Working Paper

ENERGY STRATEGIES FOR MITIGATING GLOBAL CHANGE

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Energy Consumption and Global Warming

Since the first measurements of atmospheric carbon dioxide concentrations were taken in 1958 on Mauna Loa, annual averages have portrayed a steady increase from about 315 to more than 350 ppm today. It is believed that the pre-industrial carbon dioxide concentration levels were about 280 ppm. Probably most of this increase is due to anthropogenic sources of carbon dioxide such as fossil energy use and deforestation. The emissions of other greenhouse gases are also increasing but global warming is foremost a carbon dioxide problem. It accounts for about 50 percent of the anthropogenic sources of global warming. The next largest share is due to methane with about 20 percent. The relative contributions of different sources of carbon dioxide emissions are illustrated in Figure 1. It clearly demonstrates that fossil energy consumption contributes about a half of all anthropogenic sources of carbon dioxide. The largest single source of carbon emissions from fossil fuels is coal (about 60 percent of all fossil-fuel emissions), followed by oil (around 30 percent) and gas (less than 10 percent).

Most of the carbon dioxide increase is due to the historical emissions in the now industrialized countries of the "North". With only 25 percent of world population, these countries currently account for two-thirds of the global energy-related carbon dioxide emissions. This is illustrated in Figure 2 which gives shares in current fossil energy emissions for 13 world regions. Because of the long residence time of carbon dioxide in the atmosphere of between 50 to 300 years, a substantial part of present emissions will continue to contribute to additional global warming for many decades to come. This is also true of the historical emissions. Based on our limited understanding of the global carbon cycle, some of the carbon emitted by Watt's first steam engine might still be contributing to the current concentrations.

By using a simple model of the global carbon cycle with airborne fraction of about 50 percent and a time constant for ocean uptake of carbon dioxide of about 300 years, it is possible to reproduce the Mauna Loa concentration record with high accuracy based on the historical emissions of fossil fuels and biota (e.g., see Fujii, 1990).[1] With this method one can roughly estimate the historical contribution of

1 Airborne fraction specifies the share of additional carbon dioxide emissions that remain in the atmosphere. The difference is believed to be absorbed by a number of natural sinks, the ocean being by far the largest.

different regions and countries to the current concentrations. This result is illustrated in Figure 3. It clearly shows that the developing countries have caused less than 16 percent of the carbon dioxide concentrations due to past consumption of fossil energy. Table 1 confirms this result on the basis of other current and historical indicators proposed in the literature such as emissions per unit land area or per unit GDP. In all cases, the more developed countries have a much higher share in global emissions than the developing ones. Therefore, historical responsibility clearly rests with the industrialized countries. However, future emissions are expected to increase most in the developing countries as their populations continue to grow possibly with higher per capita energy consumption. This all points in the direction of increasing concentrations in the future and the need to undertake active measures to reduce the sources of carbon dioxide, increase potential sinks, formulate a framework for allocating emissions quotas or permits, and develop effective adaptation measures to climate change.

Industrialized countries are in a position to achieve substantial emissions reductions compared to the rest of the world both because they have relatively high per capita emission levels, and larger economic and technological capabilities. At the same time, industrialized countries are in a better situation to respond and adapt to climate change. They are incurring the benefits from the historical emissions. Another way of looking at this is to imagine that the historical increase of greenhouse concentrations is an exhaustible resource with an eventual limit that the industrialized countries utilized to achieve their current levels of development. According to such an argument, developed countries enjoy a high level of affluence and material well-being because of their past industrialization, the resulting emissions and other adverse environmental impacts.

Global Energy Needs

The burden on the developing countries is two-fold. While they need to increase their per capita energy consumption in order to improve the quality of life, they are also more vulnerable to adverse consequences of climate change. Figure 4 illustrates a high degree of heterogeneity in the current distribution of per capita carbon emissions among various countries. They differ between the North and the South by nearly a factor of 9 (3.3 tons of carbon per capita in developed countries versus 0.37 tons in developing countries). A persistent per capita emission gap remains (0.5 tons to 1.1 tons carbon per capita in developing countries compared to 3.3 tons per capita in industrialized countries), even after including carbon emissions from tropical deforestation, currently estimated to range between 0.6 to 2.8 Gt carbon annually (IPCC, 1990; Houghton, 1990).

While the US and the former area of the GDR have the highest per capita carbon dioxide emissions (in excess of 5 tons of carbon per year), the reasons for the larger part of those high levels are fundamentally different. The former GDR and many of the reforming countries of Eastern Europe have relatively high emissions due to the many inefficiencies inherent in the former structure of their economies and energy systems and due to the high share of coal in their primary energy supply (especially in transportation). In the US the high per capita emissions are primarily due to very high levels of energy end-use. Other industrialized countries, as illustrated by Western Europe and Japan, have similar levels of affluence but substantially lower emissions. On the other hand, most of the developing countries have very low per capita emissions compared with the North. Although they account for about a third of total emissions this is due to their sheer size (see Figure 2). This means that decarbonization and development are not mutually exclusive provided an appropriate policy mix is found. Thus, it will make a big difference whether developing countries follow the path of energy-efficient economic development that relies on carbon-poor sources and carriers of energy or whether they embark on less energy efficient and coal intensive development paths.

In any case, it appears unavoidable that with further development global emissions will continue to increase for some time to come. Thus, supply and energy use are likely to remain one of the main determinants of economic and social development, and one of the important sources of global change. Consequently, a number of national CO_2 reductions plans have been announced, aiming to stabilize and in some cases even reduce further emissions.

The most prominent international effort to analyze global greenhouse gas emissions, atmospheric concentrations, impacts and response strategies has been undertaken by the Intergovernmental Panel on Climate Change (IPCC, 1990). Within the IPCC *inter alia* scenarios of possible future emissions are formulated corresponding to an atmospheric concentration equivalent of a doubling CO_2 over pre-industrial levels during the next century. Subsequently, additional emission scenarios were developed in which atmospheric concentrations of greenhouse gases are stabilized at a level less than a doubling of CO_2 equivalent and then further reduced.

Since 1981, Stanford University and IIASA have been jointly organizing the International Energy Workshop (IEW) with the aim of comparing energy projections made by different groups in the world and analyzing their differences (Manne and Schrattenholzer, 1991). The median of global CO_2 emissions calculated from the IEW polls of global energy consumption or, in our interpretation, the current "consensus view", corresponds to an annual growth rate of one percent per year, i.e., to an increase from about 6 Gigatons (Gt) today to some 9 Gt of carbon by the year 2020, with a range between 8 to 10 Gt as shown in Figure 5. Although lower than the "business-as-usual" scenario of the IPCC for the same year, the IEW poll range gives rise to concerns as to how such a trend could be "bent" downwards, e.g., along the lines of the Low Emission and Accelerated Policy scenarios of the IPCC. This all strongly suggests that – in the absence of appropriate countermeasures – global carbon emissions will rise, perhaps beyond environmentally acceptable levels.

CARBON DIOXIDE EMISSIONS AS A GLOBAL "RESOURCE"

In the light of the above, there is a need to reduce the sources of greenhouse gases as much as possible and, at the same time, increase the natural sinks of carbon dioxide and create new ones for storing the carbon removed from fossil fuels. Beyond that is the question of how to allocate the limited "resource" of future carbon dioxide releases. In some sense this is analogous to the concerns during the 1970s of limited global fossil resources.

During the 1970s, the main focus of many global energy studies was on resource availability and the possible time horizons for introducing new energy supply sources. Special emphasis was often given to the production of synthetic liquid fuels from coal to respond to the perceived scarcity of crude oil and the increasing costs of energy supply. Such studies represented the techno-economic perspective of future energy developments, a "second generation" of studies concentrated on end-use and demand management. Perhaps even more important, these studies pointed to the large potential for efficiency improvements, particularly in energy end uses, and to the importance of the socio-behavioral perspective for future energy systems evolution.

Today, the predominant question is whether it will actually be possible to continue consuming energy at current or even higher rates in the future. What is dramatically different is the (possible) shift from resource to environmental constraints, and the risk that adverse global change could constitute the ultimate limit of future increase in energy use. The ultimate global resource could be the environment rather than recoverable energy reserves and resources. The perceptions about factors limiting further energy growth have changed while the driving forces are still the same – population and economic growth. Some of the measures and strategies that seemed desirable in the past, however, appear to be invariant to this shift in perceptions. Efficiency improvements and conservation are instrumental in reducing both fossil fuel requirements and emissions. Thus, today it appears that the amount of carbon that can be pumped into the atmosphere is also a limited resource available to humanity. This implies many salient equity considerations not only among people and countries but also among different generations. Here, we first consider some of the equity issues implied by different carbon dioxide allocation regimes and reduction scenarios, and then focus on different techno-economic measures and strategies for reducing and mitigating further increases of emissions.

