SUMMARY OF THE WORKSHOP ON

CO_2 REDUCTION AND REMOVAL: MEASURES FOR THE NEXT CENTURY

Environmentally Compatible Energy
Strategies (ECS) Project

April 1991

International Institute for Applied Systems Analysis
A-2361 Laxenburg, Austria
Telephone: (02236) 71521; Telefax: (02236) 71313

SUMMARY OF THE WORKSHOP ON "CO_2 REDUCTION AND REMOVAL: MEASURES FOR THE NEXT CENTURY"

1. Introduction

A scoping workshop on "CO_2 Reduction and Removal: Measures for the Next Century" was held at IIASA from 18–21 March 1991.[1] The workshop was organized to assess CO_2 reduction and removal strategies worldwide and to review other studies and technological options being considered by leading research organizations in different countries. Since policy measures for environmentally compatible development of energy systems encompass so many different areas, both in terms of geography and discipline, the 48 workshop participants represented more than 11 disciplines from academic, private and public organizations from 15 countries. Emphasis was given to discussion and interaction between participants rather than to formal presentations.

The five workshop sessions were on global and regional studies, national studies, efficiency improvements and cleaning (scrubbing), low and zero carbon options (including renewables), global issues and integration. The discussions were not compartmentalized, however, and there was a large degree of overlap among these five session subjects. For instance, it is clear that a discussion on technologies with high investment requirements will only be a theoretical consideration to countries facing extensive economic restructuring or severe capital shortages, or both. As another example; it is difficult to predict costs fifty years hence with any certitude. However, although the time scale of the problem runs into decades it demands decisions now. These decisions must therefore be based on the best available information, however incomplete.

2. International and National Studies

In 1987 global CO_2 emissions from fossil energy use are about 5.7 Gt. However, the levels, structure and etiology of emissions vary greatly between individual countries and regions (Figure 1). Currently about 75 percent of energy-related CO_2 emissions comes from the highly industrialized countries, but this will change dramatically with increasing populations in the developing countries, their concomitant increase in per capita energy use,

---

The workshop was sponsored by International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria and Global Industrial and Social Progress Research Institute (GISPRI), Tokyo, Japan.

[1] See Appendix I for workshop description, agenda and list of participants.

and further tropical deforestation. There is strong consensus 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 greenhouse gas (GHG) emissions.

Although a number of initiatives have been taken to reduce emissions, there is no agreement among industrialized countries on the timing and extent of GHG reductions necessary or desirable. Developing countries, in particular, face severe capital shortages and hence have limited freedom to make structural changes in their economy, so the outlook for reductions in CO_2 emissions here is bleak. Indeed, the best that can be hoped for is a *reduction of the expected increase of* CO_2 *emissions.* Population growth will be a large contributing factor to this increase.

International organizations like the Intergovernmental Panel on Climatic Change (IPCC), formal and informal groups like the World Energy Council (WEC) and the International Energy Workshop (IEW) at IIASA, national agencies like the Office of Technology Assessment (OTA) in the U.S. or the German Enquete Commission, and private oil companies like Shell International have all made assessments of potential growth in CO_2 emissions.

The estimates of the above groups vary considerably, so although the problem is known about its magnitude is uncertain. It is also known that something has to be done. The questions are: what, how much, when and by whom? The IPCC's forecasts project, under a "business as usual" scenario, a more than doubling of global CO_2 emissions by 2030. From the point of view of possible climate change and its global consequences, there is undoubtedly a need for action. The choices made will have philosophical, economic, social and political implications far beyond the climatic effects, uncertain as they are. Sentiments frequently expressed at the workshop were not only concern for the present, but also for the sustainable well-being of future generations.

The focus of the meeting was on technological options. As the name **CO_2 Reduction and Removal: Measures for the Next Century** of the study implies, there is a need for a long term view in discussing these options. This was best epitomized by the Global Industrial and Social Progress Research Institute's (GISPRI's) "New Earth 21" (NE 21) model presented by Yoichi Kaya. NE 21 is an example of an innovative approach to evaluate potentials of various energy technologies toward reducing future CO_2 emissions. The model is intended to provide a simple and transparent, but also feasible path to long-term reductions in CO_2 emissions. Briefly, its aim is to reduce CO_2 emissions per unit of GDP by 30 percent. It was clearly designed to be a blueprint for the world in the 21st century, not simply for Japan. (The key technologies considered for reducing and controlling CO_2 content in the atmosphere are illustrated in Figure 2.)

Several other studies at the national level examined CO_2 emissions and concomitant questions. Although some important international efforts were discussed, it was not the objective of the workshop to provide a comprehensive overview.

Deanna Richards presented findings of a very comprehensive study by the U.S. National Academies that takes a broad look at reductions of emissions of all GHGs, their benefits and costs. This study, currently under review, will soon be released for distribution and basically concludes that the U.S. can mitigate the effects of GHGs by phasing out chlorofluorocarbons (CFCs) alone by the year 2000. This would significantly reduce the total greenhouse warming potential of the U.S. Should the policy objective be to only stabilize the greenhouse warming potential of all GHGs this would allow for an increase in CO_2 emissions.

Academician Mikhail Styrikovich and Sergei Chernavsky discussed numerous inefficiencies in energy use throughout the Soviet Union that invariably lead to high emissions. Elimination of the most obvious inefficiencies alone would automatically 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.

The Tata Energy Research Institute has examined the potential for reducing primary energy consumption without reducing end-use services. As reported by Ajay Mathur, the largest potential for mitigating CO_2 emissions is identified as afforestation, which also carries the lowest specific cost of all options identified. As a collaborating Institute under the aegis of the Asian Energy Institute, it also participates in a project to investigate emissions of GHGs in the major countries of Asia and Brazil. Preliminary findings show that almost all developing countries foresee an increase, perhaps even a doubling, of CO_2 emissions by 2010.

Germany's Enquete Commission report can be synopsized as aiming at a reduction of anthropogenic GHGs, oriented to the goal of limiting global warming to a maximum of 2 degrees above pre-industrial times. Germany's national targets (this includes the territory of the former GDR) in this global scenario are a reduction of CO_2 emissions of 30 percent by the year

2005. Peter Schaumann presented a related study for Germany directed by Alfred Voss at the Institute for Energy Economics and Rational Use of Energy (IER), University of Stuttgart. The IER calculated costs of various options to reach the target set by the Enquete Commission for 2005, which ranged from 46 DM per ton of carbon removed if nuclear was phased out, to 13 DM per ton under a conservation scenario in conjunction with nuclear power (Figure 3).

The International Energy Workshop (IEW) is a worldwide group of energy economists, organized by IIASA and Stanford University, which meets annually to pool its collective wisdom. It conducts an informal semiannual poll to compare energy price and supply projections. Although the IEW's range of future prices vary greatly, there is less uncertainty in its forecasts of primary energy consumption, i.e., apparently the energy community agrees less about the evolution of driving forces like energy prices than about rising energy demand. In the case of the latter, average global primary energy demand increased from 1850 to the present on the order of 2.2 percent per year, and the IEW median anticipates a similar growth rates for the next decades. Although lower than IPCC estimates, the IEW "business as usual" estimates of global carbon emissions still predict a considerable increase.

Tom Kram spoke of the objectives of the International Energy Agency's (IEA) Energy Technology Systems Analysis Program (ETSAP) study, which are 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 objective 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, Tadeusz Lis spoke of activities which include modeling energy-economy-environment interactions. In cooperation with the World Bank, Poland is also assessing the development of other sources of energy, since at present its economy is highly dependent on hard coal for energy supply. One component of Polish strategy is to reduce its dependence on a single source of natural gas.

Adrian Gheorghe reported that Rumania sees no alternative to nuclear power and currently has five CANDU-type reactors under construction. Rumania's oil reserves are depleted, it already suffers from one of the highest per capita emissions of CO_2 in the world and expects this to double by 2030.

There was high consensus that all immediate, low-cost options available should be instituted, especially in the realm of efficiency improvements. The potential for CO_2 reduction through efficiency improvements is seen to be extremely large. As will be seen in the following section, the history of efficiency improvements shows strong heterogeneity in the experience of different countries. Clearly the potential varies greatly from one region to another. In an energy efficient economy like Japan the possibilities are different from those in a currently reforming economy like the Soviet Union, 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 energy related GHG emissions in the U.S. (OTA, 1991). 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 a wide scope and many 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. Another spinoff would be lower energy-related pollution and an improvement of their local environment.

3. Efficiency Improvement and Costs

Looking back through the past centuries, paradoxically, might help improve our perspective of the future. The long-term trend shows average improvement of the energy intensity of around 1 percent per year although it did increase sporadically over varying periods of time. The rate of improvement has been generally higher since the energy crisis of 1973, averaging more than 2 percent per year. So, although the long term historical experience has varied greatly among different countries, John Gibbons, the Director of the OTA, for example, feels this performance can be sustained by the U.S. in the future to the common benefit of its economic health, environmental quality and energy security (Science, 1991).

Nebojša Nakićenović argued that there is strong evidence that historical trends do matter. Countries like France and Japan have always used energy more efficiently than the U.S., the U.K., or Germany, and the rate of efficiency improvement has been higher in both the U.K. and Germany than in the U.S. Even more surprising is that Japan, with already one of the most energy efficient economies, has also achieved the highest improvement rates since 1973. This should be contrasted with the opposite development in some of the rapidly industrializing countries where energy intensity is still increasing as is the case, e.g., in Nigeria. On the other hand, 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 (Figure 4).

The bulk of this improvement has occurred at two levels: conversion and end use. For example, over the past 20 years, aircraft engine manufacturers have managed to improve the energy efficiency of commercial transportation by 3–4 percent annually (Figure 5). In electricity generation, this improvement has been 2.5 to 3 percent per year between 1930 and the late 1970s. 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 percent. 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 not much more than 10 percent. There is a large scope therefore for more efficient energy use, in particular in 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. Some experts claim that in view of relatively high primary to final energy conversion rates (about 70 percent) further improvements will be difficult to realize. In some areas, like electricity production, improvements appear to be 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 Second Law efficiency, which allows accounting for differing qualities of various energy carriers, indicates that in the OECD countries the overall exergy efficiency is not more than a few percent[2] (Figure 6). Many studies confirm

---

[2] 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 percent. 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).

a similar result for most of the industrialized countries. In developing countries exergy efficiency is probably only about 1 percent, especially because noncommercial energy sources are used directly, resulting in very low efficiency. For example, open fires for cooking use up to four times more fuel than well-designed stoves. Steam locomotives have at best 7 percent efficiency compared to almost 30 percent for modern diesel-electric locomotives. Commercial and industrial facilities themselves are often poorly designed and maintained. As mentioned above, efficiency appears to be a bit higher in energy terms (although not much higher than 10 percent). There is, therefore, vast potential to improve efficiency up to the theoretical maximum specified by the Second Law or exergy analysis. If an increase in service efficiency is added to this, a reduction of primary energy input by a factor of 20 or even more appears feasible with energy services being maintained at current levels.

Wim Turkenberg presented a comprehensive technological analysis performed at the University of Utrecht 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. 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 percent higher than current levels. In other words, the potential for energy conservation is much larger than the Dutch government goals, which aim at an average energy efficiency increase of 20 percent between 1990 and 2000. The Netherlands study highlighted the need to compile such comprehensive assessments for other countries (Figure 7).

Such a study does exist for a developing country also. Mathur, presenting the Tata Energy Research Institute's study of CO_2 mitigation prospects for developing countries, spoke of the scope for efficiency improvements in India. There is 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. Beyond that, it would also be desirable to improve the efficiency of biomass use that will ultimately enable the sustainable and efficient provision of energy needs. In addition to the scope for improving the efficiency of renewable energy use in India, Mathur also showed other potentials for efficiency improvements and their associated costs, ranging from installation of energy efficient equipment and better instrumentation in industry, all the way to improved lighting in the domestic sector through the introduction of fluorescent tubes and compact lamps.

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) offer particularly high achievable efficiencies. For example, Eliasson described Asea Brown Boveri's (ABB) Pegus CCPP already in operation in the Netherlands, with a conversion efficiency gas–electricity in excess of 50 percent. 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 and rising overall systems efficiency well beyond 80 percent. Overall CO_2 emissions are thus dramatically lowered and Combined Cycle Power Plants 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 more than 50 percent of its primary energy supply but with very low efficiencies in conversion to electricity of around 30 percent. He pointed out that this could be improved to almost 50 percent with wider application of CCPP technology. Unfortunately there is a lack of production capacity and financial resources to manufacture CCPPs in the number and quality needed. In greater numbers, such plants could potentially save 50 percent of the gas consumed by the electricity sector in the Soviet Union. CCPPs can substantially increase efficiency and reduce emissions also in conjunction with other fossil sources of energy although the resulting efficiency 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 Cool Water 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.

In a related presentation, Atsushi Inaba spoke of the CO_2 reduction potential in electrical energy chains. In a comparison of efficiencies of coal and gas, he found that world average efficiency in electric power generation was almost the same for both fuels, although one would expect efficiency of natural gas to be much higher. He pointed out that this is due to inefficient use of natural gas in many parts of the world. Nakićenović suggested a more general explanation for this anomaly with the possibility that coal, being the oldest and a relatively "dirty" fuel, has held on to its most efficient niches, while gas is more often used inefficiently, especially by end users. This could also explain the relatively high efficiency of coal use compared to other energy sources in OECD countries (Nakićenović *et al.*, 1990).

Other presentations highlighted the entire spectrum of Energy Cascades. Takao Kashiwagi suggested tapping the broad temperature range of natural gas from the liquefied transportation stage (–155 degrees Centigrade) to its highest post-combustion temperatures (Figure 8). He advocated using the low temperature of LNG in successive stages, first to separate nitrogen from air and then for refrigeration, at a higher temperature. Further transformation stages would involve combustion of gaseous methane in CCPPs for production of some electricity and supply of 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 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 using 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 integration: institutional and spatial structures have to enable the efficient distribution of power and heat from various conversion stages to integrated multiple users from a central complex to its peripheries.

Paul Victor Gilli discussed potential efficiency improvements along the same lines, although utilizing a narrower temperature gradient, immediate to the consumer, 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. Gilli pointed out that almost 300 GW thermal installed capacity is in use worldwide (Figure 9).

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 useful to also consider the carbon flow and resulting carbon releases. Jan Kuyper presented an example of carbon efficiency accounting for petroleum refineries where impressive efficiency gains were reported. However, these gains are counterbalanced by increasing demand for more complex products, which in turn require different input structures and more energy to produce. This case illustrates therefore that energy efficiency is just one of the criteria to be considered.

Nakićenović said that product quality **and** efficient utilization of time and capital are of equal importance. Therefore the pace of improvement not only depends on the improvement potential, which has been identified as very large, but also, among other factors, on the age distribution of the capital stock. For example he showed that about 60 and 80 percent of the capital stock of the FRG and Soviet Union, respectively, are less than 20 years old. This means that during the next 20 years, 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 percent of the oldest vintages are infrastructures and similar forms of capital with extreme longevity, some of which might be around for another five decades or more.

Jim Skea illustrated this persistence of capital stock with the example of the U.K. where about half of the housing stock is of pre-1939 vintage. Given this permanency of housing stock and very small annual turnover, efficiency improvements can only be introduced very slowly based on normal replacement rates. This shows the considerable potential for retrofitting measures and difficulties encountered in improving the efficiency of older capital vintages without replacement.

Cesare Marchetti looked back at the evolution of efficiency for various energy conversion systems and found that a transition from 1 percent to 50 percent conversion efficiency took around 100 years ("the system has the mental elasticity of a donkey"). He compared efficiency improvement rates for a whole range of conversion technologies; the slowest being for heat engines, the fastest for light bulbs.

Seen from a long term perspective, improvement in energy intensity of GDP was about 1 percent per year. However, this is a long term historical average over 200 years that contains periods of rapid improvement (2–3 percent per year), stagnation and even reversal. 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 percent per year, a dollar of GDP could be produced 50 years from now with only 20 percent of current energy requirements; even less in terms of carbon emissions if energy substitution is taken in account (Figure 10). But even at the historical energy efficiency improvement rate of 1 percent per year, the intensity would improve substantially during the next 50 years, reducing the energy requirements to generate a unit value added down to 60 percent compared to current levels.

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, such as dynamic input-output simulation, mathematical programming and econometric models, 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? We are still groping in the dark here. Few attempts have been made to tackle this problem, although many argue that something needs to be done.

An examination of energy systems both at the macro and micro level in order is needed to study the potential for efficiency improvement. Analysis at the macro level involves 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. Neither approach is perfect. Analyses at both levels are subject to the limitations of assumptions, either explicit or implicit, that necessarily have to be *ad hoc*, given the large uncertainties in the best available knowledge. Despite uncertainties, however, studies at both levels are necessary and complementary, each serving as a touchstone of validity of the other.

