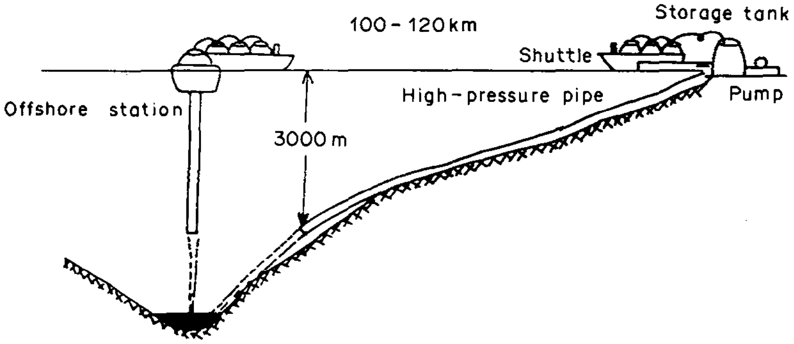


Fig. 20. CO_2 disposal in the deep ocean.[46] After CO_2 removal from flue gases, e.g., via chemical absorption (as suggested by Steinberg) or via physical absorption (selexol process), final disposal of CO_2 is required. Disposal in depleted natural gas fields or salt caverns has been suggested. In Japan disposal in the deep ocean is being investigated. CO_2 could be either pumped to the ocean floor or liquefied and transported to an off-shore station and sunk from there. There is a wide consensus that further detailed theoretical studies, as well as carefully designed experiments, are needed.

Hendriks presented storage of CO_2 in depleted natural gas reservoirs as an option of choice for The Netherlands beyond the year 2000. Steinberg also suggested using salt caverns for this, but the deep oceans are seen as the ultimate sink for CO_2. The global cycle involves the annual exchange of around 200 Gt of carbon between oceans, the atmosphere and the biosphere, the largest amount of carbon being stored in the ocean. This is estimated to be about 36,000 Gt, therefore the deep oceans might be a possible repository for the sequestered carbon.

Matsuhashi presented a detailed analysis of the results of studies being performed in Japan. Figure 20 illustrates a concept for CO_2 disposal in the deep ocean.[46] There are many types of uncertainties associated with ocean disposal; the clathrate problem, altered chemistry and pH of sea water, and miscible displacement. Methane and CO_2 clathrates occur frequently in nature and can be stable under certain conditions. Possible diffusion and migration of dissolved and liquid CO_2 under pressure are presently unknown, as are changes in pH in the deep ocean. Perhaps most important are the possible ecological impacts of CO_2 dispersion. The third unknown, miscible displacement, might possibly occur at depths below a few thousand meters and would eliminate capillary and interfacial forces between water and CO_2. Should this occur, the CO_2 enriched water would rise to the surface.

There are various disposal schemes: either to pump CO_2 in high pressure pipes to the ocean floor or transfer it from storage tanks into shuttle ships which travel 100–120 km offshore and then inject the CO_2 at a sufficient depth underwater. Liquefied CO_2 has to be injected to a minimum depth of 3000 m if it is to stay down, whereas with the gaseous form 300 m will suffice.

In sum, since little is known about diffusion rates, changes in deep ocean acidity and other ecological questions, the majority of participants were in favor of limited experiments, under carefully controlled conditions, before any decisions were taken in this direction.

5. PHOTOSYNTHESIS AND AFFORESTATION

In the context of removal strategies, photosynthesis by plants, algae or by synthetic methods, is actually seen to be the only really viable technology for absorbing carbon from the atmosphere. In view of all the difficulties expressed at the meeting in reducing energy sources of carbon emissions, it is not surprising that energy experts see massive afforestation as a great opportunity for removing the large amounts of CO_2 emitted.

Esser highlighted a major hurdle to the use of afforestation to absorb excess CO_2. Estimating total soil organic carbon at 1500 Gt and total living biomass at 600 Gt, he used the F.R.G. as an example to illustrate the practical difficulty of absorbing global CO_2 by afforestation. Putting the current entire agricultural area of the F.R.G. under reforestation would take up approximately 23 million tons of CO_2/yr. This is around 10% of F.R.G. emissions. This