EQUITY ISSUES IMPLICIT IN REDUCTION SCHEMES

Should global emissions continue to increase well into the 21st century despite even the most ambitious mitigation efforts, the question arises of how emission entitlements might be allocated between countries or individuals. In some sense, the default in emission distribution is the status quo which implies an increase of emissions levels possibly leading to environmentally unacceptable development paths. Along the lines of preserving status quo, a possible reduction scheme could involve equal across-the-board cuts for each country by a certain target year. On the other hand, the most equitable proposition would be to allow each individual the same emission quota. In view of the high degree of heterogeneity in per capita emissions (see Figure 4) this constraint is very rigid and would be difficult to implement. Nevertheless it is useful to consider the implications of such an arrangement. If we set the per capita limit low enough to stabilize and eventually reduce the atmospheric concentrations (to a stable level somewhere in the order of 1 to less than 4 Gt per year) then the implied per capita emissions would be substantially lower than the current global average. Table 2 illustrates such an extreme scenario for reducing global emissions to about 4 Gt by the year 2050 that roughly corresponds to the IPCC Accelerated Policy scenario (IPCC, 1990). The implied per capita emissions would be about 0.4 tons and thereby two and a half times lower than the current average of about one ton. Two scenarios assume equal (across-the-board) percentage cuts in all regions on the basis of their emissions in the reference year 1988 and 1980, respectively. From all of the world regions given in Table 2, only India, "Other Asia" and "Other Africa" have such low emissions today while all of the other regions would have to implement drastic reductions. Brazil and all "South" taken together have the same per capita emissions today as the assumed world average for 2050. Table 2 gives also two alternative carbon dioxide allocation schemes for two similar reduction scenarios of 4 Gt by 2050: reductions proportional to past contribution and equal emission rights per capita. These alternative schemes imply also drastic reductions for most of the industrialized regions while they allow for increases in developing regions. Table 3 illustrates the same scenarios for the three alternative allocation schemes in per capita terms.

This comparison illustrates that measures for CO_2 emission reduction face particularly intricate interrelations between reduction targets to be agreed upon and their underlying allocation criteria. Any successful agreement on reduction targets (how much, by whom and when) presupposes a prior agreement on the allocation (and by definition on equity) criteria to be used to distribute a scarce global resource, i.e., CO_2 emission rights under a reduction regime.

It should not be forgotten that the equity criteria of a greenhouse gas accounting framework go well beyond purely technical issues (such as accounting for different greenhouse gases in the form of their global warming potential). Some of these questions are being looked at in the deliberations of the Intergovernmental Negotiating Committee (INC) for a framework on climate change. For example, the time frame adopted (i.e., how to account for past emissions), what kind of greenhouse gases to include (only anthropogenic or all sources), and the distributional criteria (such as population, GNP, or land area) all hold important implications for an accounting framework and the resulting emission targets and quotas (see e.g., Grubb, 1989). Various distributional criteria and their combinations have been examined for CO_2 emissions. Some of them are shown in Table 1. Subak

(1990) concludes that each accounting scheme exhibits different biases and that no single standard is likely to be uniformly popular with different groups of countries. For example, stringent CO_2 emission quotas imposed on developing countries would make the further development of their industrial and infrastructural base extremely costly, if not impossible to achieve.

Similar problems are encountered when using land area or GNP as a denominator in a CO_2 accounting scheme. Criteria incapable of accounting for different population sizes, degrees of affluence and industrialization (as in the case of a land-based criterion), or those that penalize countries in the early industrialization phase, which – as the history of the industrialized countries clearly demonstrates – is characterized by high carbon intensity of economic activity, appear difficult to reconcile with consideration of inter-generational and international equity. Figure 6 clearly shows that developed countries also had much higher specific emissions per unit GDP during the early development phase that are comparable to current emission intensities in developing countries. Thus, any accounting framework in an international negotiation process should at least explicitly consider the significant inter-generational and spatial disparities in past and present CO_2 emissions.

EFFICIENCY IMPROVEMENT AND CONSERVATION

Ever since the beginning of the Industrial Revolution energy efficiency increased along with the improvement of labor productivity and reduction of other factor inputs. For example, energy intensity[2] has decreased in the US at an average rate of one percent per year since the middle of the last century. This decrease was punctuated rather than continuous (Nakićenović *et al*, 1990). The rate of improvement has been generally higher since the energy crisis of 1973, averaging more than two percent per year. There is strong evidence that historical development paths varied greatly and consistently during long periods among different countries as illustrated in Figure 7. For example, France and Japan have always used energy more efficiently than the US, the UK, or Germany, while at the same the rates of efficiency improvement have been higher in both the UK and Germany than in the US. Even more surprising is that Japan, which by the early 1970s had one of the most energy efficient economies, has also achieved the highest improvement rates since. This should be contrasted with the opposite development in some of the rapidly industrializing countries where commercial energy intensity is still increasing, e.g., in Nigeria. The current energy intensity of Thailand resembles the US situation in the late 1940s. The energy intensity of India and its present rates of improvement are similar to that of the US about a century ago (Figure 7).

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

Most efficiency improvements have occurred at two levels: conversion and end use. Over the past 20 years, aircraft manufacturers have managed to improve the energy efficiency of commercial jet transport by three to four percent annually (Nakićenović *et al.*, 1990). Figure 8 illustrates the dramatic improvement of aircraft fuel efficiencies. However, it also shows that new technologies may increase energy intensities due to the lower energy efficiency that can result from improved performance, as in the case of supersonic aircraft. In electricity generation, efficiency improvements have averaged 2.5 to 3 percent per year between 1930 and the 1970s (Nakićenović *et al.*, 1990). An assessment of OECD countries shows that the efficiency of conversion from primary energy to final forms for the whole energy system 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 approximately 10 percent (Nakićenović *et al.*, 1990). There is great scope therefore for more efficient energy use, particularly through the improvement of end use technologies.

The above shows that technical improvements and a change of consumption habits (increased service efficiency) are clear priorities for reducing CO_2 emissions through better energy use, especially in the near to medium term. Consensus ends at this point, however, and widely diverging opinions appear as to how, when and where efficiency improvements should begin and to what extent they can be implemented. In areas like electricity production, improvements are leveling off, as if they were approaching some upper limit. Fortunately this is not the case for most energy use categories and the potential for improvement is still vast. Even in the case of thermal electricity generation we are actually nowhere near the theoretical limit given by the Carnot Law, although the improvement potential is much higher in many other areas. An analysis of exergy (or second law) efficiency, which allows to account for differing qualities of various energy carriers, indicates that the overall exergy efficiency of current energy systems is very low.[3] Figure 9 illustrates that exergy efficiency in the OECD countries is not more than a few percent (Nakićenović *et al.*, 1990) . This is corroborated by similar results for most of the industrialized countries.

In developing countries exergy efficiency is probably even lower, especially because noncommercial energy sources are used directly, resulting in very low overall efficiency. For example, open fires for cooking use up to four times more fuel than well-designed stoves. Steam locomotives have at best 7 percent efficiency compared to almost 30 percent for modern diesel-electric locomotives. Commercial and industrial facilities themselves are often poorly designed and maintained. If an increase in service efficiency is added to this analysis, a reduction of overall pri-

3 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 poor transformation efficiency to other energy forms (for many processes governed by Carnot's cycle for heat engines).

mary energy input by up to a factor of about 20 appears feasible with energy services being maintained at current levels. Thus, the potential for efficiency improvement is indeed vast.

The potential is large even in those countries that have achieved a high degree of efficiency. For example, a comprehensive technological analysis lists ways to improve efficiency of over 300 single technologies for the Netherlands, broken down by industry and sector, ranging from greenhouse horticulture to production of aluminum to passenger transport (Blok *et al.*, 1991). The study 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. Similar studies have been conducted for other industrialized countries, (e.g., OTA, 1990; US Academy of Sciences, 1991 or Kaya *et al.*, 1991).

Such studies have also been conducted in developing countries. For example, a recent study for India identifies the overall cumulative CO_2 reduction potential during the next decade to be ten times larger than current annual fossil energy emissions of about 160 million tons of carbon (TERI, 1991). The study illustrates three strategies that would lead to a reduction of carbon dioxide emissions without loss of end-use services: increase in energy utilization efficiency throughout all sectors of the economy, larger deployment of renewable energy sources and afforestation.