Looking at costs from the micro viewpoint essentially involves ranking numerous technologies according to their costs, usually resulting in an upward sloping cost curve (e.g., see Figure 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 due to large inefficiencies in transforming economies and developing countries (perhaps due to institutional and other inertia in the system) some reduction can be achieved at practically no cost. A recent study by the OTA for the U.S. also identifies significant CO_2 reduction potential with little or even negative cost (Figure 12). This is the case with many of the cost curves of mitigation measures. Unfortunately, these low cost efficiency improvement and emission reduction measures sometimes refer to loss of service (e.g., smaller vehicles) but often there is no loss of quality (e.g., more efficient cookers or aircraft).

Yuri Sinyak presented an analysis of the possible negative costs of CO_2 emissions reduction for the USSR (Figure 12). It must be pointed out, however, that these figures are the result of certain 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 beneficial economically, in addition to their positive environmental effects.

Mathur presented an aggregate cost curve for CO_2 emission mitigation measures for India (Figure 13). Despite a high national savings rate of over 20 percent, the constraint here is shortage of capital, the available total being on the order of $150 per capita per year. There are many other desperate needs such as creation of new jobs for the burgeoning population estimated to cost $2000 per workplace. 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 in the first instance 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.

Manfred Strubegger and Sabine Messner reported on an effort within the **CO_2 Reduction and Removal: Measures for the Next Century** study with the main objective of developing a technology data bank that will allow assessment and comparison of a large number of GHG reduction options worldwide. The data bank is now complete. 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. Turkenburg showed a cost curve for efficiency improvement based on a comprehensive comparison of technologies for the Netherlands that can be transferred into an emission cost curve. Examples of the reduction costs for Japan were also presented by Kenji Yamaji.

As mentioned earlier it is possible to view the various mitigation strategies from the point of 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. Often this is 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 intensely discussed at the meeting. The most famous proponents of these models are Edmonds and Reilly, Manne and Richels, Nordhaus and Yohe, and Yamaji. Yamaji presented a model for Japan (based on the Kaya approach) that estimates the effects of a carbon tax on both emissions and GDP.

In conclusion the questions of implied equity and distributional effects of various carbon taxes and other regulatory mechanisms were discussed. 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 therefore 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 the former course would produce an asymmetry in favor of industrial countries. 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.

4. Low Carbon and Carbon Free Options

Efficiency improvements are a fundamental measure for reducing carbon emissions especially in the near to medium term. In the long run there is a clear need to shift to energy sources with low carbon content, such as natural gas, and ultimately to those without carbon whatsoever, such as solar, nuclear and fusion. Technological and economic structural change will be of importance for improvement of efficiency and lowering of carbon emissions. Both the above are important means for reducing GHG emissions from the viewpoint of the whole economy as well as of the energy sector itself. In one sense economic structural change is being discussed because such shifts operate in individual sectors of the economy and lead to a broad restructuring, e.g., from scale to scope, heavy industry to services, low value added to high value added, material intensive to information intensive, etc. On the other hand, a parallel structural change in the energy sector alone and of efficiency improvements that are the equivalent of less material inputs in other economic activities is also being talked about. What is discussed here is 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 and conversely gas 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.[3] 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 and hydrogen. In fact the historical trend has been the transition from one primary fuel to another, from wood to coal to oil, i.e., to an increasing hydrogen to carbon ratio. Consequently, some participants identified the methane age as the logical interim possibility to reduce CO_2 beyond those achievable only by efficiency improvements.

Marchetti referred to Central Place Theory and suggested another evolutionary imperative in the choice of energy vectors. In addition to a increasing hydrogen to carbon ratio in the average fuel consumed since the beginning of the industrial revolution, successive sources of primary energy throughout history have another salient characteristic: an increasing distribution range. For example, the share of electricity in total final energy consumed has increased and with it the scale of the electricity distribution grid. Marchetti's point is that 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. This would again indicate natural gas as a possible intermediary before the eventual shift to truly carbon free sources of energy is achieved during the next

---

[3] 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 – 1 hydrogen atom per carbon; oil – about 2 hydrogen atoms per carbon and methane, 4. Therefore CO_2 emissions are lowest for methane and highest for coal.

century.

Some saw resource shortages and leakage as limiting factors to enhanced use of natural gas. Kuyper and Turkenberg pointed out that economic reserves might not be adequate for natural gas to play a substantive role in reducing carbon emissions. Arnulf Grübler insisted on a perspective of abundance rather than of shortage and held out the promise of discovery (Figure 14). His argument was based on potential occurrences and speculative resources that are so large that new discoveries are unavoidable if prospecting efforts throughout the world come even close to the American experience. 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 TWyrs of energy have been discovered during the last three years alone. This only indicates 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. Being a GHG with a radiative forcing around 30 times that of CO_2, the instantaneous global warming potential of natural gas is of major concern. Leakage rates of all energy-related sources of methane, in addition to natural gas use, are not well known. But 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 Albert 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 the 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 earlier mentioned Poland's need to acquire "expensive" gas from abroad 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 ten years, thus its contribution to the greenhouse effect is relatively small over longer periods. From a global perspective, for substitution of coal by natural gas, David Victor calculated the break-even point of methane leakages to be between 4 percent to 6 percent, a figure far above that probable for high pressure gas pipelines. The figures mentioned for the Netherlands and the U.S. were less than 1 percent. Some concern was voiced about high leakage rates in the gas distribution grid in the USSR. Official figures of 0.5 percent were questioned. Soviet participants emphasized that in no case was the true figure above 3 percent, since the majority of gas in the Soviet Union was consumed by industry, power plants and district heating plants, all with high pressure gas pipeline systems where leakage rates are extremely low.

Returning to the subject of emissions, Atsushi Inaba discussed global CO_2 reduction potential in electricity generation by looking at changes in the fuel mix; 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 percent and 14 percent. 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 would 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 percent of global final energy used. A number of schemes were proposed at the meeting for generation of carbon free energy vectors. Meyer Steinberg advocated a "no regrets policy," using the HYDROCARB process to separate hydrogen from carbon in coal, store the carbon generated and use hydrogen as a clean fuel. 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 (Figures 15 and 16).

Marchetti proposed steam reforming of natural gas into H_2 with CO_2 removal. 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 absorption 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 Meyer Steinberg, Chris Hendriks and Ryuji 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 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 (Figure 17). The major disadvantage here is that in removing elementary carbon from the fuel by the HYDROCARB process for storage, one would be also losing the energy content of fuel associated with the carbon atom. Unfortunately most of the energy of biomass is connected with carbon so that net yield from burning only hydrogen after removal of the former is very low.

Several biomass schemes were discussed at the meeting. Unfortunately all were associated with low energy yield such as oxygenated fuels based on alcohols and bio oils. In contrast to natural gas, the economics of biomass are far from being demonstrated. For example, Kurt 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 feasibility of an economy with massive 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 amounts to almost the entire fuel consumption tax per kilogram of fossil fuels. Furthermore, production is limited and efficiency is low in energy terms (Figure 18). The total share of biomass in primary energy consumption is on the order of 11 percent 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 program does decrease energy related CO_2 emissions if the biomass production for the alcohol program is sustained 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 ten year old solar thermal electric plant run by Luz 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 predominantly used. 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 photovoltaic 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 (rather than public opinion) systems considerations behind future energy systems would be the primary deciding factor in a possible increase of nuclear power use. Presenting the other side of the argument, Turkenberg 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, 144 nuclear power plants are still in operation today. 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, so the domestic market for new nuclear plants is practically dead.

The basic idea behind most of the "inherently safe" reactors is that all of the heat generated after emergency shutdown should be able to dissipate from the reactor vessel through thermal conduction.[4] Such a reactor would therefore not need active emergency cooling after shutdown, eliminating one of the major single mode failure 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. Baldur Eliasson mentioned the PIUS (Process Inherent Ultimate Safety) Reactor and the "walkaway safety features" currently available in modern reactor designs. 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 (Figure 19).

Commercial nuclear power is almost exclusively used for electricity generation, except for some amounts of district heat supplied in the Soviet Union. 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 concerns to acceptability of nuclear energy. Economics, because of the long regulatory

---

[4] 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.

process and liabilities from accidents; waste disposal, or lack of a permanent site 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 collocation of nuclear plants with industry and commercial areas. Even in decades to come, this most probably will not be accepted for safety reasons. Along these lines, 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. Marchetti's suggestion to marry nuclear and natural gas is to open the cycle, whereby nuclear provides 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. Depending on future development, a touch of bigamy could possibly be introduced into this marriage between nuclear and natural gas with the introduction of solar thermal as an alternative source of heat for reforming the latter.

Marchetti discussed the contribution of nuclear and solar in the long run to generate hydrogen in large conversion facilities on what he called energy islands (Figure 20). He envisages 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.

Oskar 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 as liquid hydrogen. 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 distribution to a number of end users; households, power plants, or transportation (Figure 21).

If one goes into schemes for the long term future, it is also conceivable that aircraft could play the role currently filled by oil tankers, transporting liquid hydrogen or liquefied natural gas (LNG) worldwide. 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 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 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.

5. Scrubbing and Removal

Since carbon-free energy sources, such as nuclear and solar, are future technologies for massive contributions to energy supply, carbon scrubbing and removal from energy carriers prior to combustion is a very important interim priority (Figure 22). Scrubbing has been identified as a promising solution for the near term future. 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, being 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. Of all known processes for sequestering carbon from the atmosphere the best is photosynthesis, a removal strategy that nature has practised from the beginning of plant life forms. This question will be revisited in the next section on afforestation. Fortunately, due to the high concentration of CO_2 in the flue gases of fossil fuel power plants in comparison to the atmosphere, scrubbing systems work.

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. 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 Wim Turkenberg also showed the study's calculations of the costs of various options (Figure 23). The cost estimates of the various options ranged from \$25 to \$45 per ton of CO_2 removed.

A few plants are in existence today that 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 per 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 percent might operate at a total net efficiency of 35 percent with 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 over 5 Gt per year. And, as already mentioned, electricity's share is about 2 Gt per year.

Eliasson dubbed CO_2 the raw material of the 21st century, pointing out commercial opportunities for its use. An example was given of CO_2 piped from Colorado to a Texas oilfield for use in enhanced oil recovery. Marchetti suggests use of CO_2 that could be obtained from steam reforming of natural gas by the Soviet Union for enhanced oil recovery in some of its depleted fields. Other possible users are 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. 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 the over 5 Gt that are available. For example, steel and concrete production worldwide was only 679.5 and 962.3 million tons, respectively, in 1985 (i.e., less than 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.

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 is estimated to be about 36,000 Gt. Therefore, the deep oceans might be a possible repository for the carbon sequestered. Unfortunately, such schemes are speculative and associated with many unknowns, so deep ocean disposal poses a number of questions.

There are various disposal schemes: either to pump it 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 meters if it is to stay down, whereas with the gaseous form 300 meters will suffice. Matsuhashi presented a detailed analysis of the results of studies being performed in Japan (Figure 24). Japan, having no natural geological cavities for storage, sees ocean disposal in the 7000 meter deep Japan trench as a possible long term alternative.

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 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. The practical result of this is that the CO_2 enriched water would rise to the surface should this occur.

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.

6. Photosynthesis and Afforestation

Given the fact that, despite the possibility of global warming, atmospheric CO_2 concentrations as low as 350 ppm were being discussed, biomass was often mentioned as a potentially practical way to bind carbon and lead to minimal net emissions. 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.

Gerd Esser's study (Figure 25). 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 gave an example of the FRG in order to illustrate the practical difficulty of absorbing global CO_2 with afforestation. Putting the current entire agricultural area of the FRG under reforestation would take up approximately 23 million tons of CO_2 per year. This is around 10 percent of FRG emissions. This 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 FRG alone, is around 25 percent of the annual discharge of the River Rhine. Secondly, due to the loss of soil organic carbon, net fixation is less than 50 percent 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 percent of 1985 fossil fuel emissions. Given these daunting figures, it seems clear that there is no single solution to the CO_2 problem.

Kuyper showed how afforestation can be successful on a limited scale; in this case over an area of 300,000 hectares, with timber being harvested in six to ten year cycles, leading to carbon fixation estimated at ten tons per hectare. Hiroshi 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 ten tons/ha per year, in close conformity with Kuyper's figures.

Of course, in afforestation, the ultimate question remains, once having in theory sequestered large amounts of carbon in forests, what happens after 20 years when forest decay releases the "collected" CO_2. The real problem is to break nature's cycle, which reduces the effectiveness of carbon storage after 20 years. 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.

Bo 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 percent. 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 26). At sea, Saiki proposed carbon reduction by means of phytoplankton, calcification or kelp. The most radical among the three was the John Martin proposal to remove atmospheric CO_2 using iron fertilizer to stimulate growth of algal blooms in the Antarctic. Several assumptions of this scenario are in doubt, in particular the hypothesis that lack of iron is the limiting factor in algal growth. Costs of manufacturing liquid ferrous chloride are between $150-200 per 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.

7. Postscript

The workshop was organized to explore ideas, find out how far research has progressed, investigate work underway, avoid re-inventing the wheel or repeating mistakes made elsewhere.

The topic being of a global nature, the discussions were proportionately wide-ranging; but despite a diversity of opinions, the following issues seemed to emerge in strong profile.

- Climate change is a global problem that calls for global solutions; until now there have been only national programs. This sentiment was underlined by a statement made by Academician Mikhail Styrikovich, the most senior participant at the workshop: *the expression for global warming in Russian is global warming.*
- CO_2 represents only 50 percent of the problem of greenhouse gases. Other GHGs must be included in reduction and mitigation strategies.
- The cheapest measures must be instituted immediately. Although costs are uncertain, the majority of estimates are comparatively low for an initial range of measures. Even with uncertainty, cheap measures instituted immediately are perceived as an insurance or "no regrets" policy with multiple benefits. International cooperation makes economic sense, as a CO_2 abatement dollar is initially invested more effectively in a country with low levels of energy efficiency and high carbon intensity than one that has already achieved relatively high levels of energy efficiency.
- Nature never optimizes on one criterion alone. Taking a cue from this insight, a very 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 the esthetic, that can be gained by this step.

Many of the questions raised during the discussions were identical in scope, if not in nature. The subject of global warming has to do with behavioral and cultural attitudes as well as development and economics. There is a vast unknown represented by the familiar word "culture", a word that is so nonchalantly used, considering that it denotes the complex area in the psyche of nations where religion, art, literature, scholarship, polity, economy, technology and science all meet. This is the interface human beings live in, day in and day out, yet find impossible to quantify.

It must also be remembered that people speak of the same problem at completely different levels. For some, global change is a nuts-and-bolts problem that requires a bit of tinkering here, a bit of fixing there. For others, on a completely different plane, there are moral and ethical considerations, like intergenerational equity, or the destruction of habitats of human and 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 implicitly gone through whenever choices are made, explicit choices that are sometimes hard to justify.

It is precisely this interface that the "Social Behavior, Lifestyles and Energy Use" Workshop will attempt to explore in June 1991 at IIASA.

In view of the global and long-term nature of the problem, no immediate solutions were expected to emerge from a single workshop, nor can they be. 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 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.