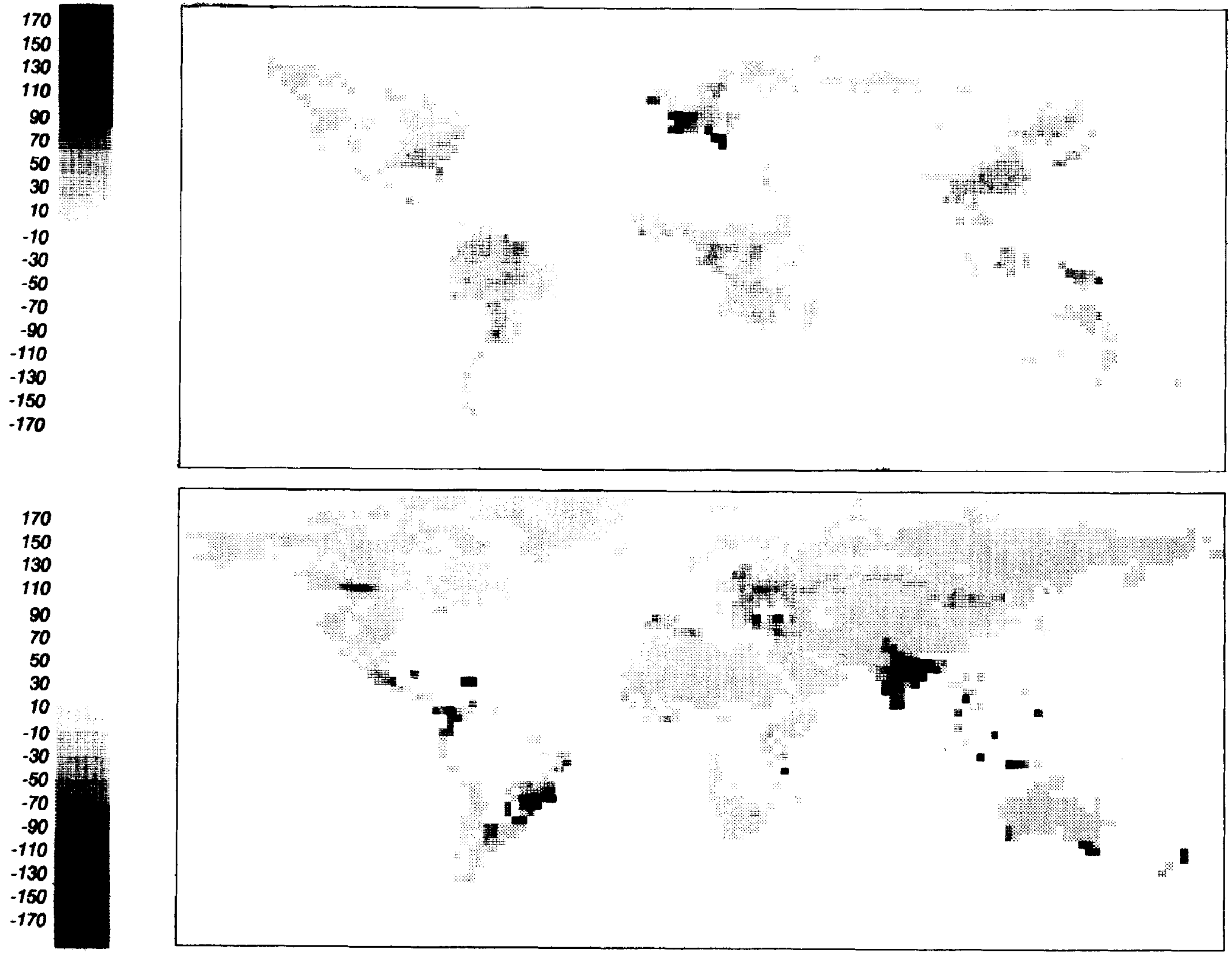
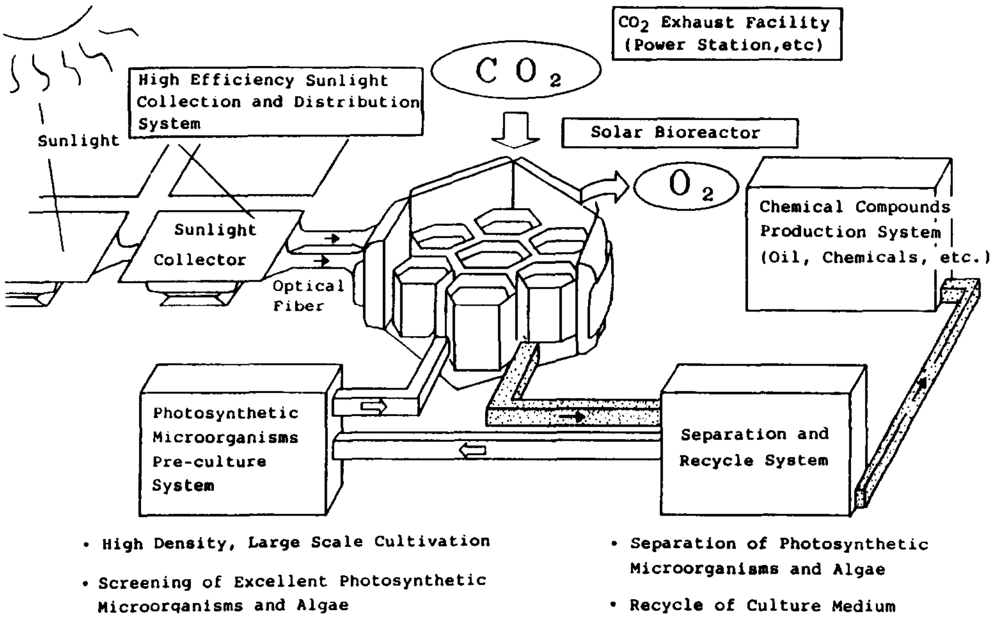