Despite this large reduction potential of carbon dioxide emissions the shortage of capital in most of the developing countries is one of the major obstacles in implementing the mitigation measures. There are many other urgent needs for the limited investment capabilities such as the creation of new jobs for the growing population. This is one of the many reasons why efficiency improvements that appear possible in theory are difficult to implement in practice. This is also true in many of the industrialized countries where it is often not in the interest of all decision makers to implement all of the efficiency potentials that are in theory possible.

In fact Socolow (1991) defines conservation as the gap between technical promise and practical achievement. Thus, in general all of these reduction potentials have an implicit assumption that conditions not in existence now for their implementation would be expected in the future. This involves not only the adoption of more efficient technologies and energy conservation measures but also a whole host of institutional and behavioral changes. Figures 10 and 11 compare carbon dioxide reduction cost curves for a number of countries. In all cases the first class of mitigation measures that are achievable either at low or almost no additional cost rely on efficiency improvement and conservation measures. For example, the cost curve for the Soviet Union shows that the elimination of large inefficiencies throughout the economy could facilitate emission reduction at practically no additional cost. Most of the other mitigation measures, such as changes in the structure of energy supply and introduction of energy sources with low carbon content, are in contrast associated with much higher costs than mitigation through efficiency improvements.

Unfortunately, there are a number of severe barriers that may delay or inhibit the achievement of the efficiency potential in the near future. One of them is the cost of these measures and the associated capital requirements as explicitly illustrated in the mitigation cost curves in Figures 10 through 11. The other class of barriers is related to the inherently long process of innovation diffusion and technology transfer. The introduction of new energy technologies takes anywhere from between a decade to up to half a century in the case of infrastructural investments. Thus the vintage structure of the capital stock and its replacement dynamics also determine the likely rates of future efficiency improvements. Figures 12 and 13 show that in the case of the transport system, for example, the replacement of vehicles and the rolling stocks took between one to two decades in most countries. On the other extreme, the replacement of the housing stock is a much longer process lasting many decades and in some cases even centuries. For example, a study for the UK indicates that the replacement rate might be as low as one percent per year (Skea, 1990). Thus, the realization of some of the efficiency improvement potential will need to be associated with retrofitting some of the older vintages, and these may not be replaced in the near future. Figure 14 illustrates that in most industrialized countries almost 80 percent of the capital stock is replaced over a period of twenty years, meaning that substantial efficiency gains could be achieved over the next two decades in most of the energy-end uses.

LESS CARBON INTENSIVE ENERGY OPTIONS

Efficiency improvement is a fundamental step 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 also be important in improving efficiency and lowering carbon emissions. A parallel structural change in the energy sector associated with efficiency improvements is the equivalent of less material inputs in other economic activities.

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.[4] Today, the only carbon-free energy carriers are electricity and 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

4 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 – one hydrogen atom per carbon; oil – about two hydrogen atoms per carbon and methane, four. Therefore CO_2 emissions are lowest for methane and highest for coal.

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.

Figure 15 shows that the diffusion of new energy sources is an indeed very long process lasting many decades. The replacement of coal by oil and gas lasted almost one hundred years. The difficulty in shortening the diffusion time of an energy technology lies in the extensiveness and cost of energy infrastructures; it may not be possible to build up or decommission systems on this physical and social scale in much less than 50 years. Nevertheless, the fact is that the carbon content of the average fuel mix has continuously decreased during the last two hundred years. Figure 16 indicates that the introduction of carbon free sources of energy, such as sustainable use of renewables and nuclear energy, would be required in order to achieve further reductions of the carbon to hydrogen ratio beyond the current level. Some reductions can be achieved by an increase in the use of natural gas. In addition to the 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. In addition to lower specific emissions, 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 pervasive (i.e., used in many places and activities) like 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 century.

Natural gas intensive global energy scenarios indicate that it might be possible to achieve a substantial reduction in global carbon emissions while still using some fossil fuels. One such possibility is to imagine a "global methane economy" where natural gas shares would increase steadily during the next 50 years (as outlined in Figure 16). With these changes in the energy mix it would be possible to maintain the current average per capita consumption in the world during the next century without any substantial increase in total carbon emissions (Ausubel *et al.*, 1988). In the hypothetical methane economy, emissions would peak in the year 2025 and would be substantially lower than the IPCC Low Emissions scenario. The additional methane leakage implicit in such a scenario might increase the total greenhouse effect by another 10 percent but still results in low total emissions (Victor, 1990). One obstacle to the methane intensive scenarios is the possibility of inadequate natural gas resources. We presently have no conclusive evidence on how much oil and natural gas might be available to future generations. However, in all probability the resource base will increase with technological advances and improved theories of hydrocarbon formation.

CARBON-FREE ENERGY OPTIONS

A number of longer term options for introducing entirely carbon-free fuels based at least in part on fossil energy sources are also possible. These would involve the 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 contribution to meeting energy demand. For example, at present electricity supplies 30 percent of global final energy used. A number of schemes are possible in addition to electricity. Meyer Steinberg advocates 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 (Steinberg and Grohse, 1989). 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 the production of liquid synthetic fuels since of all the carbon based energy sources, coal is, and will continue to be, the most abundant.

Marchetti proposes 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 (Marchetti, 1989). This strategy of using natural gas with or without an external source of heat could become 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. Many variations of this basic process are being pursued. For example, an integrated gasifier combined cycle (IGCC) plant has the advantage that coal is converted to an intermediate synthesis gas (Hendriks *et al.*, 1991). 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 it is exploited on a sustainable basis.

Most biomass schemes are associated with low energy yield such as in the case with oxygenated fuels based on alcohols and bio oils. In contrast to natural gas, the economics of biomass are far from being demonstrated. Furthermore, production is limited and efficiency is low in energy terms. 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. 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 India, for example, more extensive and sustainable use of biomass is likely to be cost-effective and might help halt deforestation (TERI, 1991). In general, there are many opportunities for joint programs of land restoration and biomass production. Nevertheless, major innovations in biomass production and conversion to fuels are still required before it could become a more important source of energy at the world scale. Today the overall efficiency of converting solar energy into fuels via biomass is about one percent, implying that areas as large as the global agriculture would be required to generate global energy supply using current biomass technologies.

In the long run the only genuinely carbon free sources of energy available in potentially vast amounts are solar and nuclear fission and fusion. 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 their contributions to global CO_2 reduction is very limited. There is no doubt a wide-ranging consensus that their potential should be used to the economic maximum.

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. 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., extra-terrestrial facilities, like solar power satellites). In the long run, the photovoltaic systems hold the promise of substantial cost reductions and efficiency improvements. If conversion efficiencies in the range of 30 to 40 percent can be achieved, the photovoltaic farms would require about a tenth of the global agriculture area to provide all the energy at current global consumption levels. In view of the very long time constraints for the diffusion of new energy technologies and infrastructures, the solar options would take decades before making a significant contribution towards lowering CO_2 emissions.

The future of nuclear power will depend on safety and proliferation issues, namely, the technical and economic performance of the second generation of nuclear technologies and public perceptions of their safety. In some countries where nuclear prospects look bleak, in practice, as opposed to popular perception, usage is very wide. An example is the US where, despite the Three Mile Island accident and the strong anti-nuclear movement, 144 nuclear power plants are still in operation. However there have been no new orders in the US since, so the domestic market for new nuclear plants is practically dead. Additions to the capacity are decreasing worldwide.

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[5] be able to make a significant contribution to the reduction of greenhouse gases 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. In addition to safety, there are three other major concerns to acceptability of nuclear energy. Economics, because of the long regulatory 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 co-location of nuclear plants with industry and commercial areas. Even in decades to come, this will probably be unacceptable for safety reasons. Along these lines, the so-called "Adam and Eva" system has been studied in Germany. This system uses a high temperature reactor to reform methane into CO and hydrogen in a closed cycle which, 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 integrate 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 (Marchetti, 1989). Depending on future development, the introduction of solar thermal power could provide an alternative source of heat for reforming methane.

If one goes into schemes for the distant future, also promising from the point of reducing greenhouse gas emissions are the 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.

The concept of novel integrated energy systems (IES) generalizes this idea of flexible conversion of a number of primary energy sources into different energy carriers while reducing emissions of carbon dioxide and other gases (Häfele and Nakićenović, 1984). Figure 17 illustrates schematically the IES concept. The basic idea is to decompose and purify the fossil energy inputs before combustion, to in-

5 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. 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.

tegrate these decomposed (clean) products and to allocate them stoichiometrically to produce required energy carriers. These systems could rely on solar and nuclear energy to provide the process heat. The resulting fuels would either have low carbon dioxide emissions or as in the case of electricity and hydrogen they would have none.