FIGURES

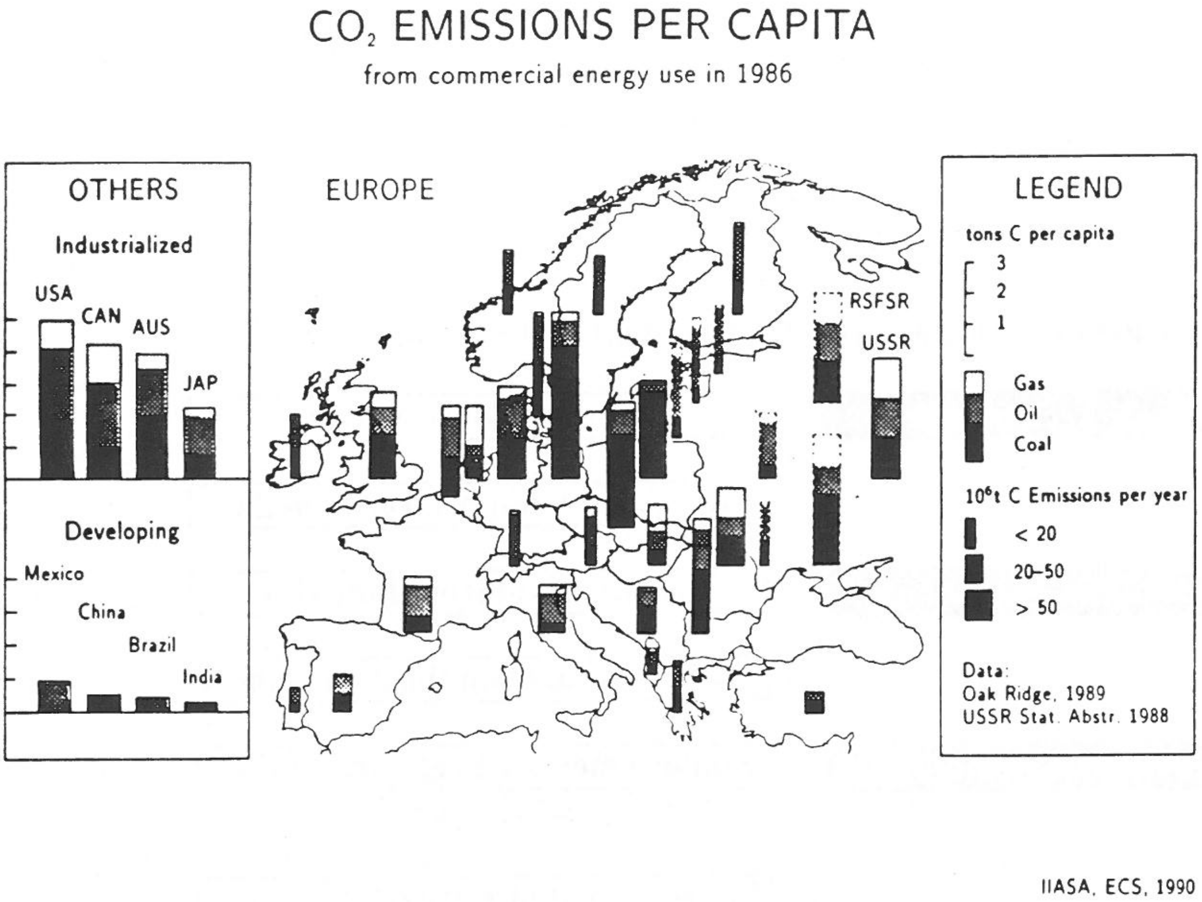


Figure 1. Per capita CO_2 emissions from commercial energy use, by source and for selected countries (in tons carbon per year per capita). A graphical representation of per capita carbon emissions from energy use reveals extreme disparities and heterogeneity. These are the result of differences in degree 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 vividly the significant North–South divide in energy related CO_2 emissions. Also noticeable are the high per capita emission levels in Eastern Europe, most of them stemming from coal use. Even in cases when per capita emissions are of similar magnitude, they are often so for entirely different reasons. For example, both the USA and the former GDR have per capita CO_2 emissions in excess of 5 tons carbon per year per capita. In the case of the USA this is due to high energy consumption and energy intensive lifestyles, like the high oil consumption for private transportation. In the former GDR 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. Source: ECS Project, IIASA, 1990.

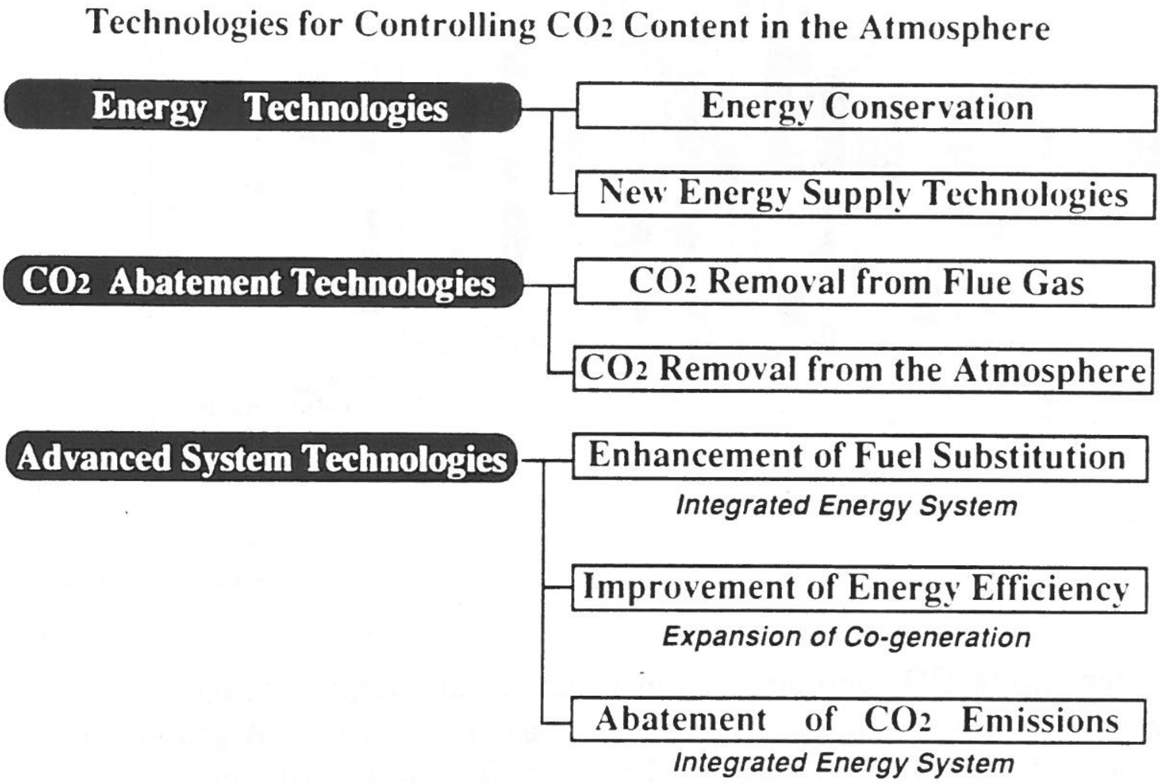
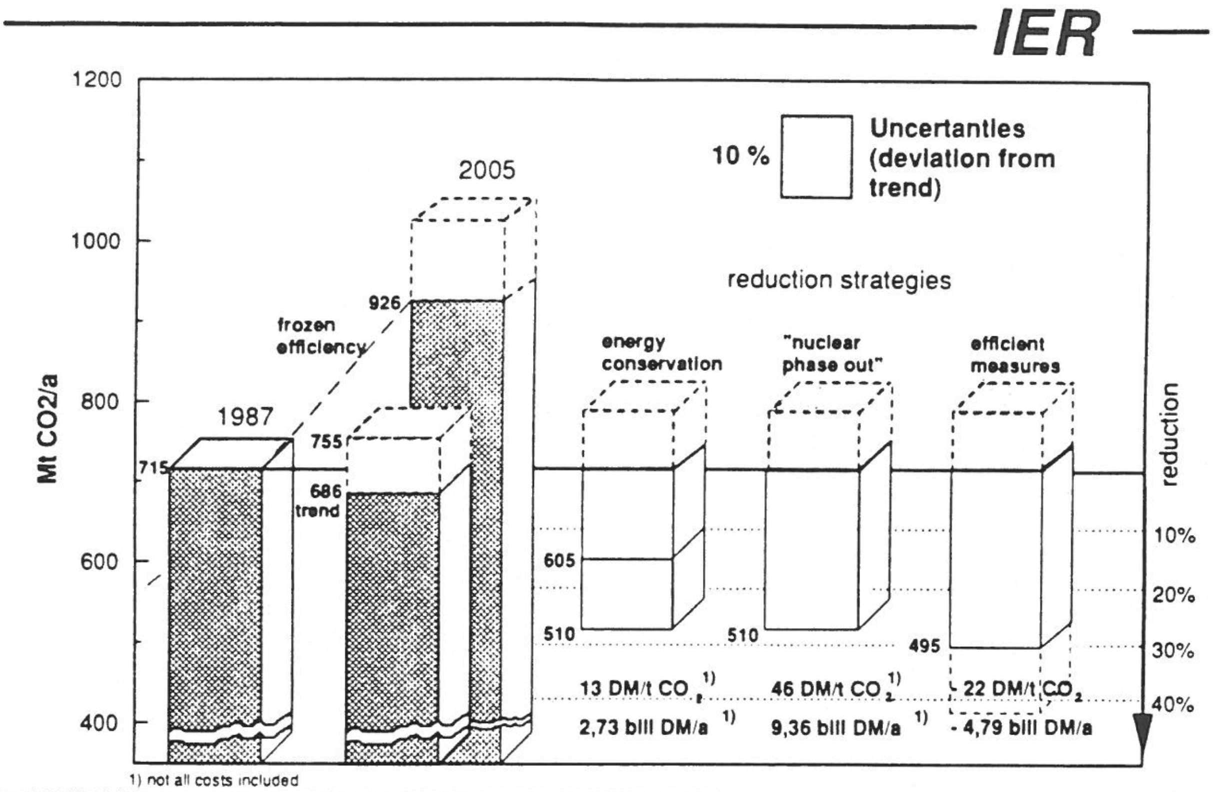
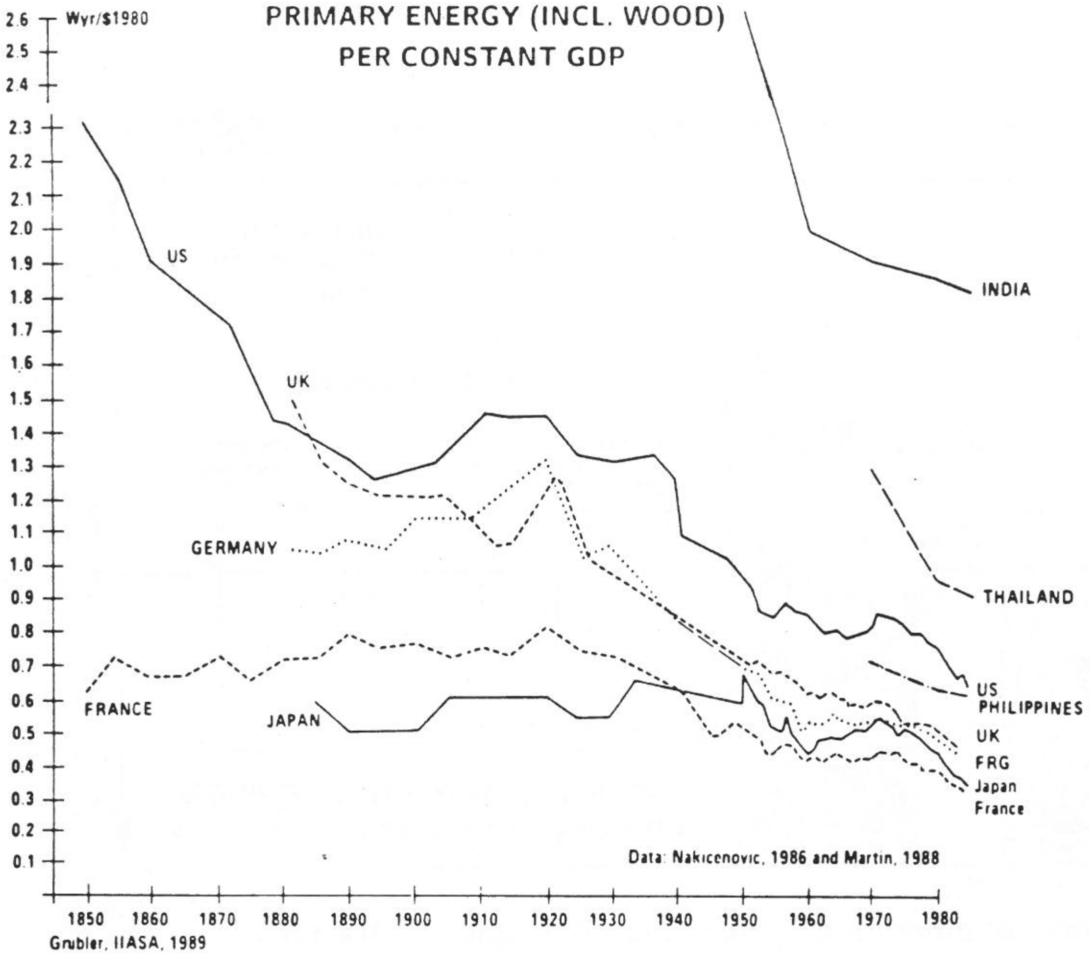


Figure 2. Overview of technological options to reduce atmospheric CO_2 concentrations. Improvements in energy efficiency, interfuel substitution, and CO_2 removal technologies can all contribute towards a common goal of an environmentally sustainable energy future. Their systemic evaluation is the objective of the IIASA study **CO_2 Reduction and removal: Measures for the Next Century.** Source: Y. Kaya.



Comparison of different CO_2 - reduction strategies for the FRG

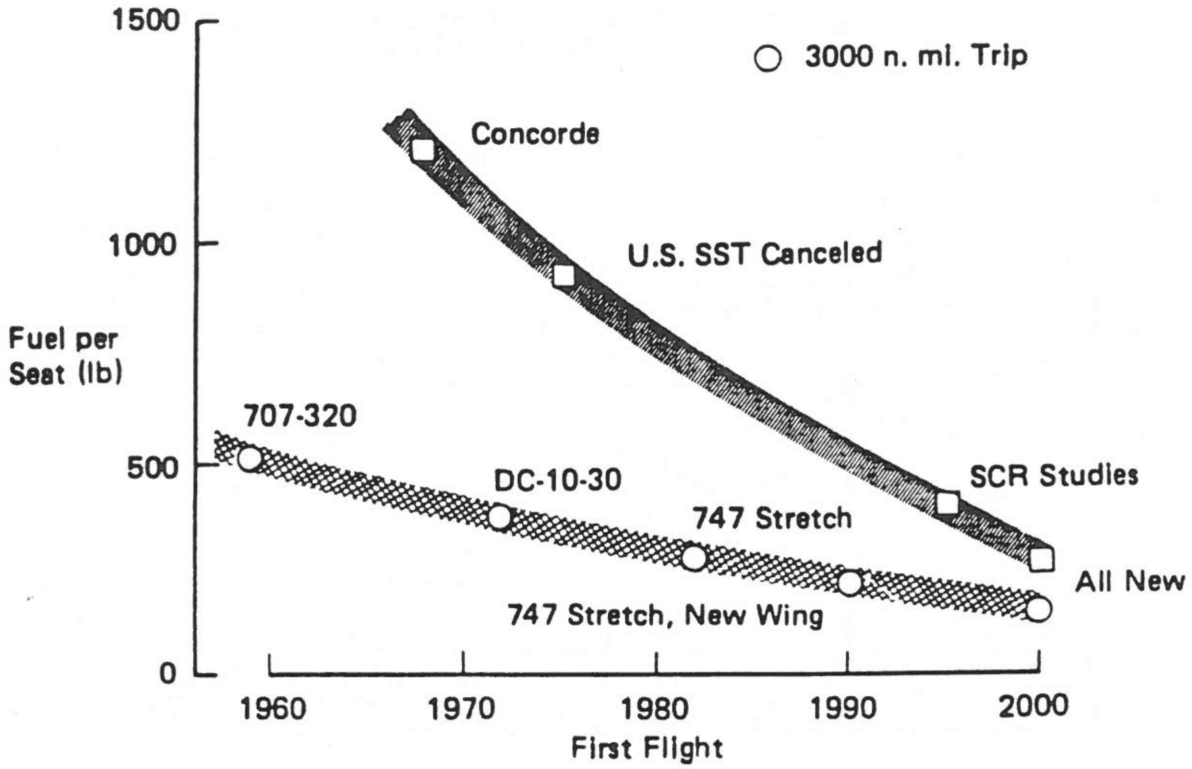
Figure 3. CO_2 reduction scenarios for Germany as prepared for the German Parliamentary Enquete Commission were presented by P. Schaumann at the meeting. Three strategies for reducing energy related CO_2 emissions by the year 2005 by 30 percent of present day levels were investigated. The first relied mostly on energy efficiency improvements and conservation measures; the second investigated a nuclear phase out and consequently had to rely on even more conservation and increased contribution of renewables; the third scenario includes a portfolio of measures based on the least cost criterion. Particularly noticeable are the results for the nuclear phase out scenario; the CO_2 reduction target is still feasible, however, at very high costs (over three times the cost of the conservation scenario). Compared to the trend or business as usual scenario a 30 percent reduction of emissions could be reached without extra cost for CO_2 control under a scenario combining measures under least cost criteria as indicated by the negative CO_2 reduction costs reported in the figure. Source: A. Voss.


PRIMARY ENERGY (INCL. WOOD)
PER CONSTANT GDP

Data: Nakicenovic, 1986 and Martin, 1988

Grubler, IIASA, 1989

Figure 4. Primary energy intensity (including biomass energy) per constant GDP (Wyr/yr per constant [1980] US $). Historically the energy intensity declined at an average rate of one percent per year. This means that a dollar GDP is produced today with only one fifth of the primary energy consumption some 200 years ago. Since the early 1970s the energy intensity has improved at rates of 2 to 3 percent annually. Also visible from Figure 4 are distinct differences in industrialization paths between various countries. The actual performance of an economy in terms of its energy consumption per unit of value added is thus path-dependent. 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 per Dollar GNP than countries in Western Europe or Japan does not necessarily imply that improvements are easier to achieve 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. Source: N. Nakićenović.