Fig. 21. Global phytomass change in 1980 due to deforestation, afforestation, and CO_2 fertilization effects. Positive (top) and negative (bottom) balances are shown in grams per m^2 per year.[47] The terrestial biota carbon cycle is complex and significant regional variations exist. Consequently, the impacts of afforestation programs on atmospheric CO_2 sequestering must be analyzed comprehensively by also considering changes in the soil-carbon content. Afforestation is constrained by competing land utilization for agricultural purposes and significant fertilizer and water requirements.

afforestation effort is a disturbance and causes changes in the water balance. Since trees consume more water than field crops, the required additional water, again for reforesting the F.R.G. alone, is around 25% of the annual discharge of the river Rhine. Secondly, due to the loss of soil organic carbon, net fixation is <50% of annual deposition in phytomass. Global reforestation of the entire area used worldwide for agriculture would result in total potential annual carbon fixation of around 50% of 1985 fossil fuel emissions. Given these daunting figures, it seems clear that there is no single solution to the CO_2 problem. Figure 21 shows global phytomass change due to deforestation, afforestation, and CO_2 induced fertilization.

Kuyper showed how afforestation can be successful on a limited scale; in this case over an area of 300,000 ha, with timber being harvested in 6–10 yr cycles, leading to carbon fixation estimated at 10 tons/ha. Saiki also presented calculations of the gains to be achieved through afforestation. Approximating carbon storage in a forest at around 280 tons/ha, he estimated yearly carbon storage in a tropical rain forest at about 10 tons/ha/yr, in close conformity with Kuyper's figures.



Greenhouse Gas	GHG emission (ton-C equivalent/forage ton-C)			
	Micro-algae[(a)]	Micro-algae[(b)]	Hydrogen bacteria[(c)]	Forage crop
CO_2 (resulting from energy consumption)	0.08	1.08	2.9	0.157
N_2O[(d)]	0	0	0	0.01
CH_4[(d)]	0	0	0	8.0[(e)]
Total	0.08	1.1	2.9	8.2
Replacement effect	8.1	7.1	5.3	–

(a) Extensive culture. (b) Assuming intensive culture based on the data of bacterial SCP production. (c) H_2 is derived from LNG. (d) Greenhouse effect equivalent to $CH_4 = 80 \times CO_2$, the greenhouse effect equivalent to $N_2O = 200 \times CO_2$. (e) Assuming that 10% of the plant residue is converted to methane by anaerobic fermentation.

Fig. 22. CO_2 sequestering via photosynthesis. A general flow chart for photosynthesis with microorganisms and algae is shown for the production of chemical compounds (top)[23] or animal feed (forage), together with the resulting GHGs emission balance (bottom).[48] CO_2 sequestering via technologies based on photosynthesis has been suggested as a more promising alternative than afforestation programs. For example, the integrated GHG emissions of forage production via extensive micro algae culture would produce only one-tenth of the GHG emissions that arise from conventional agricultural crops used for animal feed.