CARBON SCRUBBING AND REMOVAL

Since carbon-free energy sources, such as nuclear and solar, are future technologies that may take decades before they make larger contributions to energy supply, carbon scrubbing and removal from energy carriers prior to combustion is a very important interim priority. In the long run, the IES concept offers possible options for carbon removal. Scrubbing is 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. 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 (Steinberg and Grohse, 1989). There are three different scrubbing technologies to remove CO_2 from flue gases: cryogenic distillation of CO_2 from flue gases, separation by membrane, and chemical absorption. Each of the alternatives proposed has some 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. The cost estimates of the various options range from \$25 to \$45 per ton of CO_2 removed (Hendriks *et al.*, 1991).

A few plants are in existence today that produce CO_2 for use as a raw material. Eliasson (1991) notes 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, on average 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.

The sequestered carbon could be used as raw material in the future, and there are already some commercial opportunities for its use. An example is the exhaustion of CO_2 in Colorado that is piped 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 for enhanced oil recovery in some of its depleted fields (Marchetti, 1989). 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.

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).

For example, storage of CO_2 in depleted natural gas reservoirs might be an option of choice for the Netherlands after the year 2000 (Hendriks *et al.*, 1990). In addition to deplete oil and gas fields, salt caverns are another viable possibility, 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. In fact the total amount of carbon dioxide in the atmosphere is about 160 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 deep ocean 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.

There are many types of uncertainties associated with ocean disposal. Perhaps most important are the possible ecological impacts of CO_2 dispersion. In sum, since little is known about diffusion rates, changes in deep ocean acidity and other ecological questions so that further research of this possible sink for anthropogenic sources of carbon is needed.

PHOTOSYNTHESIS AND AFFORESTATION

Biomass is often mentioned as a potentially practical way to bind carbon from the atmosphere and lead to minimal net emissions. In the context of removal strategies, photosynthesis by plants, algae or by synthetic methods are the only really viable technology for absorbing carbon from the atmosphere. In view of all the difficulties 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.

Unfortunately there are similar major hurdles to the use of afforestation to absorb excess CO_2 as there are in using biomas to lower carbon dioxide emissions. The total soil organic carbon in the world is estimated at 1500 Gt and total living biomass at 600 Gt (Esser and Overdieck, 1991). The net fixation is less than 50 percent of annual deposition in phytomass due to the loss of soil organic carbon. This leads to large area requirements. For example, devoting the entire agricultural area of Germany to reforestation would remove less than ten percent of German fossil energy emissions.

Marland (1988) estimated that an area of about five million square kilometers, corresponding to about a third of land used worldwide for agriculture (15 million square kilometers of arable land and permanent crops), would be required to sequester about five billion tons of carbon released through fossil fuel emissions. This estimate corresponds to current atmospheric carbon removal by tropical plantation (Brown *et al.*, 1986). Given these daunting figures and the unprecedented scale of required global management, it seems clear that there is no single solution to the CO_2 problem. However, afforestation can be successful on a limited scale and in many regions of the world.

There have also been a number of 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 are often practised far below theoretical calculations.

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.

Apart from afforestation, other alternatives for carbon reduction include application of innovative biotechnologies on land such as micro-organisms, the cultivation of green microalgae, cyanobacteria and hydrogen bacteria. At sea, there are also potential alternatives for carbon uptake by mean of phytoplankton, calcification or kelp. The most radical among the three was the proposal to remove atmospheric CO_2 using iron fertilizer to stimulate growth of algal blooms in the Antarctic (Martin *et al.*, 1990). 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 create major disturbances in the marine food chain and prove worse than now anticipated by the proponents.

INVENTORY OF MITIGATION TECHNOLOGIES

Further social and economic development in the world will lead to increases in global energy consumption. This strongly suggests that in the absence of appropriate countermeasures global emissions of greenhouse gases will continue to increase well into the 21st century, perhaps beyond environmentally acceptable levels. Thus, it might be prudent to reduce the sources of greenhouse gases to the greatest extent possible and at the same time to increase the natural sinks of carbon dioxide and create new ones for storage of carbon removed from fossil fuels. It will make a big difference whether in the future paths of energy efficient economic development will be followed that rely on carbon-poor sources and carriers of energy or whether less energy efficient and coal intensive ones continue to predominate in the world. Also, there are other important problems facing humanity so that the limited resources available for investment and consumption have to be distributed. A comparative assessment of different strategies for mitigating and adapting to possible global warming is therefore required.

Such an evaluation constitutes the main part of an ongoing study within the area of energy and the environment at IIASA. This activity includes development of an integrated data base for a comprehensive inventory of technological options available globally over long time horizons. The data base includes descriptions of their comparative characteristics, important linkages to other enabling technologies, development status and availability, their timing and implementation prospects, applicability in different geographical, economic and cultural settings, transfer to developing countries, cost structure, technical performance, and market potential. It will be used to produce an inventory 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.

The data base includes detailed descriptions of the technical, economic, and environmental performance of technologies as well as data pertinent to their innovation, commercialization, and diffusion characteristics and prospects. Additional data files contain literature sources and assessments of data validity and concurrent uncertainty ranges. It is an interactive software package designed to enter, update, and retrieve information on CO_2 reduction and removal technologies (Messner and Strubegger, 1991).

The data base can facilitate the assessment of CO_2 reduction strategies by combining many individual technologies together, i.e., to analyze measures throughout the energy chain from primary energy extraction to improvements in energy end-use efficiencies. Figures 18 and 19 give two applications of the inventory of mitigation technologies to assess overall carbon dioxide emissions of different transportation systems. They illustrate that substantial carbon dioxide reduction potentials exist both for passenger vehicles and aircraft by a shift to alternative fuels. The specific carbon emissions include both the direct releases from the vehicles themselves and all the emissions that result from the rest of the energy supply system such as conversion of primary energy into fuels, transport of fuels and distribution to end-use. A shift to hydrogen or electricity in passenger cars would not only reduce the overall emissions but would also move the bulk of them from vehicles to conversion facilities when the removal and storage of carbon are possible and perhaps even cost-effective. Such a comparative assessment of different options and measures for reducing and removing emissions might identify future technological systems and development paths with low specific energy requirements and adverse environmental impacts. Progress has also been achieved in improving efficiency and in decarbonizing economies, as illustrated in Figure 20. All countries shown have achieved improvements in both domains. The overall objective of this research area at IIASA is to assess the conditions that would direct the future development trajectories toward further decarbonization and energy disintensification in the world.

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Table 1. Different indicators for relative contributions of less developed and more developed countries in global carbon dioxide emissions (see Subak and Clark, 1990). The contributions are expressed relative to the world average. The last row gives the ratio of more to less developed countries. It illustrates that industrialized countries are mostly responsible for increase of both current and cumulative emissions.

Total CO_2 Emissions Relative to World Average by Different Criteria

	Current Average (1980–1986)			Historical Cumulative (1860–1986)			Share in Concentration (percent)
Region	Country	Capita	Land	Country	Capita	Land	
MDCs	2.39	3.68	1.37	2.92	3.18	1.65	
LDCs	0.54	0.52	0.78	0.36	0.35	0.49	15.9
Ratio	4.4	7.0	1.8	8.1	9.1	3.4	5.3

Table 2. Current carbon dioxide emissions for different world regions are compared for alternative emission allocation schemes for the year 2050. Global carbon dioxide emissions are assumed to be reduced to 4 Gt of carbon by the year 2050 roughly corresponding to the IPCC Accelerated Policy Scenario. They illustrate possible distributional changes among regions if the allocations are based on an equal (across-the-board) percentage cut, proportional to past contributions or in equal emission rights per capita.

DIFFERENT ALLOCATION CRITERIA FOR
CO_2 REDUCTION STRATEGIES
(to 4 Gt C by 2050)
Fossil Fuel and Industry CO_2, Gt C

		1988 Emissions	Equal Percent Cuts		Cutbacks Proportional to Past Contribution	Equal Emission Rights Per Capita (by 2050)
			1988 Base	1980 Base		
1	OECD NA	1.43	1.01	1.09	0.88	0.13
2	OECD EU	0.85	0.60	0.76	0.41	0.16
3	Eastern EU	0.36	0.25	0.27	0.27	0.06
4	USSR	1.09	0.77	0.71	0.85	0.15
5	Japan	0.27	0.19	0.20	0.21	0.05
6	Oceania	0.07	0.05	0.05	0.05	0.01
7	China	0.61	0.43	0.32	0.52	0.69
8	India	0.17	0.12	0.08	0.14	0.64
9	Other Asia	0.16	0.11	0.09	0.13	0.70
10	NAME*	0.24	0.17	0.14	0.21	0.37
11	Other Africa	0.12	0.09	0.08	0.10	0.70
12	Brazil	0.06	0.04	0.04	0.05	0.11
13	Other LatAm	0.24	0.17	0.17	0.18	0.24
	"North" (1–6)	4.07	2.87	3.08	2.67	0.56
	"South" (7–13)	1.60	1.13	0.92	1.33	3.44
	World	5.66	4.00	4.00	4.00	4.00

*North Africa and Middle East

Table 3. Current per capita carbon dioxide emissions for different world regions are compared for alternative emission allocation schemes for the year 2050. Global carbon dioxide emissions are assumed to be reduced to 4 Gt of carbon by the year 2050 roughly corresponding to the IPCC Accelerated Policy Scenario. They illustrate possible distributional changes among regions if the allocations are based on an equal (across-the-board) percentage cut, proportional to past contributions or in equal emission rights per capita.