Fuel-use trends as a result of SCR/VCE programs.

Figure 5. Aircraft fuel efficiencies (lbs fuel per seat). Improvements in energy efficiency in the aircraft industry have been particularly dramatic. Improvement rates of 3 to 4 percent annually over the last 20 years have been achieved. This means that the same transportation service can be provided with as little as 40 percent of the energy requirements some 20 years ago. At the same time there might also be counter-balancing trends, e.g., the introduction of new high speed aircraft designs like supersonic or hypersonic air transport. For these new technologies specific energy requirements would be significantly higher due to their revolutionary increase in level of service and performance. Source: NASA, 1985.

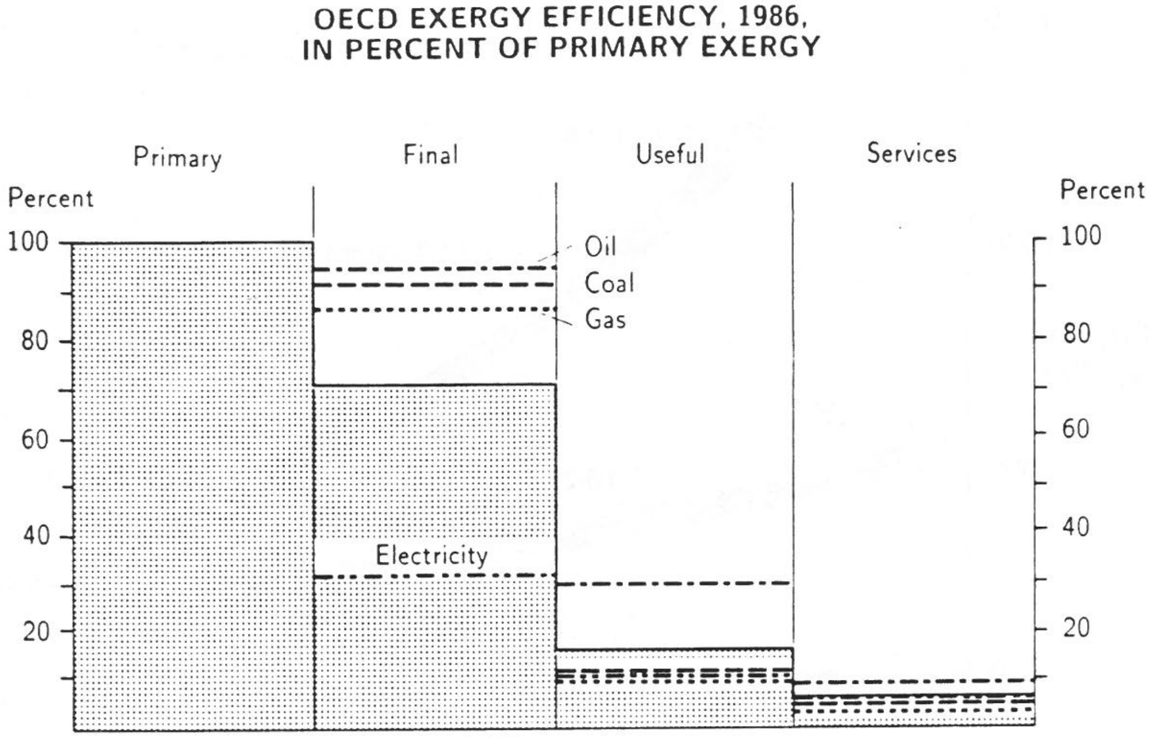


Figure 6. Exergy balance for the OECD countries in 1986 (in percent of primary exergy). A second law analysis of the exergetic efficiency of the exergy (and energy) system in the OECD countries, shows that while the efficiency in the provision of final exergy is already quite high, efficiencies at the 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 USSR and developing countries are probably even lower. This indicates the large theoretical potential for efficiency improvements of between a factor 20 to 100. Realization of this potential depends on the implementation of many technological options and organizational innovations. Their different tradeoffs, the costs and timing involved need detailed study. Source: N. Nakićenović.

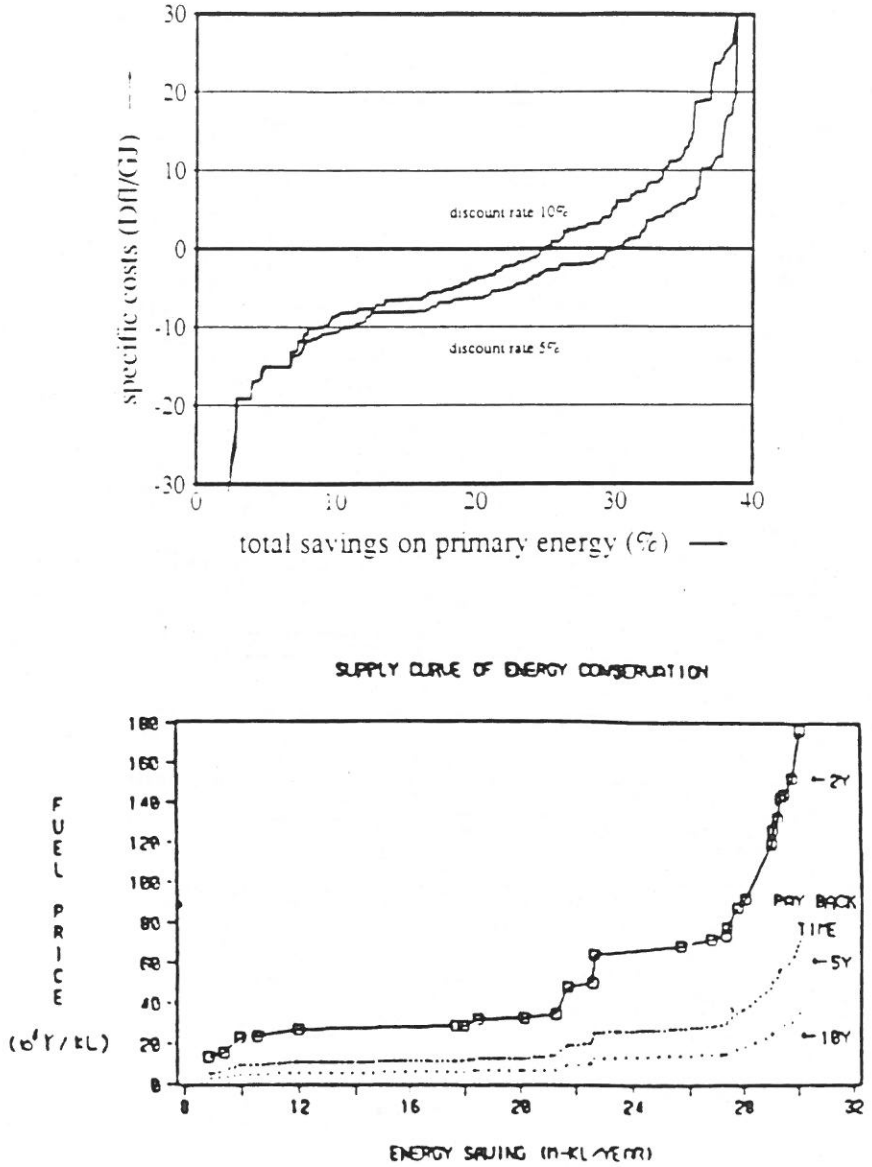


Figure 7. National energy conservation and efficiency improvement cost curves for the Netherlands (top) and Japan (bottom). Specific costs of energy conservation measures, based on discount rates of 10 and 5 percent, respectively, for the Netherlands indicate a maximum potential of close to 40 percent of primary energy consumed. Specific costs range from net savings to costs of between Dfl 20 to 30 per GJ. The energy conservation cost curve estimated for Japan expresses the conservation potential as a function of energy prices and of different financial payback times. It is interesting to note the still large efficiency improvement and conservation potential under a range of relatively modest energy price increases, even in a country with traditionally high energy prices and high overall energy efficiency. Sources: Netherlands: W.C. Turkenburg; Japan: K. Yamaji.

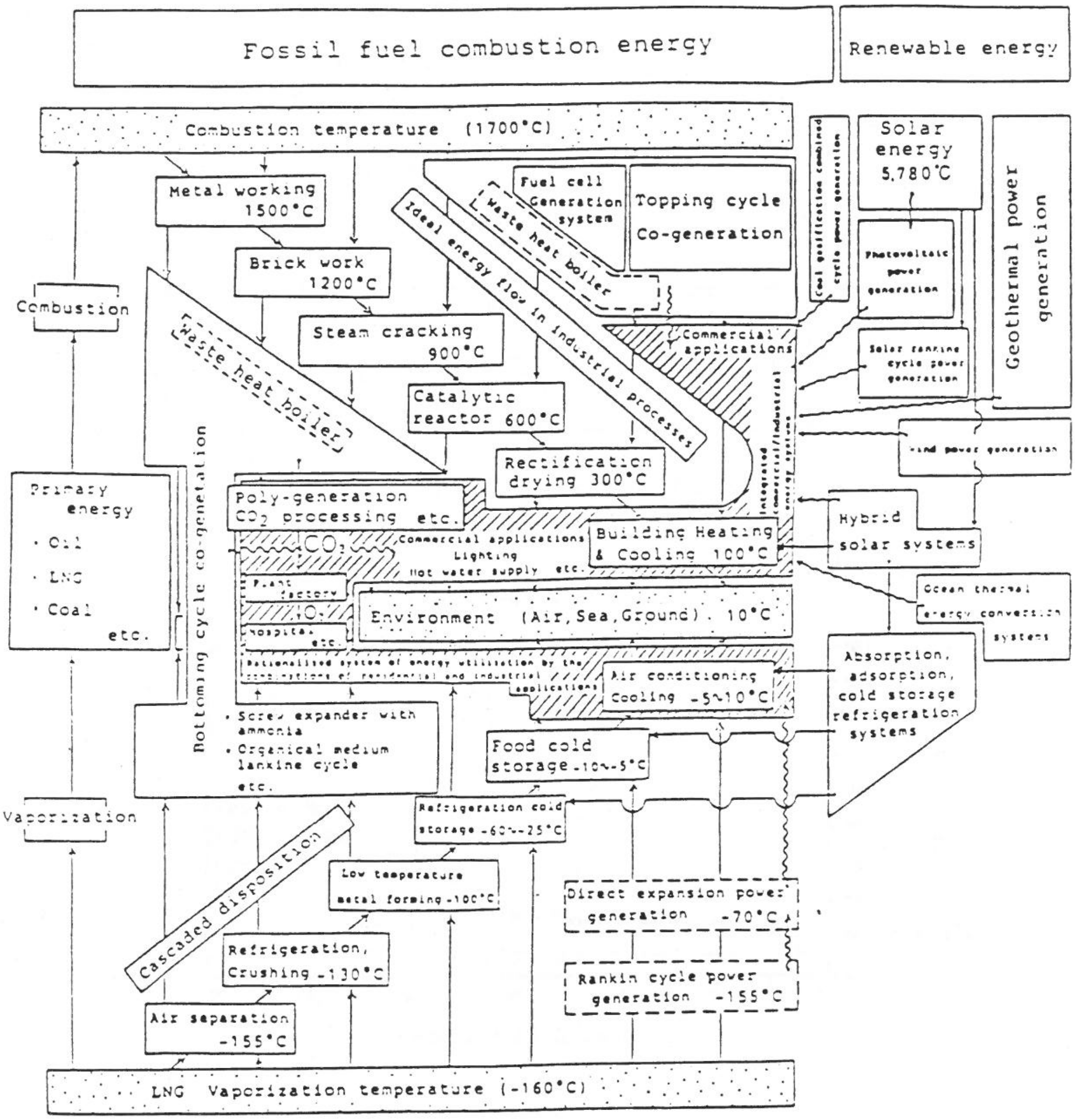


Figure 8. Energy cascading, an innovative concept introduced at the conference for improved efficiency and minimization of exergy losses. The concept takes full advantage of the temperature gradient of LNG (–155 degrees C) on the one hand and combustion temperatures of natural gas (1700 degrees C) on the other. In order to minimize exergy losses, energy is passed on to successively lower (or higher in the case of cooling) temperature ranges. Such innovative concepts would, however, require significant changes in the spatial and institutional organization of society. Source: T. Kashiwagi.

Present Utilization of Heat Pumps

	Nos.	Power (Heat)		Utili-sation Factor	Annual Heat Supply
		per unit	total		
	-	kW	MW	h/a	TWh/a
1) Residential					
1.1 Single Room (Flat) Units					
Japan	22 Mio.	3,5	77000		
USA	8 "	8	64000		
others	5 "	4	20000		
Total 1.1	35 Mio.	4,1	161000	1000	161
1.2 Commercial	8 "	15	120000	1000	120
Total 1	43 Mio.	6,5	281000		281
(of which heating-only heat pumps)	(3 Mio.)	(8)	(24000)	(1000)	(24)
2) Industry	ca.5000	ca.500	2500 (2000)	4000	10 (8)
3) District Heat					
S (> 2 MW)	155	18000	2800		
others	ca. 45	4500	200		
Total 3	200	15000	3000 (2900)	5000 (5000)	15 (14,5)
4) Total (1 to 3)			286500		306
(of which heating-only heat pumps)			(28900)		(46,5)

Note: Values in brackets refer to "heating-only" heat pumps, i.e. units without cooling.

Figure 9. Present utilization of heat pumps in selected countries and sectors. Utilization of heat pumps is already considerable, contributing towards increasing the efficiency of energy end use for low temperature heat applications. Nearly 300 GW heat pump capacity are estimated to be installed worldwide supplying some 300 TWh of heat annually. Source: P.-V. Gilli.

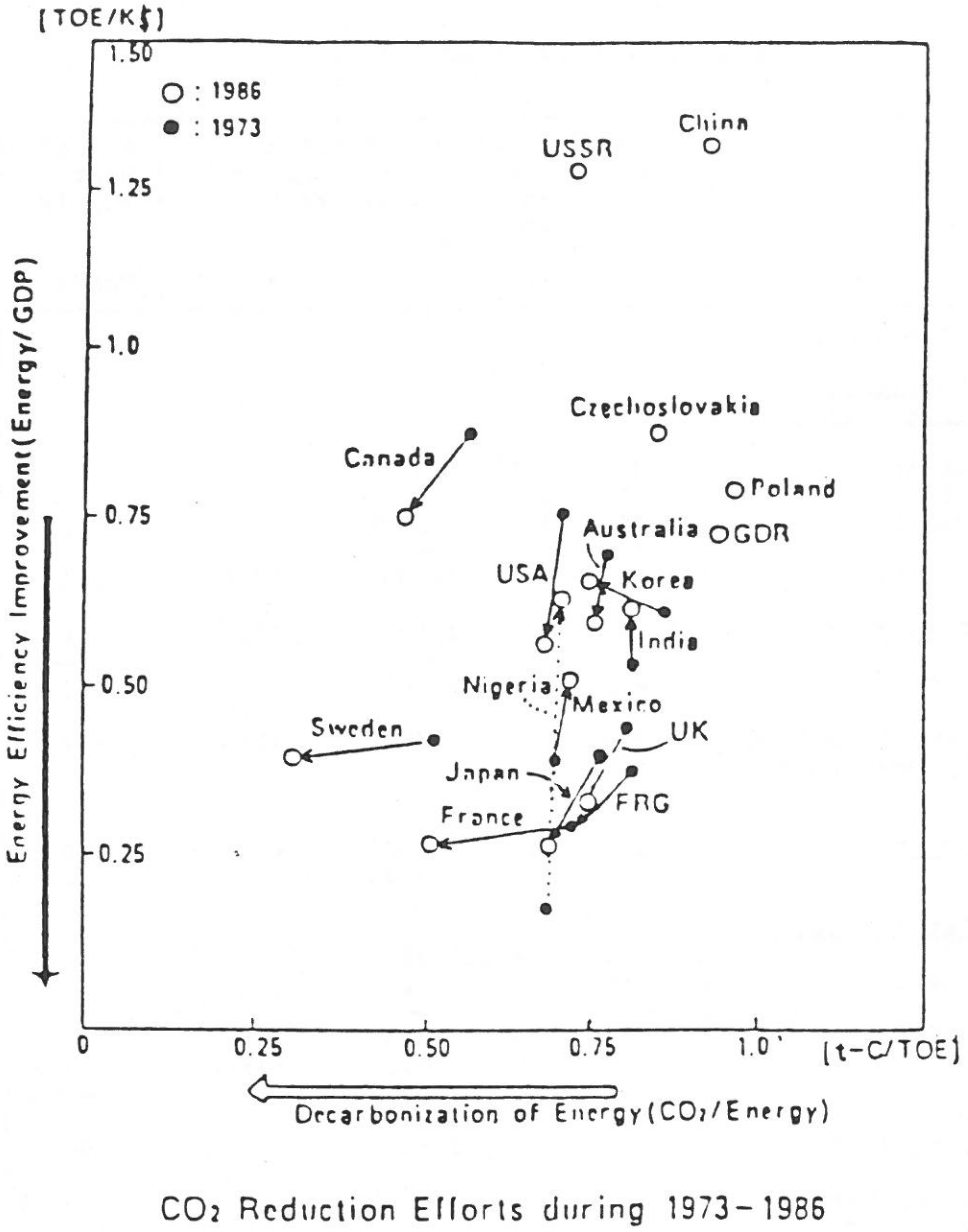


Figure 10. 1973 to 1986 trends in energy (TOE per 1000 $ GDP) and carbon intensity (tons C per TOE) of various countries. Improved energy efficiency (lowering the energy intensity) and interfuel substitution (lowering the carbon intensity of energy use) are two important options for lowering carbon emissions. The graph shows the diverse policy mix and strategies followed in different countries over the time horizon considered. Sweden and France appear to follow a decarbonization strategy, whereas the U.S. mostly an efficiency improvement strategy. Canada, the FRG, Japan and the U.K. achieved improvements in both domains. Also noticeable are the increasing (commercial) energy intensities of developing countries such as Nigeria. Source: K. Yamaji.