Of course, in afforestation, the ultimate question remains, once having in theory sequestered large amounts of carbon in forests, what happens after 20 yr when forest decay starts to release the collected CO_2. The real problem is to break nature's cycle, which reduces the effectiveness of carbon storage after 20 yr. Maybe the final answer to this key question lies in copying nature's strategy on a geological time scale, burying whole forests to make artificial coal beds for distant generations. This illustrates that biomass might turn out to be more a postponement strategy than a permanent solution.

Döös spoke of hitherto unsuccessful efforts at reforestation, with large losses in established plantations in Angola, Nigeria, Morocco, and several other countries. In China, the rate of survival of reforestation efforts is estimated to be not higher than 20%. Success rates in practice are far below theoretical calculations.

Saiki focused on biotechnologies for carbon reduction. Apart from afforestation, other alternatives for carbon reduction on land are microorganisms; the cultivation of green microalgae, cyanobacteria and hydrogen bacteria. Figure 22 shows a general flow chart for photosynthesis with microorganisms and algae together with the resulting GHGs emission balance. At sea, Saiki proposed carbon reduction by means of phytoplankton, calcification or kelp.[48] The most radical among the three was the Martin proposal to remove atmospheric CO_2 using iron fertilizer to stimulate growth of algal blooms in the Antarctic.[49] Several assumptions of this scenario are in doubt, in particular the hypothesis that the iron fertilization would significantly reduce the atmospheric CO_2 content.[50] Costs of manufacturing liquid ferrous chloride are between $150 and $200/ton, without including the cost of transportation to the Antarctic. Furthermore, the proliferation of algal blooms might lead to oxygen depletion on the ocean floor and destroy Antarctic krill by interfering with the hatching of their eggs. It is also not known what the other possible ecological impacts of this strategy might be. Thus, the suggested remedy might wreak major havoc in the marine food chain and prove worse than now anticipated by the proponents.

6. POSTSCRIPTS

The following are the primary issues that were identified in the discussions: (i) climate change is a global problem that calls for global solutions; until now, there have been only national programs; (ii) CO_2 contributes only 50% of the warming caused by greenhouse gases. Other GHGs must be included in reduction and mitigation strategies, (iii) the cheapest measures should be instituted immediately. Although costs are uncertain, the majority of the cost estimates are comparatively low for an initial range of measures. Even with uncertainty, cheap measures instituted immediately are perceived as an insurance policy with multiple benefits. International cooperation makes economic sense, since a CO_2-abatement dollar is initially invested more effectively in a country with low levels of energy efficiency and high carbon intensity than in one that has already achieved relatively high levels of energy efficiency and decarbonization; (iv) an important priority is to stop tropical deforestation. In addition to the CO_2 mitigation effects of this effort, there are diverse multiple benefits, ranging from improved local and regional ecology, preservation of animal and plant diversity, to esthetic improvements.

The subject of global warming has to do with behavioral and cultural attitudes, as well as development and economics. The commonly used word culture represents an unquantifiable area where religion, art, literature, scholarship, polity, economy, technology, and science all meet. People speak of the same problem at completely different levels. For some, global change is a nuts-and-bolts problem; for others, on a completely different plane, there are moral and ethical considerations, like intergenerational equity, the destruction of human habitats, or of other biological species.

Regardless of problems of quantification, all the above factors have to be weighted in considering technological options to mitigate global warming. This weighting process is implicit in our existing policies and institutions which often conceal explicit choices that would be hard to justify.

In view of the global and long-term nature of the problem, no immediate solutions were expected to emerge from a single workshop. Many of the actions that mitigate CO_2 emissions and greenhouse warming presume global acceptance in order to be successful. Implementation of these measures calls for coordinated international action. But it also implies widespread acceptance of the problem throughout many cultures. Like fashions, public perceptions change with time. A few years ago, before the tremendous international political changes in Eastern Europe, the issue debated was not global warming but its opposite; nuclear winter in the aftermath of a global holocaust. Today, as in the past, concerns are expressed about a new Ice Age; in this context, global warming might appear to be the solution to a problem of global change rather than the problem itself.

Thus, while questions concerning global climate change will most likely continue to be associated with scientific uncertainty, what is known is that the greenhouse effect of many gases in the atmosphere from anthropogenic sources is real. Perhaps planetary concerns in the future will increasingly encompass other dimensions of global change besides climate. With all these points in view, it might be advisable to institute a broad spectrum of relatively cheap measures immediately. Whatever the future direction of global change, measures not geared to a single objective and providing a multitude of benefits could be an insurance policy that humankind will not regret having taken.

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