DIFFERENT ALLOCATION CRITERIA FOR
CO_2 REDUCTION STRATEGIES
(to 4 Gt C by 2050)
Per Capita **Fossil Fuel and Industry CO_2,** *tons C/capita*

		1988 Emissions	Equal Percent Cuts		Cutbacks Proportional to Past Contribution	Equal Emission Rights Per Capita (by 2050)
			1988 Base	1980 Base		
1	OECD NA	5.28	3.26	3.37	2.83	0.42
2	OECD EU	2.22	1.61	1.96	1.11	0.42
3	Eastern EU	3.17	1.91	1.97	2.02	0.42
4	USSR	3.83	2.11	1.87	2.34	0.42
5	Japan	2.20	1.51	1.53	1.64	0.42
6	Oceania	3.69	2.10	1.88	2.23	0.42
7	China	0.56	0.26	0.19	0.32	0.42
8	India	0.21	0.08	0.05	0.09	0.42
9	Other Asia	0.21	0.07	0.05	0.08	0.42
10	NAME*	0.73	0.19	0.16	0.23	0.42
11	Other Africa	0.25	0.05	0.05	0.06	0.42
12	Brazil	0.41	0.16	0.15	0.18	0.42
13	Other LatAm	0.84	0.30	0.29	0.32	0.42
	"North" (1–6)	3.41	2.16	2.22	2.01	0.42
	"South" (7–13)	0.41	0.14	0.11	0.16	0.42
	World	1.11	0.42	0.40	0.42	0.42

*North Africa and Middle East

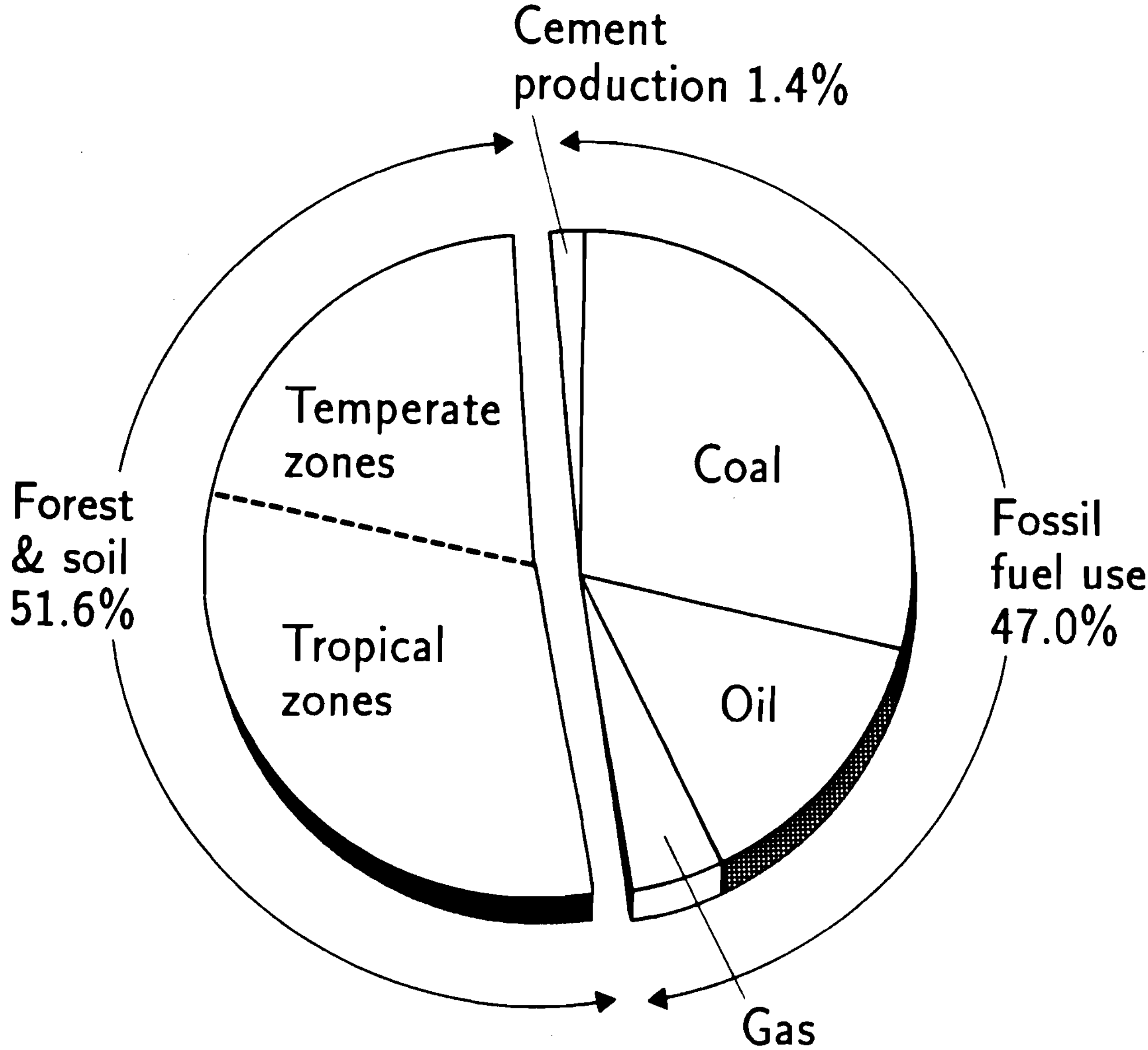


Figure 1. Contribution to the increase in atmospheric CO_2 concentration since 1800 by carbon sources (in percent). The division of forest and soil carbon emissions by latitude zones is approximate and affected by uncertainties associated with the global carbon cycle. Fossil energy consumption contributes about a half of all anthropogenic sources of CO_2. The largest single source of carbon emissions from fossil energy is coal followed by oil and then natural gas.