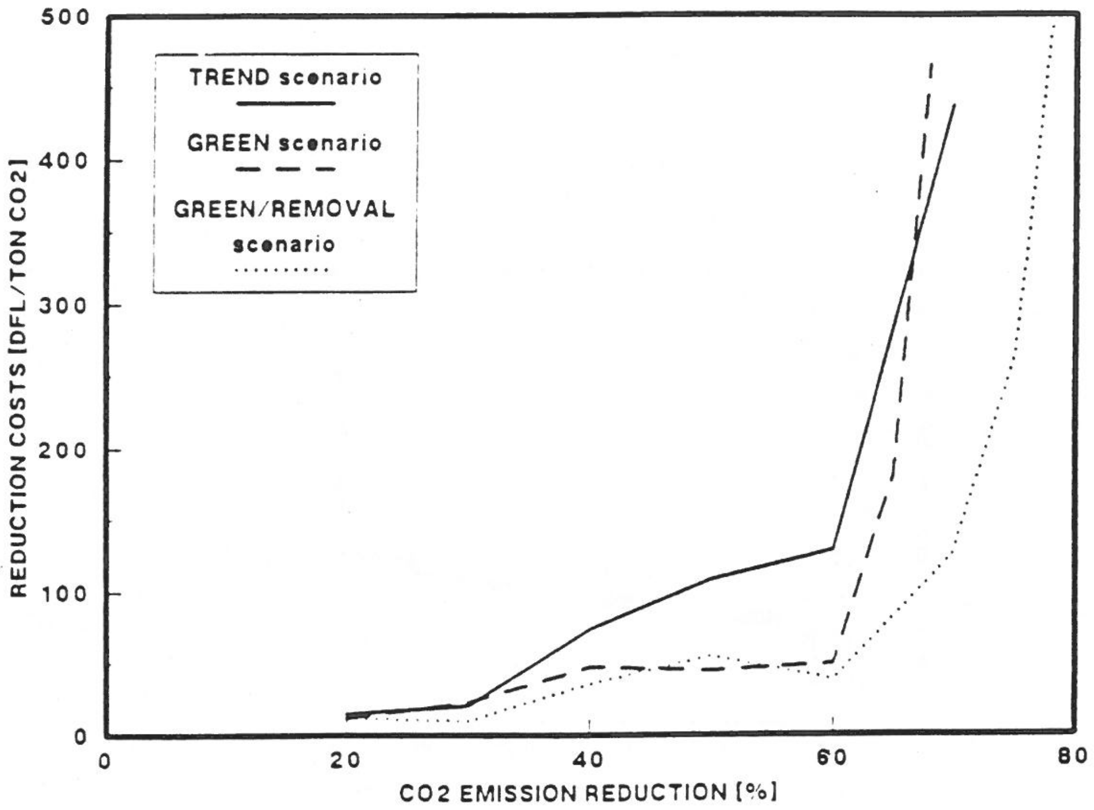
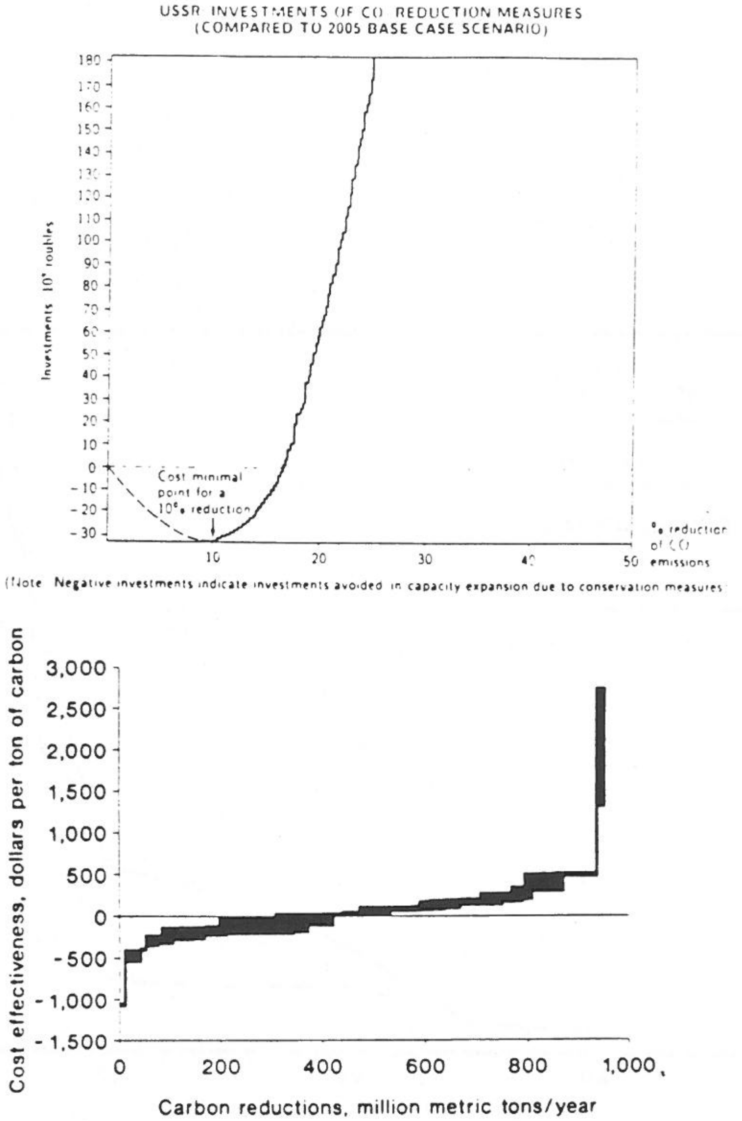
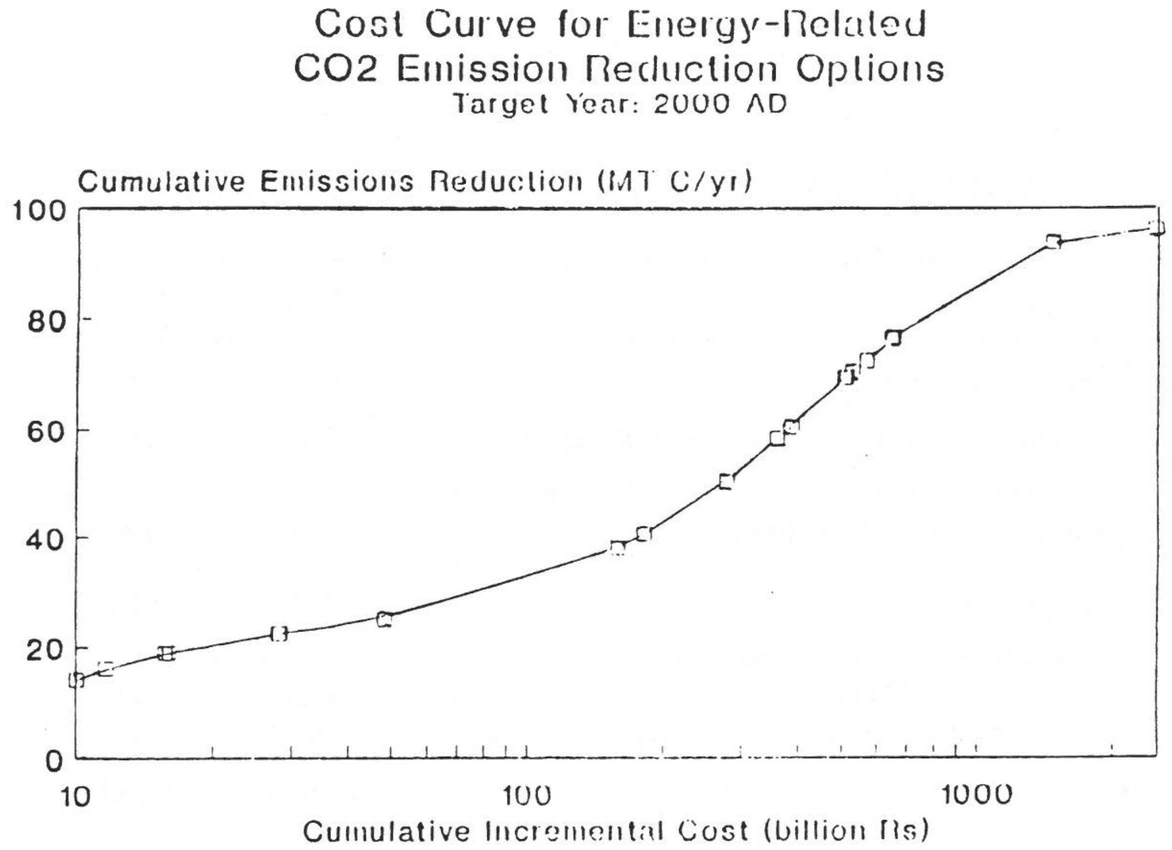


Figure 11. Marginal CO_2 reduction cost curves for the Netherlands (in Dfl per ton CO_2). Based on detailed energy models, the economic impact of various CO_2 reduction strategies can be assessed. The particular shape of the marginal cost curve gives an indication of economic boundary values for CO_2 reduction. In this particular study for the Netherlands, the marginal cost curves suggest that reductions up to 60 percent of present emission levels are possible before entering the steep exponential part of the marginal cost curves. Source: T. Kram.



(Note Negative investments indicate investments avoided in capacity expansion due to conservation measures)

Figure 12. National CO_2 emission reduction and avoidance costs: estimates for the USSR (top) and the USA (bottom). Emission reduction costs are compared to a base case scenario without any reduction measures. Time frame for the reference scenarios are the year 2000 for the USSR and 2015 for the USA. Note that costs in the USSR refer to investments only. "Negative" investments indicate investments saved by energy conservation measures compared to capacity expansion. Maximum investment savings could be achieved by a mix of policy measures resulting in a reduction of the reference CO_2 emissions by 10 percent. Emission reduction costs in the USA are for a "Tough" reduction scenario (0.9 Gt carbon emissions in 2015) compared to a business as usual scenario (1.9 Gt carbon emissions in 2015) from a recent OTA (1991) study. Fuel savings are not included in the cost figures. Between one third to one half of the reductions in emissions between the two USA scenarios either save money or are of very low costs. Sources: USSR: Y. Sinyak; USA: OTA, 1991.



Each symbol represents the complete exploitation of an emission reduction option

Figure 13. Cost curve for reduction of energy related CO_2 emissions in India (in billion Rs). Recent work at the TATA Research Institute in India has investigated 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 based on a detailed assessment of various measures which highlights its innovative character. It was stated at the conference by Mathur that in view of population growth and necessary economic development absolute emission reductions would be both infeasible and unequitable for developing countries. Instead, the concept of emission avoidance, i.e., pursuing social and economic development in minimizing emissions, was suggested. The curve illustrates the costs of lowering CO_2 emissions in India over the short-term (by the year 2000) compared to a base case with no mitigating measures. Despite the fact that a number of very cost effective options exist, particularly in the area of sustainable exploitation of biomass, capital shortages remain the most serious bottleneck for CO_2 avoidance measures in developing countries. Source: A. Mathur.

Natural Gas Reserves and Resources, 10^{12} m^3

Category	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	?
Total	2,600	3,200
Clathrates	21,000	?
Deep Gas	??	??

* Tight gas sands, fractured shales, methane in coal seams, geopressured aquifers, gas hydrates. Estimates primarily for North America.

Source: API and BP (1989); Parent and Linden (1977); Grossling (1976); Kuuskraa and Mevers (1983); MacDonald (1989).

Figure 14. Natural gas reserves, resources and occurrences (in 10^{12} m^3). A summary contrasting the present estimates of identified, technically and economically recoverable reserves to resources, and even exotic methane occurrencies 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 supply would last for centuries rather than for decades. Source: A. Grübler.

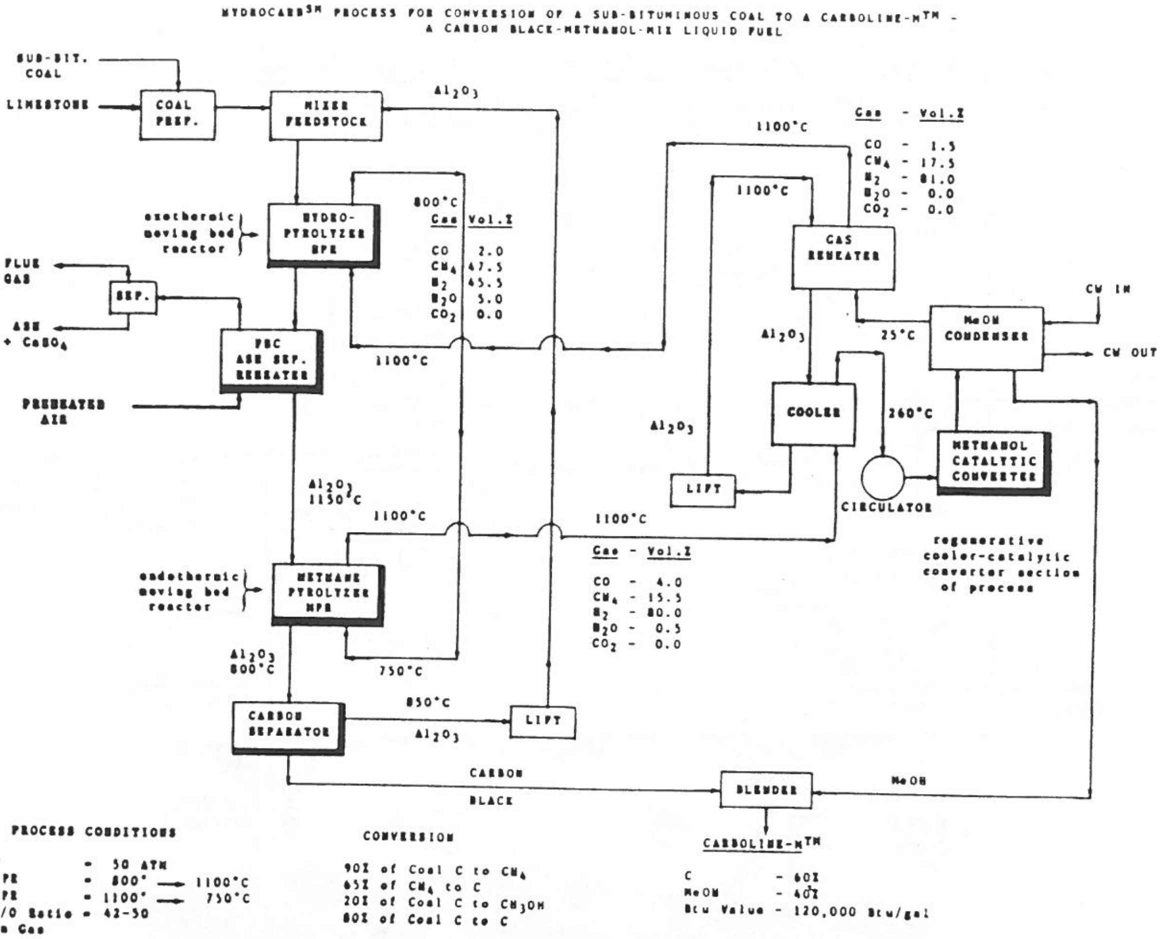
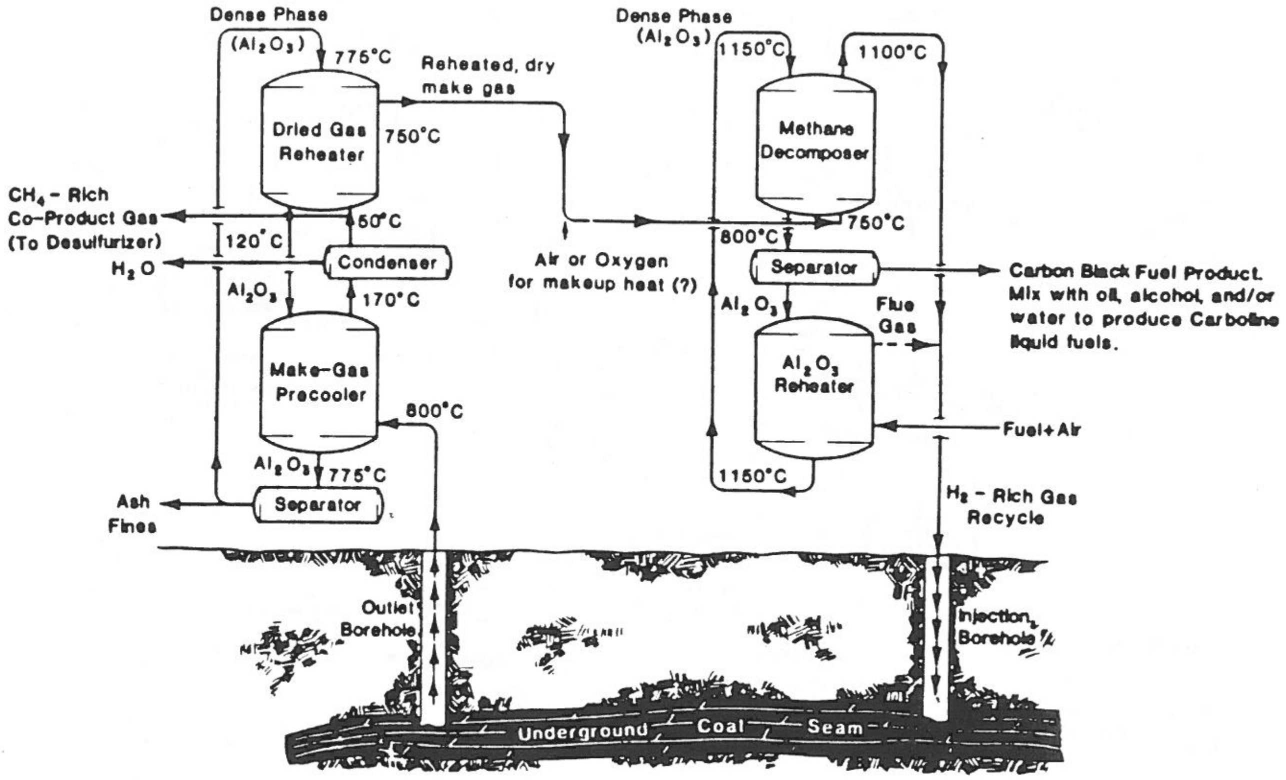