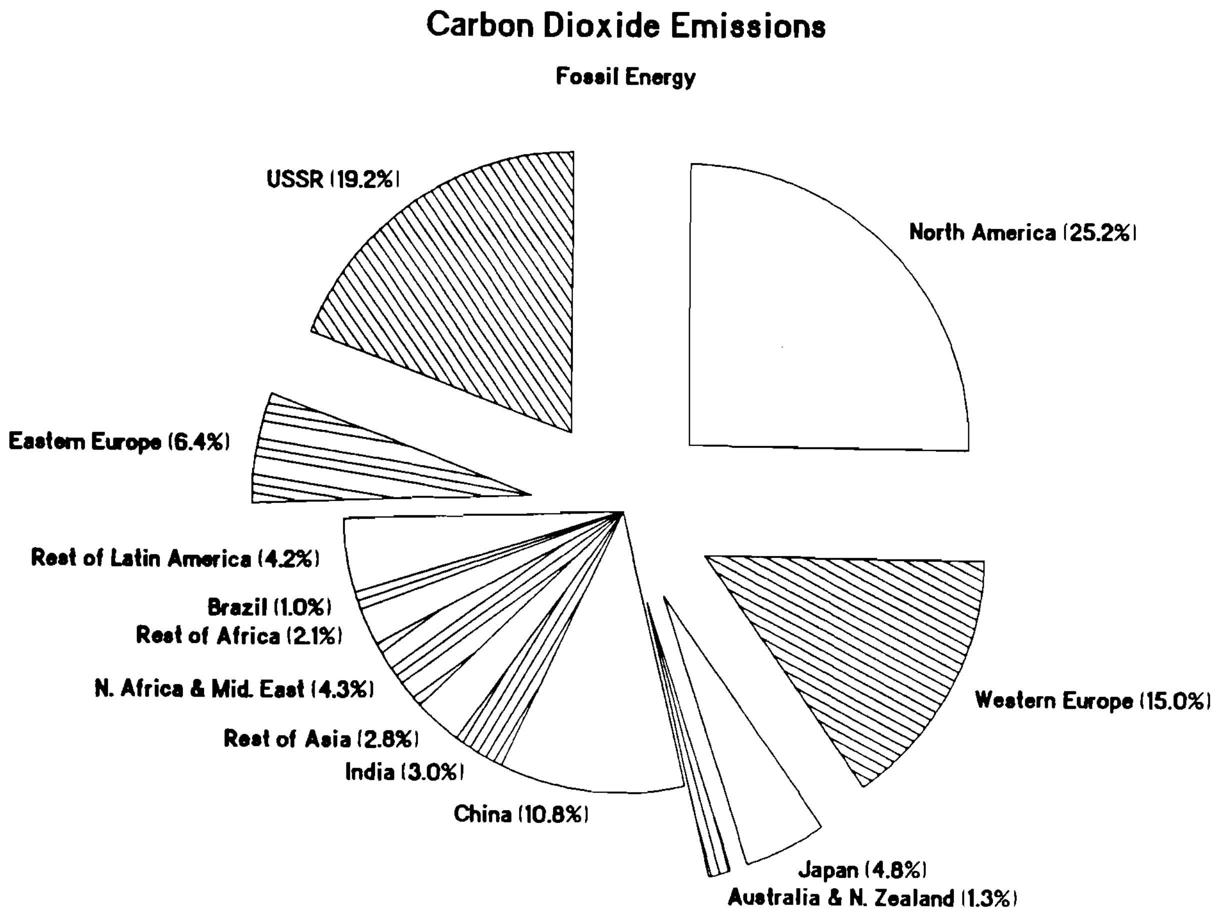


Figure 2. Share of different world regions in 1988 fossil energy CO_2 emissions (in percent). With only a quarter of global population more developed countries account for two-thirds of CO_2 emissions from fossil energy.

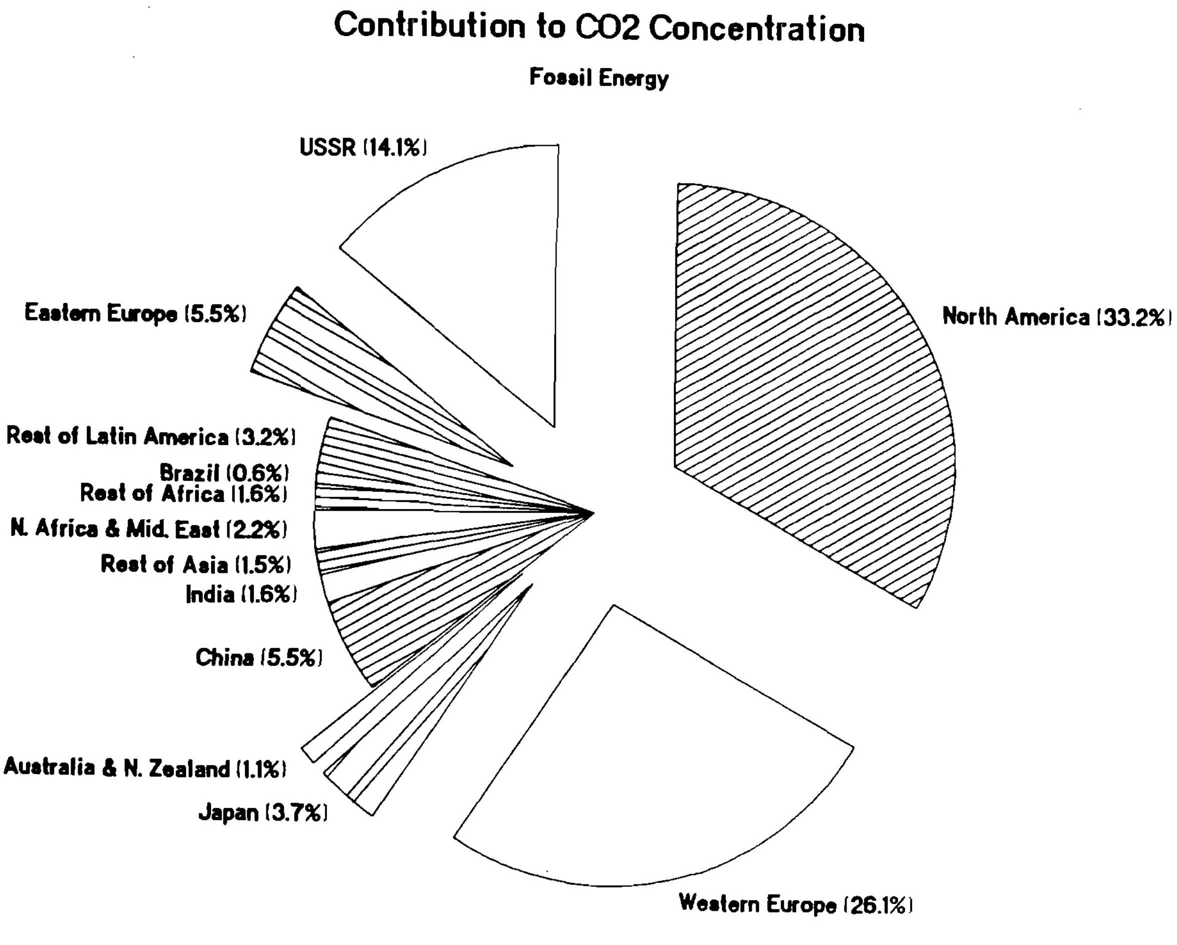


Figure 3. Share of different world regions in the historical increase of atmospheric CO_2 concentration due to fossil energy consumption since 1800 (in percent). It shows that developing countries are responsible for less than 16 percent of CO_2 concentration from past consumption of fossil energy.

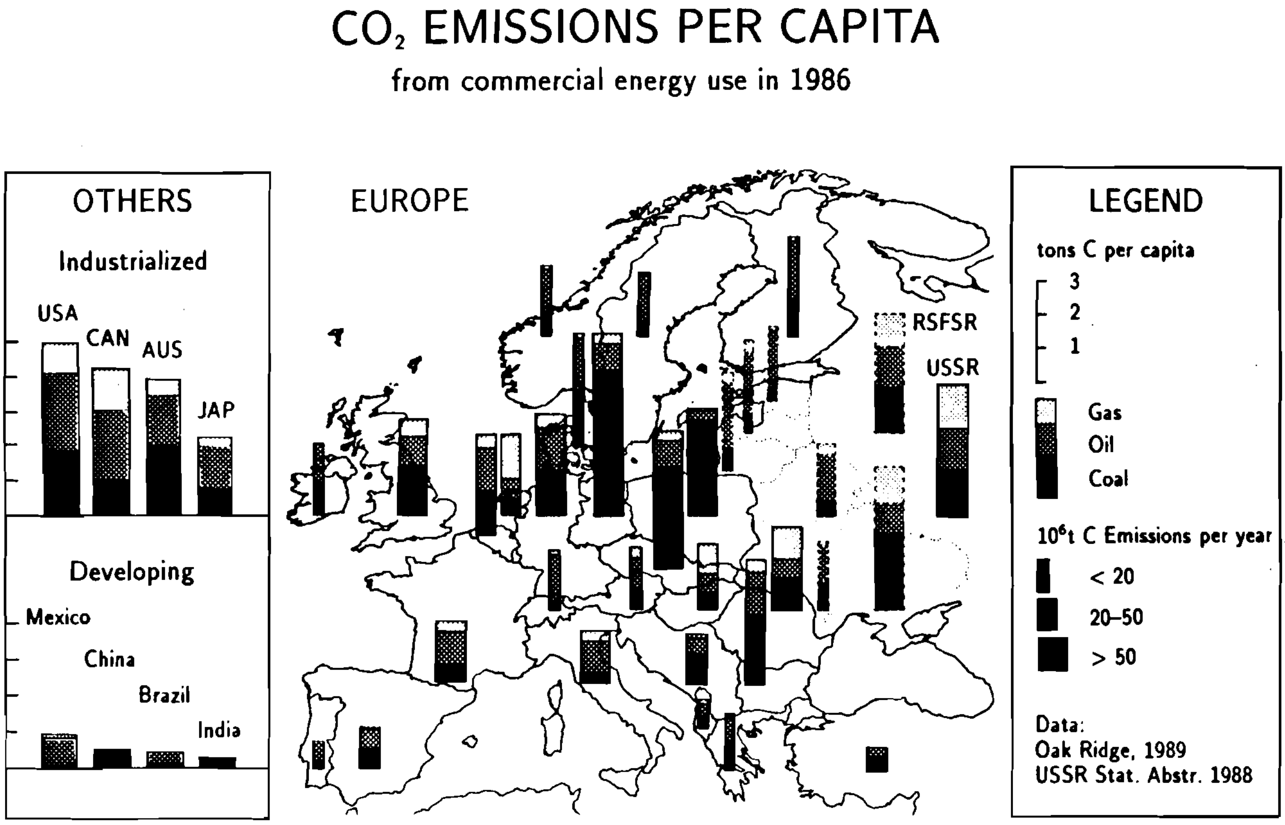


Figure 4. Per capita CO_2 emissions from commercial energy use, by source and for selected countries (in tons carbon per year per capita). A graphical representation of per capita carbon emissions from energy use reveals extreme disparities and heterogeneity. These are the result of differences in the degree of economic development, level and efficiency of energy consumption and the structure of the energy supply system (i.e., its carbon intensity). The figure illustrates 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 US 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 US 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.