Figure 15. HYDROCARB process as suggested by Steinberg and under study at Brookhaven National Laboratory in the U.S. In this particular flow scheme, carbon black produced from subbituminous coal is blended with methanol to produce CARBOLINE, a 60 percent carbon and 40 percent methanol mix liquid fuel. Although originally conceived to produce a clean pure carbon fuel from coal, the HYDROCARB process lends itself also for CO_2 reduction strategies. Hydrogen contained in fossil fuels like coal could be used for energy purposes, whereas the carbon black could be deposited to be used in the future as fuel or as a permanent mode of carbon disposal, for instance in coal mines. Source: M. Steinberg.

Underground Coal Gasification via HYDROCARB Process for Production of Clean Carbon Fuels and Gaseous Co-Product Fuels



$CH_{0.8}O_{0.08}S_{0.016}N_{0.015} + 1.692H_2 = CH_4 + 0.08H_2O + 0.016H_2S + 0.0075N_2$

Figure 16. HYDROCARB process applied to underground coal gasification. Due to the abundance of coal resources in many countries, safe and clean production of energy carriers from the resources located underground is an attractive option. Again the process could be used within a CO_2 reduction strategy by only using methane and hydrogen rich gases for energy purposes and storing elementary carbon for later use or final disposal. Source: M. Steinberg.

CO_2 GENERATED OR REMOVED FROM THE ATOMOSPHER BY VARIOUS METHANOL SYNTHESIS AND CO-PROCESSING PROCESS SYSTEMS USING FOSSIL FUEL FEEDSTOCK

Feedstock	Methanol Process	Energy Utilization Efficiency 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	+170
Oil	Partial Oxidation	50	+280
Coal - Bit.	Steam-Oxygen Reforming	42	+330
HYDROCARB - Stores Carbon			
Bit. Coal	HYDROCARB	35	+130
Lignite	HYDROCARB	35	+130
Co-processing with Biomass Store Carbon			
II Biomass + Nat. Gas	Photosynthesis + HYDROCARB	166	-78
III Biomass + Oil	Photosynthesis + HYDROCARB	115	-78
IV Biomass + Bit. Coal	Photosynthesis + HYDROCARB	50	0

Figure 17. Overview of processes of methanol synthesis and co-processing systems using fossil fuel feedstocks, also in combination with biomass. The table compares different processes in terms of their overall energy utilization efficiency and their CO_2 generation or removal per unit of energy delivered. Particularly the "marriage" between biomass and fossil fuels via the HYDROCARB process offers interesting possibilities of carbon removal from the feedstock and its subsequent storage. The overall carbon balance could thus become negative, i.e., constituting an effective carbon "sequestering" strategy via photosynthesis and subsequent processing and storage of elementary carbon. Source: M. Steinberg.

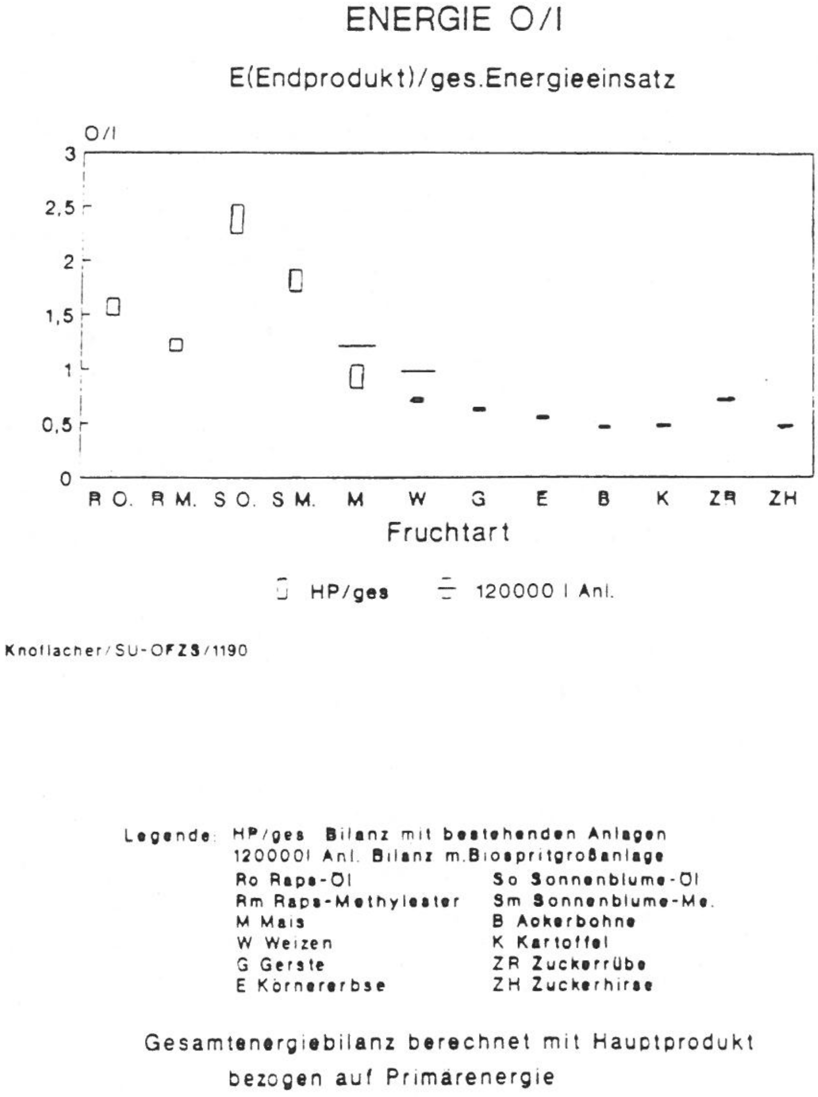


Figure 18. Energy yield ratios for different biomass fuels (O/I: energy output per energy input). The overall energy balance of many biomass fuels appears to be rather unfavorable, in many cases even negative. This means that in such cases more (fossil) energy is spent in production and processing biomass fuels than the energy content of the fuel produced. A recent Austrian study suggests therefore that the potential of biomass use as transport fuels (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. Source: K. Pollak.

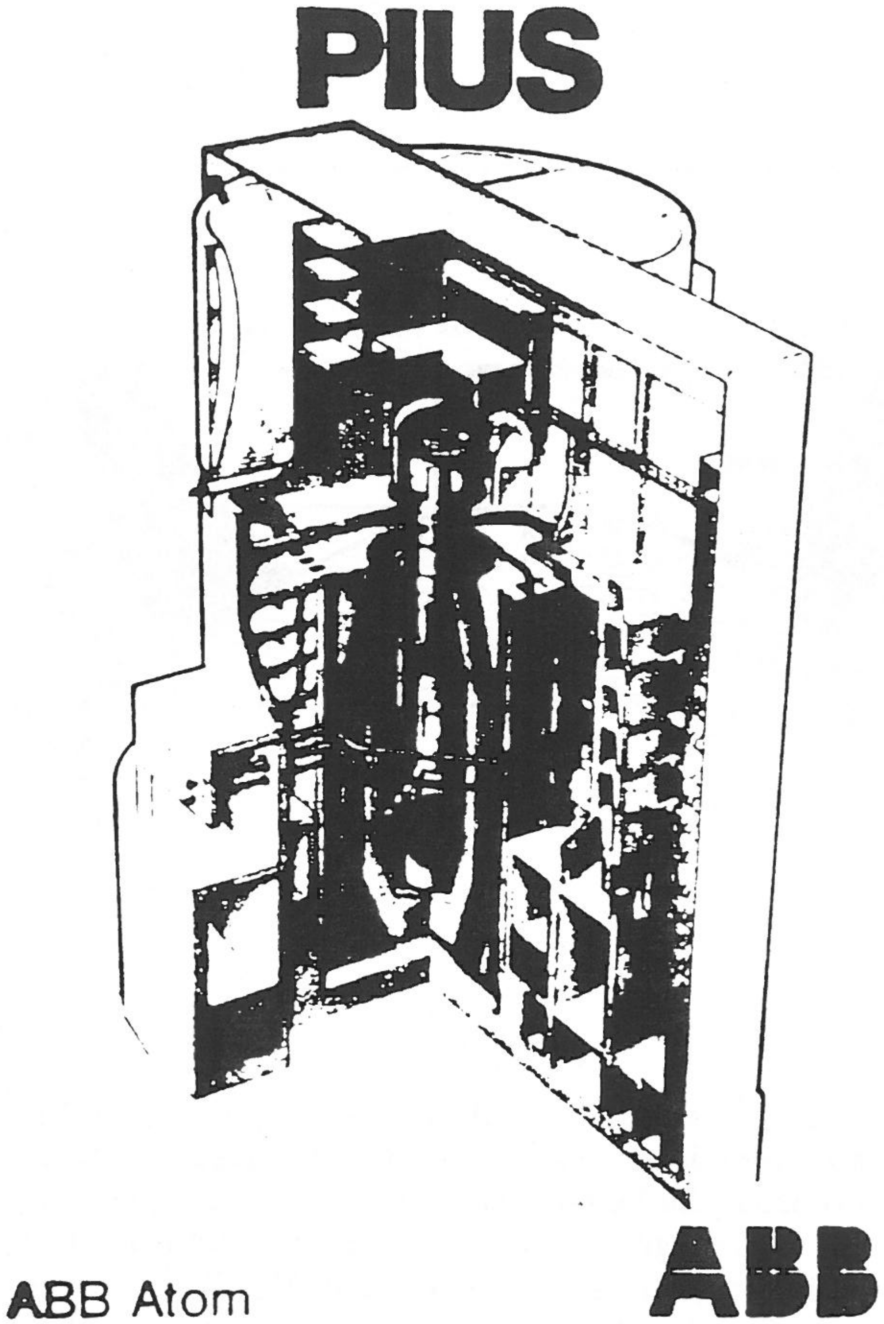


Figure 19. PIUS (Process Inherent Ultimate Safety) reactor design combining autonomous emergency cooling features with flat economies of scale. New inherently safe reactor designs could be a first step in overcoming public opposition and enhancing the contribution of carbon free energy sources. Source: B. Eliasson.

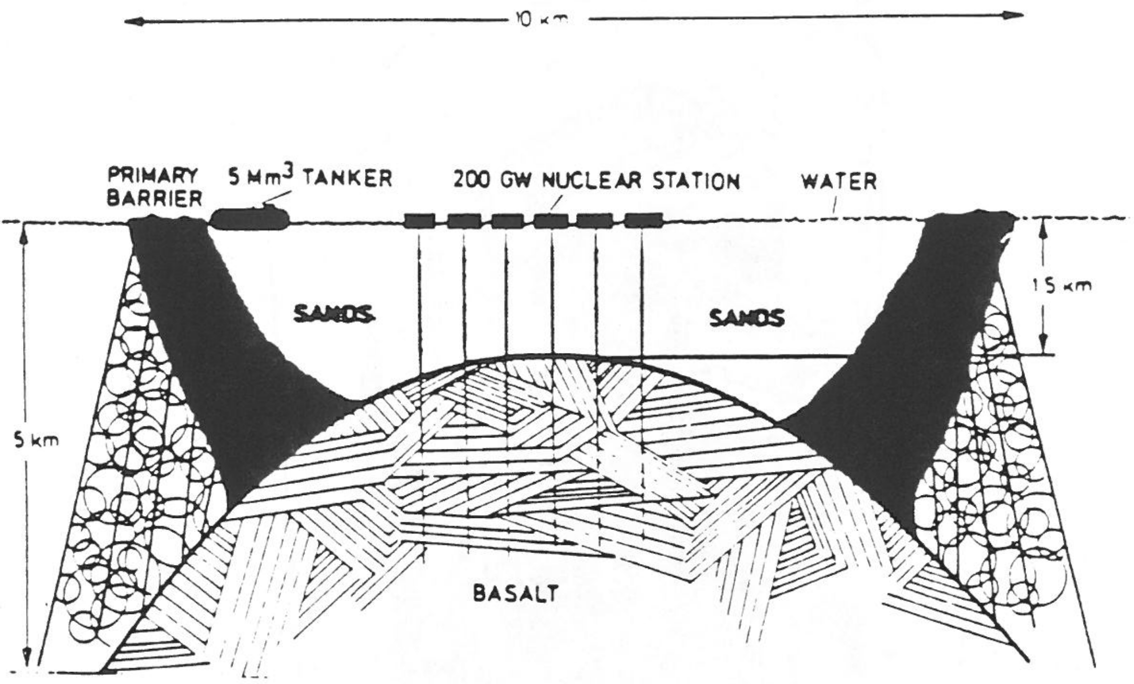


Figure 20. "Futuristic" sketch of an ultimate carbon-free energy supply system. The Energy Island as suggested by C. Marchetti at the conference. Located far away from the human sociosphere on a Pacific island, the concept provides for full integration: uranium supply, fuel cycle facilities and waste disposal, nuclear reactors, hydrogen production from seawater and facilities for shipping liquid hydrogen to consumers are all located on one site. 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 also large-scale photovoltaic facilities could provide for primary energy. In order to minimize albedo changes (that would arise from the location of large "solar farms" in desert areas) Marchetti suggested large floating platforms on the oceans: the solar equivalent of the Energy Island concept. Source: C. Marchetti.

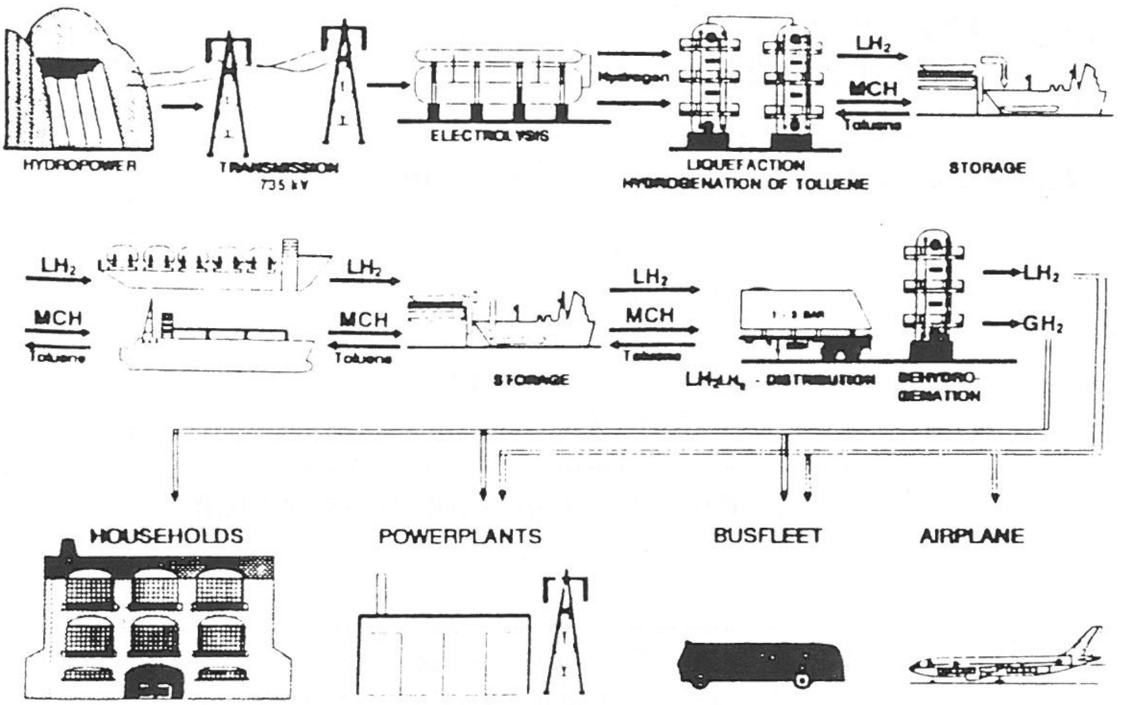


Figure 21. Overview representation of the Euro-Québec Hydro-Hydrogen Pilot Project energy chain. 100 MW hydropower electricity are used to produce hydrogen via electrolysis, which is then liquefied (the Toluene route was excluded during the feasibility study) and transported from Canada to Europe for use in stationary and mobile applications. The overall energy balance indicates a conversion efficiency between primary to final energy of around 52 percent. Still, the economics of the hydrogen delivered is, with 148 ECU cents per liter gasoline (equivalent) rather unfavorable, being between two and three times higher than European gasoline prices (including taxation). Estimates indicate that the delivered hydrogen costs could ultimately be brought down to about 73 ECU cents per liter assuming large scale implementation in the order of 1 TW. Source: O. Ullmann.

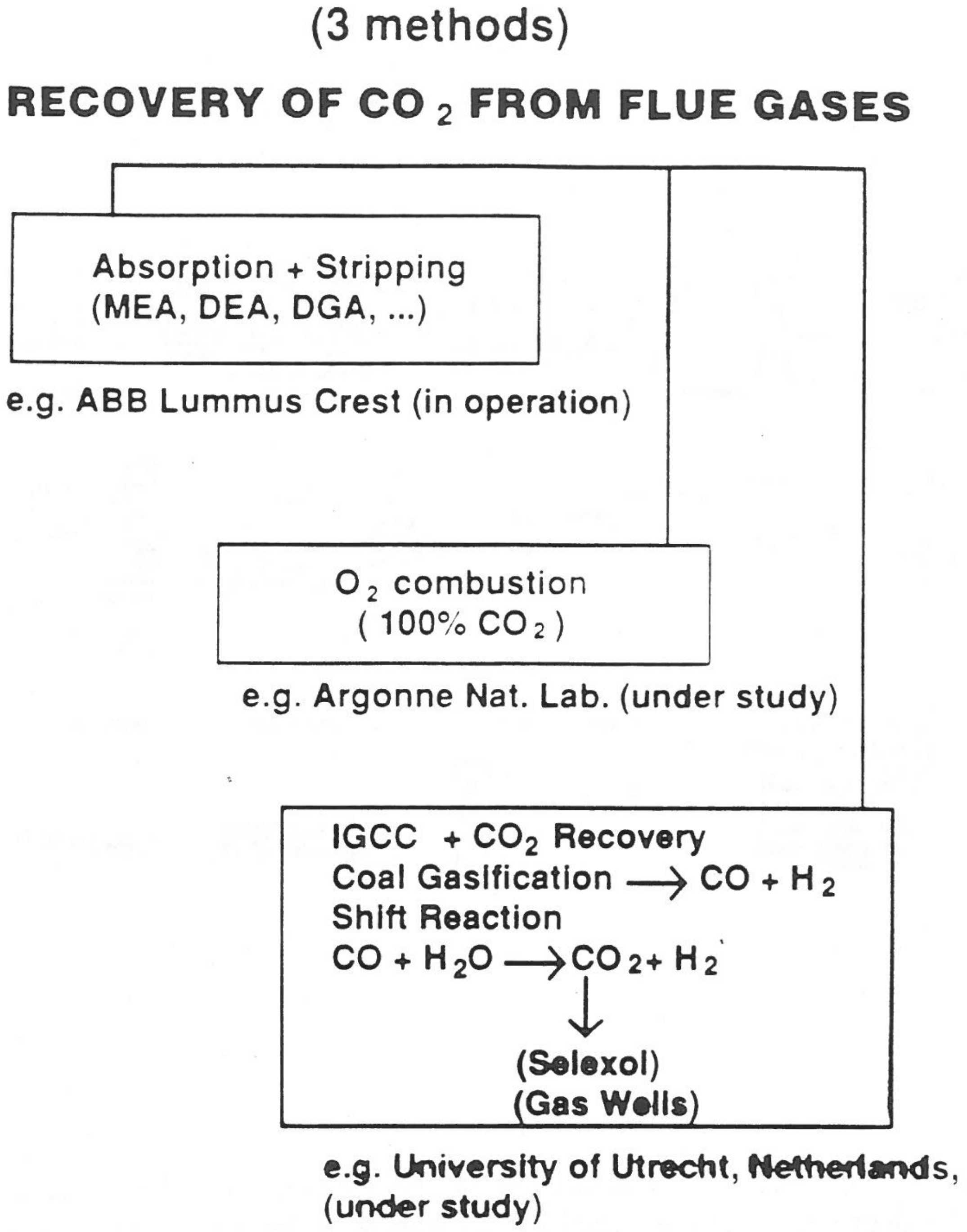
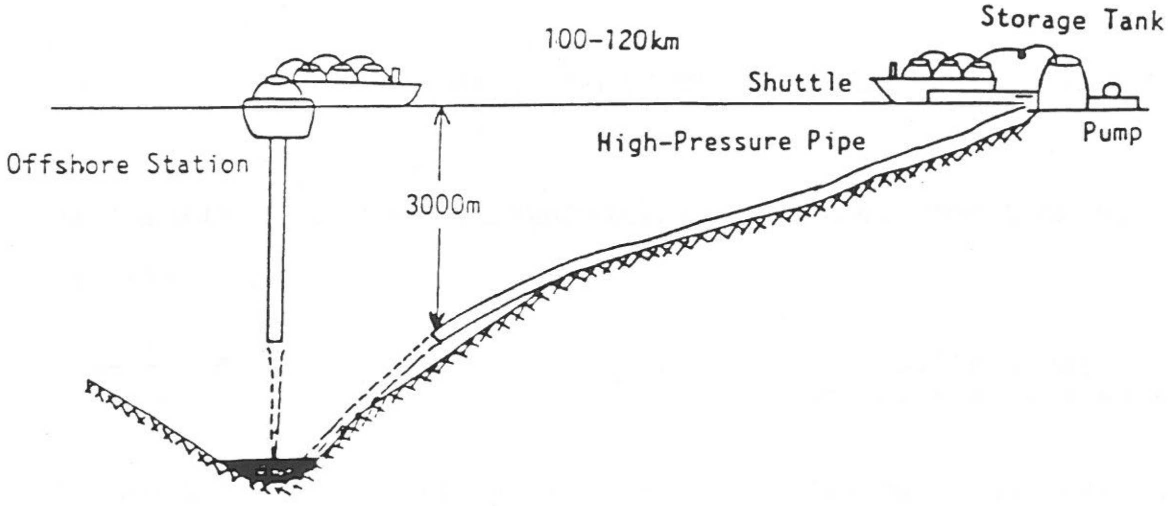


Figure 22. Three principal routes for CO_2 recovery from flue gases: e.g., removal via chemical absorption, a process already in use commercially today. Also possible are cryogenic distillation or membrane separation. Other possibilities include combustion with pure oxygen, or coal gasification in conjunction with a combined cycle power plant and a shift reaction for CO_2 separation. Cost estimates presented by C. Hendriks from the University of Utrecht, the Netherlands, indicate typical costs of about US $ 30 per ton CO_2 removed. Source: B. Eliasson.

CARBON DIOXIDE RECOVERY FROM POWER PLANTS

Type of power plant	Efficiency effect (%)	Price effect (¢/kWh)
Conventional coal (chemical absorption)	41 ⟶ 29	3.5 ⟶ 5.9
Conventional natural gas combined cycle (chemical absorption)	48 ⟶ 42	3.2 ⟶ 4.2
Coal gasification (shift + physical absorption)	43.6 ⟶ 38.1	3.5 ⟶ 4.4

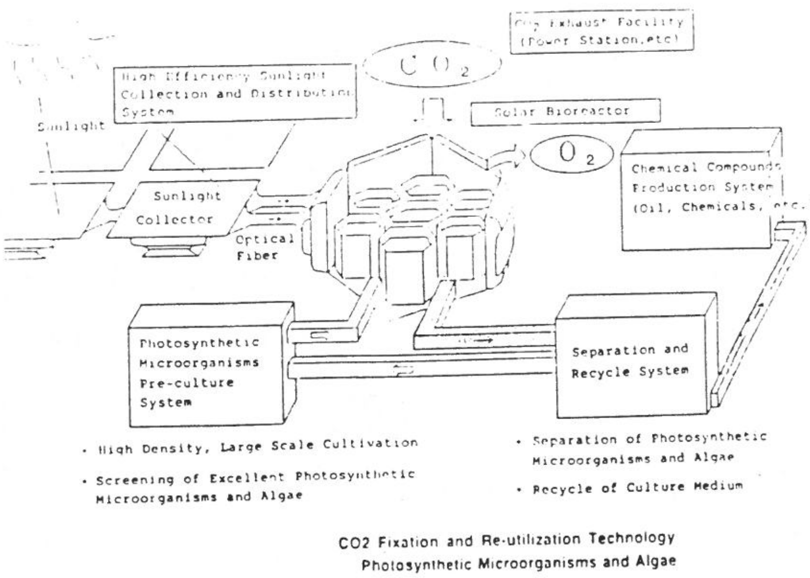
Figure 23. Three technological routes for CO_2 removal from power plants. Most noteworthy are the significant energy penalty and increased costs per kWh produced. Improvements in technical and economic performance of CO_2 removal technologies was considered a likely consequence of commercialization and large scale application of the technology. The history of SO_2 scrubbers is a case in point. Source: C. Hendriks.



Basic Concept of Disposal Systems to Ocean

Figure 24. CO_2 disposal in deep ocean. After CO_2 removal from flue gases, e.g., via chemical absorption as suggested by M. Steinberg or via physical absorption (SELEXOL process), final disposal of CO_2 is required. Disposal in depleted natural gas fields or salt caverns have been suggested. In the case of Japan, such disposal possibilities are not available, therefore storage in the deep ocean is investigated. CO_2 could be either pumped to the ocean floor, or liquefied and transported with tankships to an off-shore station and sunk from there. The latter option is currently being studied in more detail. In particular the diffusion properties of CO_2, clathrate formation and possible ecological impacts need careful attention. Interesting findings from the study were shared at the meeting. There was wide consensus that further detailed studies as well as carefully designed experiments are needed. Source: R. Matsuhashi.

Figure 25. Global phytomass change in 1980 due to deforestation, reforestation, and CO_2 fertilization effect. Positive (top) and negative balance (in grams per m^2 per year). 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, e.g., in considering also changes in soil carbon content. Afforestation is further constrained by competing land utilization for agricultural purposes and significant fertilizer and water requirements. Source: G. Esser.



GHG emission in forage production.

	GHG emission (ton-C equivalent/forage ton-C)			
	Micro-algae[a]	Micro-algae[b]	Hydrogen bacteria[c]	Forage crop
CO_2 (derived from energy consumption)	0.08	1.08	2.9	0.157
N_20 [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 from the data of bacterial SCP productin.
[c] H_2 derived from LNG.
[d] Greenhouse effect equivalent to $CH_4 = 80 \times CO_2$, greenhouse effect equivalent to $N_20 = 200 \times CO_2$.
[e] Assuming that 10% of plant residue is converted to methane by anaerobic fermentation.

Figure 26. CO_2 sequestering via photosynthesis. General flow chart of photosynthesis system with microorganisms and algae for production of e.g., chemical compounds (top), or animal feed (forage) and resulting GHG emission balance (bottom). CO_2 sequestering via technologies based on photosynthesis were suggested at the meeting as a more promising alternative than afforestation programs. For instance, the integrated GHG emissions of forage production via extensive micro algae culture would produce only one tenth of the GHG emissions of conventional agricultural crops used for animal feed. Source: T. Kashiwagi (top) and H. Saiki (bottom).

REFERENCES

American Petroleum Institute (API), 1989, Basic Petroleum Data Book, Petroleum Industry Statistics, Vol. III, No.2, May 1988, Washington, D.C.

British Petroleum (BP), 1989, *BP Statistical Review of World Energy*, BP, London.

Kuuskraa, V.A. and Meyers, R.F., 1983, Review of World Resources of Unconventional Gas, in M. Grenon and C. Delahaye (eds.), *Conventional and Unconventional World Natural Gas Resources*, CP-83-S4, International Institute for Applied Systems Analysis, Laxenburg, Austria, pp. 409–458.

MacDonald, G.J., 1989, The Near- and Far-Term Technologies, Uses, and Future of Natural Gas, in *Energy Technologies for Reducing Emissions of Greenhouse Gases*, Vol. 1, OECD, Paris, pp. 509–535.

Nakićenović, N., Bodda, L., Grübler, A., and Gilli, P.-V., 1990, *Technological Progress, Structural Change and Efficiency Energy Use: Trends Worldwide and in Austria*, International Part of the Study supported by the "Osterreichische Elektrizitätswirtschafts A.G." (Verbundgesellschaft), International Institute for Applied Systems Analysis, Laxenburg, Austria.

Office of Technology Assessment (OTA), 1991, *Changing by Degrees: Steps to Reduce Greenhouse Gases*, OTA-O-482, US Congress, OTA, Washington, D.C.

Parent, J.D. and Linden, H.R., 1977, A Survey of United States and Total World Production, Proved Reserves and Remaining Recoverable Resources of Fossil Fuels and Uranium as of December 21, 1975, Institute of Gas Technology, Chicago.

Science, 1991, **251**(5000), 1405.

APPENDIX I

SCOPING WORKSHOP ON CO_2 REDUCTION AND REMOVAL: MEASURES FOR THE NEXT CENTURY

19–21 March 1991

IIASA, Laxenburg, Austria

CO_2 Reduction and Removal: Measures for the Next Century

19–21 March 1991
Seminar Room
IIASA, A-2361 Laxenburg, Austria

Policy measures for environmentally compatible development, particularly in energy, encompass a wide range of techno-economic adjustments on one hand and social-behavioral responses on the other. Technological and economic measures to minimize energy-related emissions have been studied in great detail in the past. However, in many instances, the studies focus rather narrowly on individual measures and technologies without a systematic and comparative treatment of the broad spectrum of technologies that are needed to delay and mitigate climate change. There is a need for such a comprehensive evaluation of innovative technologies with an account of their current status, implementation prospects, applicability in different parts of the world, cost structure, technical performance, market potential, technology transfer to developing countries and timing over various horizons.

Such an assessment should provide an inventory but not necessarily an exhaustive treatment of the full range of technological and economic measures spanning efficiency improvements, conservation, enhanced use of low-carbon fuels, carbon free sources of energy and other options such as afforestation and enhancement of carbon sinks. In addition to the evaluation of technical, economic and environmental characteristics of technologies, it is also important to specify their applicability in different geographical, economic or cultural settings, and to specify the time horizon of their availability and their forward and backward linkages to other technologies in the energy system. Such a systems approach in assessing the contribution of individual technologies could lead to a better understanding of the aggregate potential for future reductions in emissions of greenhouse gases.