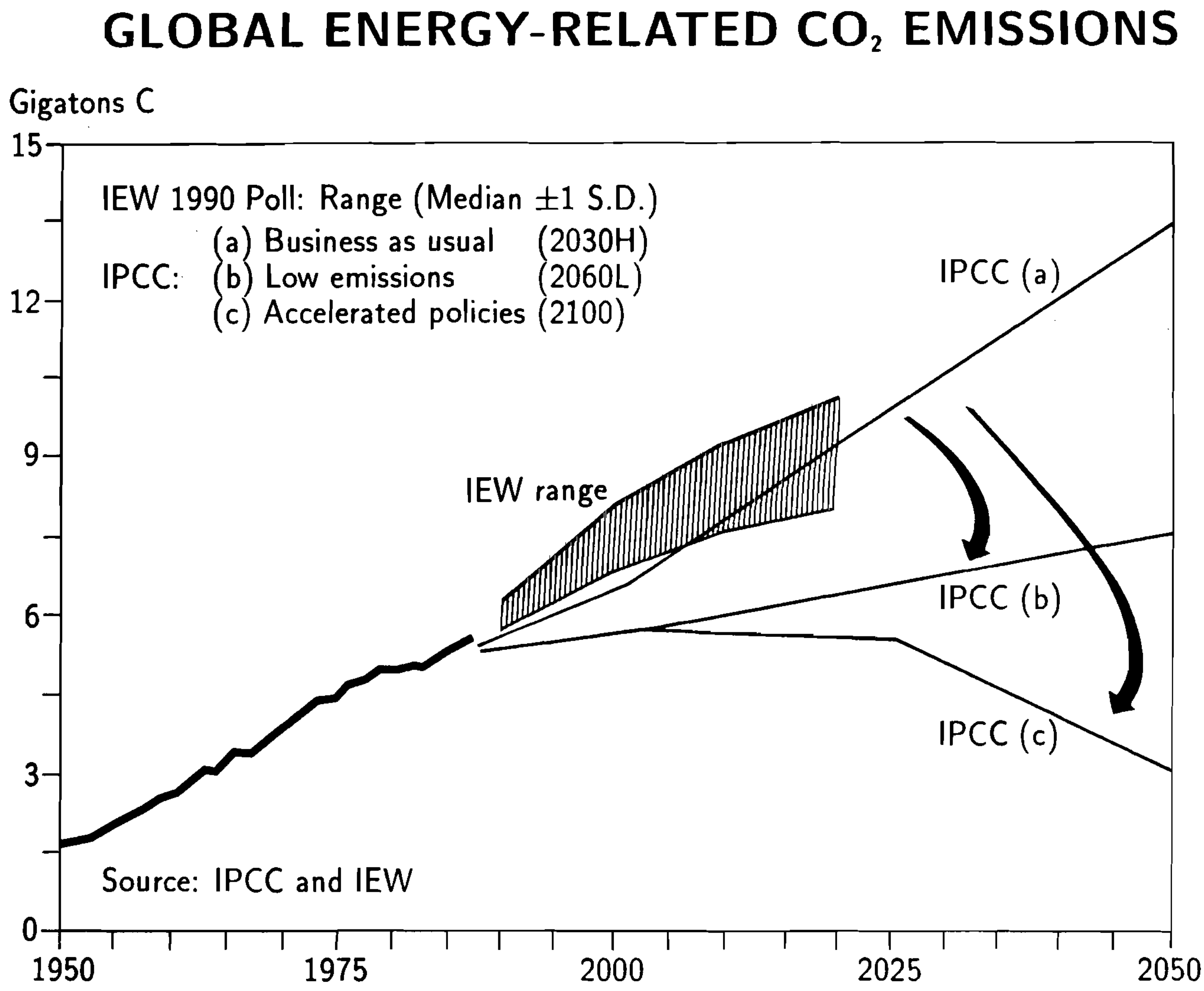


Figure 5. Historical and future global energy-related CO_2 emissions. From 1950 to present emissions have increased on average at about two percent per year. Possible future global energy-related CO_2 emissions are indicated by International Energy Workshop (IEW) poll-response range and by three Intergovernmental Panel on Climate Change (IPCC) scenarios. IEW is jointly organized by Stanford University and IIASA with the aim to compare energy projections made by different groups in the world and to analyze their differences.

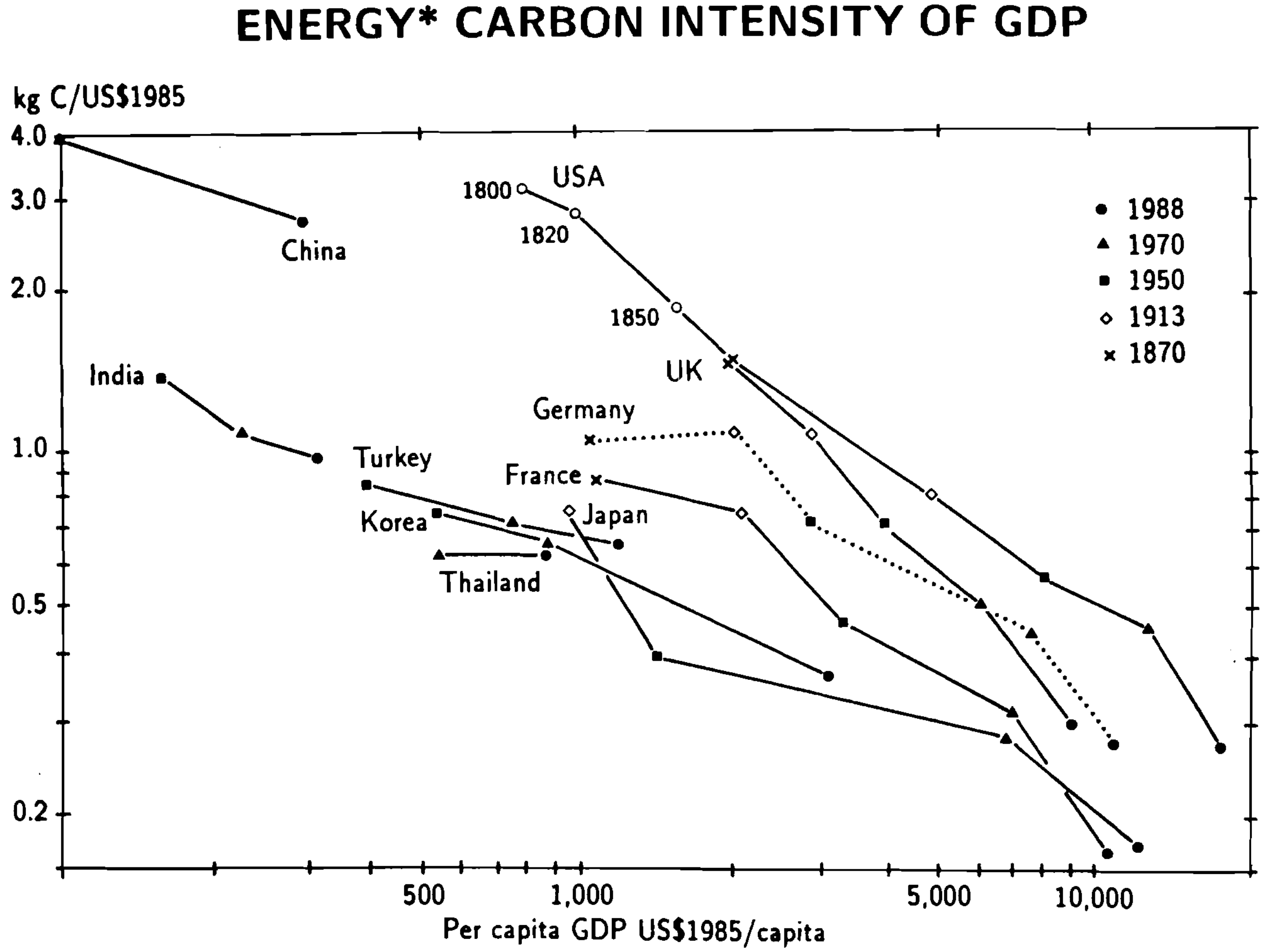


Figure 6. Energy CO_2 emissions intensity per constant GDP, in kg per constant 1985 US$ versus per capita GDP in constant 1985 US$. Energy data include also non-commercial sources such as fuelwood. In general, carbon intensity of economic activities improves as a function of an increasing level of economic development but there remain large differences between countries for similar per capita GDP levels. It shows that developed countries had higher specific emissions per unit GDP during early development phases that are comparable to current emission intensities of GDP in developing countries.