Furthermore, future rates and direction of technological change in different countries will not only depend on their social and economic characteristics, but also on various salient features of their history and development paths taken. They will depend for instance on capital vintages, lifestyle changes, new tax structures, etc. Therefore the question is whether the same technological solutions *per se* are applicable everywhere (i.e., across different economic systems, societies and cultures), which options are available and where they may be introduced. Another question relates to costs implied by technological restructuring, rapid diffusion, efficiency improvements and capital deepening.

The Energy and the Environment research activities within the Environment Program at IIASA will include such evaluation and assessment of innovative technologies that can contribute toward postponement and mitigation of global change during the next hundred years with emphasis on CO_2. This research effort will include *inter alia* a review of recent and current studies in the field, and an evaluation of various measures and technologies for reducing global carbon dioxide emissions in the long run. As part of this effort, IIASA will hold a two-and-half day workshop from 19 to 21 March 1991.

The objective of the meeting is threefold: first, to review current research and present understanding of appropriate measures to reduce carbon dioxide emissions in the future covering a wide range of technologies; second, to critically evaluate IIASA's assessment of mitigation and reduction technologies; and finally, to provide an overview of other similar international and national studies. Emphasis will be given to discussions and interactions between participants, rather than to formal presentations.

PROGRAM

Tuesday, 19 March 1991

08:30 **Registration**

09:00 Welcome Address, P. de Jánosi, IIASA Director

09:10 IIASA's Environment Research, B. Döös, Leader, Environment Program

09:30 Introduction to the meeting and presentation of IIASA study, N. Nakićenović

10:00 Coffee Break

SESSION I: GLOBAL/REGIONAL STUDIES

Chairperson: M. Styrikovich

Panel: Y. Kaya, Y. Sinyak, T. Kram, A. Grübler, A. Mathur

10:30 Overview and Presentations by Panelists

11:45 General Discussion

12:30 Lunch

SESSION II: NATIONAL STUDIES

Chairperson: P.-V. Gilli

Panel: D. Richards, S. Chernavsky, K. Yamaji, A. Gheorghe, T. Lis, P. Schaumann, J. Skea

14:00 Overview and Presentations by Panelists

16:00 Coffee Break (Computer Demonstration)

16:30 General Discussion

18:00 Departure for Heurigen
(Beethovenhaus, Mayer am Pfarrplatz, Pfarrplatz 3, A-1190 Vienna)

Wednesday, 20 March 1991

SESSION III: EFFICIENCY IMPROVEMENTS AND CLEANING

Chairperson: M. Steinberg

Panel: C. Hendriks, W. Turkenburg, B. Eliasson, J. Kuyper, P.-V. Gilli, R. Matsuhashi, N. Nakićenović

09:00 Overview and Presentations by Panelists

10:30 Coffee Break (Computer Demonstration)

11:00 General Discussion

12:30 Lunch

SESSION IV: LOW AND ZERO CARBON OPTIONS, INCLUDING RENEWABLES

Chairperson: Y. Kaya

Panel: G. Esser, K. Pollak, H. Saiki, O. Ullmann, C. Marchetti, A. Inaba, A. Grübler

14:00 Overview and Presentations by Panelists

15:45 Coffee Break (Computer Demonstration)

16:15 General Discussion

18:00 Reception (Schloss Restaurant)

Thursday, 21 March 1991

SESSION V: GLOBAL ISSUES AND INTEGRATION (LINKAGES BETWEEN MEASURES AND CLUSTERS OF TECHNOLOGIES)

Chairperson: A. Voss

Panel: C. Marchetti, M. Steinberg, M. Styrikovich, T. Kashiwagi, D. Victor

09:00 Overview and Presentations by Panelists

10:30 Coffee Break

11:00 General Discussion

12:30 Lunch

14:00 Informal discussions and *vin d'honneur*

17:00 Bus to Vienna (transportation to airport will be provided)

List of Participants

Dr. Joseph Alcamo, IIASA, Austria
Dr. Sergei Chernavsky, Institute of Long-term Energy Forecasting, USSR
Prof. Bo Döös, Deputy Director, IIASA, Austria
Dr. Baldur Eliasson, Asea Brown Boveri, Switzerland
Dr. Gerd Esser, IIASA, Austria
Mr. Yasumasa Fujii, University of Tokyo, Japan
Prof. Adrian Gheorghe, International Atomic Energy Agency, Austria
Prof. Paul-Victor Gilli, Technische Universität Graz, Austria
Dr. Arnulf Grübler, IIASA, Austria
Prof. Albert Hackl, Academy for Environment and Energy, Austria
Dr. Chris Hendriks, University of Utrecht, The Netherlands
Dr. Atsushi Inaba, IIASA, Austria
Dr. Peter de Jánosi, Director, IIASA, Austria
Mr. Aviott John, IIASA, Austria
Prof. Takao Kashiwagi, Tokyo University of Agriculture and Technology, Japan
Prof. Yoichi Kaya, University of Tokyo, Japan
Dr. Osamu Kobayashi, Global Industrial and Social Progress Research Institute, Japan
Dr. Tom Kram, Energy Research Foundation, The Netherlands
Dr. Jan Kuyper, Shell International Petroleum Co., Ltd., UK
Mr. Tadeusz Lis, Institute of Fundamental Technological Research, Poland
Dr. Cesare Marchetti, IIASA, Austria
Dr. Ajay Mathur, Tata Energy Research Institute, India
Dr. Ryuji Matsuhashi, The University of Tokyo, Japan
Mr. Alan McDonald, American Academy of Arts and Sciences, USA
Dipl. Ing. Sabine Messner, IIASA, Austria
Mr. Koji Nagano, IIASA, Austria
Dr. Nebojša Nakićenović, IIASA, Austria
Ms. Catherina Nystedt, Asea Brown Boveri, Sweden
Dipl. Ing. Kurt Pollak, ÖMV Aktiengesellschaft, Austria
Dr. Deanna Richards, National Academy of Engineering, USA
Ms. Susan Riley, International Institute for Applied Systems Analysis, Austria
Dr. Hiroshi Saiki, Central Research Institute of Electric Power, Japan
Dipl. Ing. Peter Schaumann, University of Stuttgart, Germany
Dr. Roderick Shaw, IIASA, Austria
Dr. Yuji Shindo, National Chemical Laboratory for Industry, Japan
Dr. Yuri Sinyak, IIASA, Austria
Dr. Jim Skea, Science Policy Research Unit, University of Sussex, UK
Dr. Josef Spitzer, Joanneum Research, Austria
Dr. Meyer Steinberg, Brookhaven National Laboratory, USA
Dipl. Ing. Manfred Strubegger, IIASA, Austria
Acad. Mikhail Styrikovich, Presidium of the Academy of Sciences, USSR
Prof. Wim C. Turkenburg, University of Utrecht, The Netherlands
Dr. Oskar Ullmann, Ludwig Bölkow Stiftung, Germany
Mr. David G. Victor, Massachusetts Institute of Technology, USA
Prof. Dr. Alfred Voss, University of Stuttgart, Germany
Dr. Kenji Yamaji, Central Research Institute of Electric Power, Japan

CO_2 REDUCTION AND REMOVAL: MEASURES FOR THE NEXT CENTURY

19–21 March 1991

LIST OF PARTICIPANTS

Dr. Sergei Chernavsky
Working Consulting Group on
Long-term Energy Forecasting
USSR Academy of Sciences
Vavilov Street 44/2, Room 79-80
117333 Moscow
USSR
tel: (007-095) 137-5771

Dr. Baldur Eliasson
Asea Brown Boveri
Forschungszentrum Business Development
CH-5405 Baden-Dattwil
Switzerland
tel: (56) 768-031
fax: (56) 834-569

Mr. Yasumasa Fujii
Kaya Laboratory
University of Tokyo
7-3-1 Hongo, Bunkyo-ku,
Tokyo 113
Japan
tel: (0081-3)-812-2111-7490
fax: (0081-3)-3816-4996

Dr. Adrian Gheorghe
International Atomic Energy Agency
P.O. Box 100
A-1400 Vienna
tel: 2360/6082
fax: 234-564

Prof. Paul Victor Gilli
c/o Vorstand des Institutes
für Wärmetechnik
Technische Universität Graz
Infeldgasse 25
A-8010 Graz
tel: (0316) 873-7300
tel: (9-877-1291) (home-Vie)
fax: (0316) 873-7305
tlx: 1 31221 tugraz a

Prof. Albert Hackl
President
Akademie für Umwelt und Energie
Schlossplatz 1
A-2361 Laxenburg
tel: (02236) 712-410
fax: (02236) 72-527

Dr. Chris Hendriks
University of Utrecht
Oude Gracht 320
3511 PL Utrecht
The Netherlands
tel: (030) 392-380 or 392-689
fax: (030) 367-219

Prof. Takao Kashiwagi
Department of Mechanical Systems Engg.
Tokyo University of Agriculture
and Technology
Kaganei, Tokyo 184
Japan
tel: (81-423) 814-221 ext. 444
fax: (81-423) 843-804

Dr. Yoichi Kaya
Kaya Laboratory
Department of Electrical Engineering
The Faculty of Engineering
University of Tokyo
7-3-1 Hongo, Bunkyo-ku
Tokyo 113
Japan
tel: (81-3) 3812-2111 ext. 6758
fax: (81-3) 3816-4996
fax: (81-3) 5684-3986 (private)

Dr. Osamu Kobayashi
Manager
Global Industrial and Social Progress
Research Institute (GISPRI)
Mori Building, No. 33
3-8-21 Toranomon, Minato-ku
Tokyo 105
Japan
tel: (81-3) 3435-8800
fax: (81-3) 3435-8810

Dr. Tom Kram
Programme Manager
Global Issues
ECS - Energy Studies
Netherlands Energy Research Foundation
Westerduinweg 3
P.O. Box 1
1755 ZG Petten
The Netherlands
tel: (0031) 2246-4427
fax: (0031) 2246-3338
tlx: 57211 reacp-nl

Dr. Jan Kuyper
Group Planning, Technology/Environment
Shell International Petroleum Co., Ltd.
PL/11
Shell Centre
London SE1 7NA
United Kingdom
tel: (04471) 934-5967
fax: (04471) 934-8060

Mr. Tadeusz Lis
Energy Systems Group
Institute of Fundamental
Technological Research, PAN
Swietokrzyska 11/21
PL-00049 Warsaw
Poland
tel: (4822) 262-522
fax: (4822) 269-815

Dr. Ajay Mathur
Tata Energy Research Institute
7 Jor Bagh
New Delhi 110003
India
tel: (11) 615-032 or 617-025
fax: (11) 4621-770

Dr. Ryuji Matsuhashi
Research Associate
The University of Tokyo
7-3-1 Hongo, Bunkyo-ku
Tokyo 113
Japan
tel: (81-3) 3812-2111/7053
fax: (81-3) 3818-7492

Mr. Alan McDonald
Executive Director
U.S. Committee for IIASA
American Academy of Arts and Sciences
136 Irving Street
Cambridge, Massachusetts 02138
U.S.A.
tel: (617) 576-5019
fax: (617) 576-5050

Ms. Catherina Nystedt
Asea Brown Boveri - Fäkt AB
S-12086 Stockholm
Sweden
tel: (0046-8) 714-4160
fax: (0046-8) 643-5485

Dipl. Ing. Kurt Pollak
R&D, Processes and Environment
ÖMV Aktiengesellschaft
Postfach 75
A-2320 Schwechat
fax: 7720-2120

Dr. Deanna J. Richards
Senior Program Officer
National Academy of Engineering
2101 Constitution Ave., N.W.
Washington, D.C. 20418
USA
tel: (202) 334-1516
fax: (202) 334-1563

Dr. Hiroshi Saiki
Manager
Bio-Technology Section
CRIEPI
1646 Abiko, Abiko-shi
Chiba-ken 270-11
Japan
tel: (81-3) 3201-6601
fax: (81-471) 827-922

Dipl. Ing. Peter Schaumann
Institut für Energiewirtschaft
und Rationelle Energieanwendung (IER)
Universität Stuttgart
Heßbrühlstrasse 49a
D-7000 Stuttgart 80
Germany
tel: (06-0711) 78-061 ext. 14
fax: (06-0711) 780-3953

Dr. Yuji Shindo
Senior Research Scientist
National Chemical Laboratory
for Industry
1 Higashi, 1-chome
Tsukuba 305
Japan
tel: (81) 298-54-4656
tel: (81) 298-55-1397

Dr. Jim Skea
Energy Group
SPRU
Mantell Building
University of Sussex
Brighton BN1 9RF
United Kingdom
tel: (273) 686-758
fax: (273) 685-865

Dr. Josef Spitzer
Institut für Energieforschung
Joanneum Research
Elizabethstrasse 11
A-8010 Graz
tel: (0316) 8020/338
fax: (0316) 8020/320

Dr. Meyer Steinberg
Department of Applied Science
Brookhaven National Laboratory
Associated Universities, Inc.
Upton, Long Island
New York 11973
USA
tel: (516) 427-0768 (priv)
tel: (516) 282-3036 (off)
fax: (516) 282-3000

Acad. Mikhail Styrikovich
Presidium of the Academy of
Sciences of the USSR
14, Leninski PRsp.
117071 Moscow
USSR
tel: (007-095) 137-5771

Prof. Wim C. Turkenburg
Head
Dept. of Science, Technology and Society
University of Utrecht
OudeGracht 320
3511 PL Utrecht
The Netherlands
tel: (030) 392-375
fax: (030) 367-219

Dr. Oskar Ullmann
Ludwig Bölkow Stiftung
Daimlerstr. 15
D-8012 Ottobrunn
Germany
tel: (06-089) 608-1100
fax: (06-089) 609-9731

Mr. David G. Victor
Department of Political Science
Massachusetts Institute of Technology
Cambridge, Mass. 02139
USA
tel: (617) 253-6979
tel: (617) 923-1592 (home)
fax: (617) 258-8118

Prof. Dr. Alfred Voss
Institut für Energiewirtschaft
und Rationelle Energieanwendung (IER)
Universität Stuttgart
Heßbrühlstrasse 49a
D-7000 Stuttgart 80
Germany
tel: (06-0711) 78-061 ext. 14
tel: (06-0711) 685-2008 (direct)
fax: (06-0711) 780-3953

Dr. Kenji Yamaji
Manager, Energy Systems Section
Economic Research Center
CRIEPI
1-6-1 Otemachi, Chiyoda-ku
Tokyo 100
Japan
tel: (81-3) 3201-6601
fax: (81-3) 3287-2864

IIASA:
Dr. Joseph Alcamo, Leader, Toxic Pollution and the European Environment
Prof. Bo Döös, Leader, Environment Program and Deputy Director
Dr. Gerd Esser, Leader, Biosphere Dynamics
Dr. Arnulf Grübler, Research Scholar, Environmentally Compatible Energy Strategies
Dr. Atsushi Inaba, Research Scholar, Environmentally Compatible Energy Strategies
Dr. Peter de Jánosi, Director
Mr. Aviott John, Science Writer
Dr. Cesare Marchetti, Research Scholar, Sponsored and Exploratory Projects Core
Dipl.Ing. Sabine Messner, Research Scholar, Environmentally Compatible Energy Strategies
Mr. Koji Nagano, Research Scholar, Global Energy and Climate Change
Dr. Nebojša Nakićenović, Leader, Environmentally Compatible Energy Strategies
Ms. Susan Riley, Manager, Office of Sponsored Research
Dr. Leo Schrattenholzer, Research Scholar, Environmentally Compatible Energy Strategies
Dr. Roderick Shaw, Leader, Global Environmental Security
Dr. Yuri Sinyak, Principal Investigator, Global Energy and Climate Change
Dipl.Ing. Manfred Strubegger, Research Scholar, Environmentally Compatible Energy Strategies

PARTICIPANTS:


Sergei Chernavsky


Baldur Eliasson


Yasumasa Fujii


Adrian Gheorghe


Paul-Viktor Gilli

Michael Grubb


Albert Hackl


Chris Hendriks


Takao Kashiwagi


Yoichi Kaya


Osamu Kobayashi


Tom Kram


Jan Kuyper


Tadeusz Lis


Ajay Mathur


Ryuji Matsuhashi

Friedrich Niehaus

Catherine Nystedt


Kurt Pollak


Deanna Richards


Hiroshi Saiki


Peter Schaumann


Yuji Shindo


Jim Skea


Meyer Steinberg


Josef Spitzer


Mikhail Styrikovich


Wim Turkenburg


Oskar Ullmann


David Victor


Alfred Voss


Kenji Yamaji

IIASA PARTICIPANTS:


Joseph Alcamo


Bo Döös


Gerd Esser


Arnulf Grübler


Atsushi Inaba


Peter de Jánosi


Cesare Marchetti


Susan Riley


Sabine Messner


Koji Nagano


Nebojša Nakićenović


Roderick Shaw


Yuri Sinyak


Manfred Strubegger


Aviott John