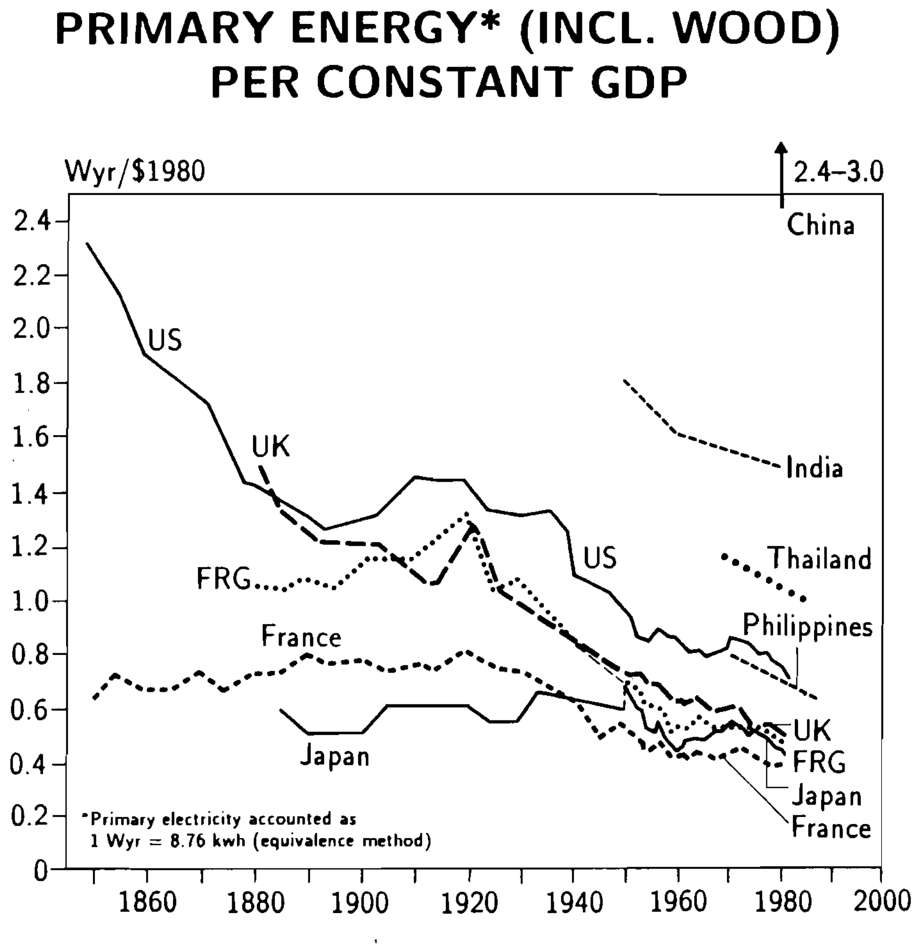


Figure 7. Primary energy intensity (including biomass energy) per constant GDP (Wyr/yr constant [1980] US$). Historically, energy intensity declined at an average rate of one percent per year. This means that a dollar GDP is produced today with only one-fifth of the primary energy consumption some 200 years ago. Since the early 1970s energy intensity has improved at rates of two to three percent annually. Also visible from Figure 6 are distinct differences in the industrialization paths between various countries. The actual performance of an economy in terms of its energy consumption per unit of value added is thus path--dependent. Present intensities, as well as future improvement potentials are deeply rooted in the past, in the particular industrialization path followed, the settlement patterns that developed, consumption habits of the population, etc. The fact that the US consumes about twice as much energy per US$ GDP 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.

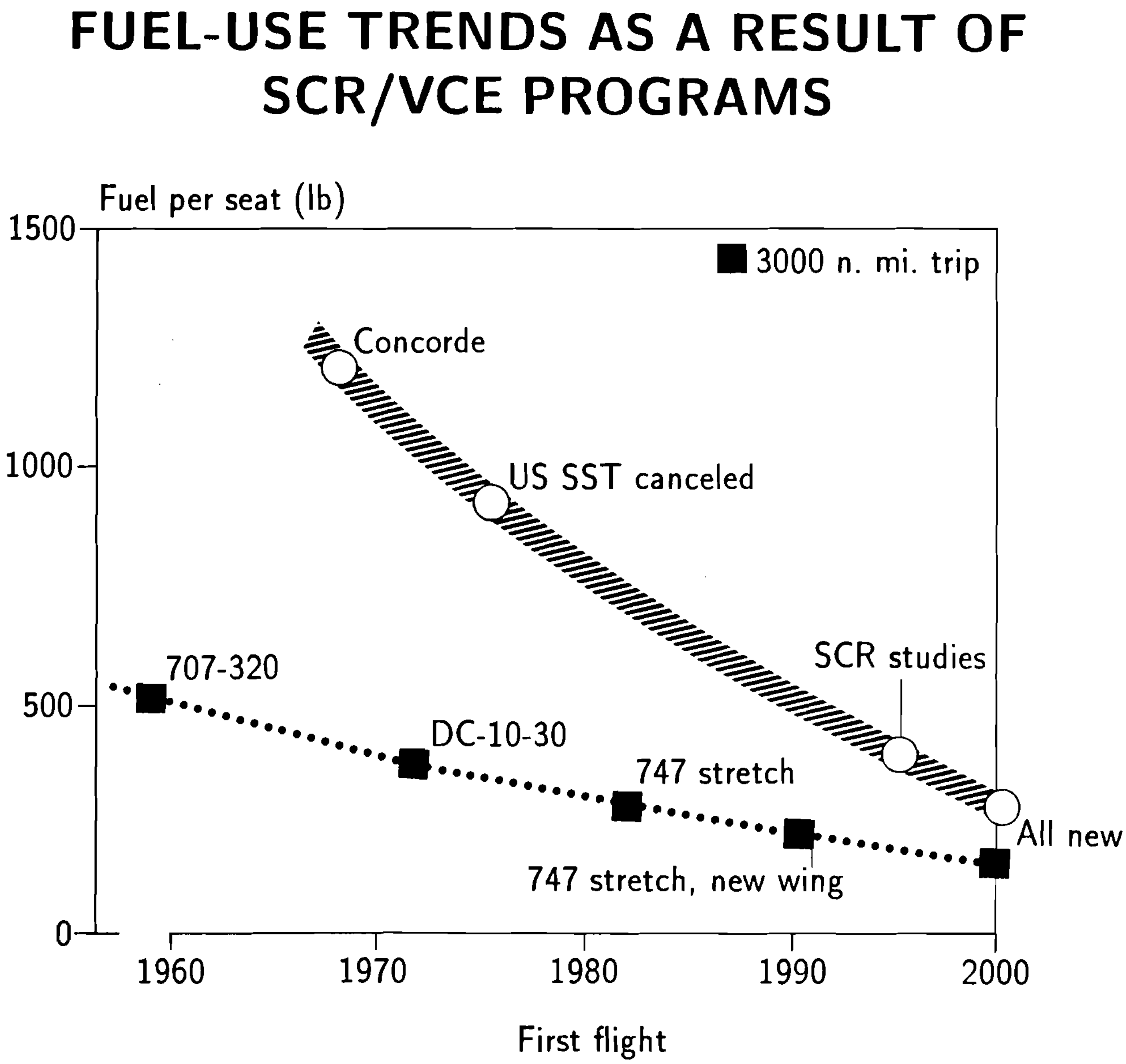


Figure 8. Aircraft fuel efficiencies for 3000 nautical miles trips in pounds (lbs) of fuel per seat (McLean, 1985). Improvements in energy efficiency in the aircraft industry have been particularly dramatic. Improvement rates of three to four percent annually over the last 20 years have been achieved, which means that the same transportation service can be provided now with as little as 40 percent of the energy requirements some 20 years ago (Nakićenović *et al.*, 1990). There are also counter-balancing trends, e.g., the introduction of new high-speed aircraft such as supersonic or hypersonic air transports. For these new technologies the specific energy requirements are significantly higher than for older aircraft but the loss in fuel efficiency is compensated for by time savings.

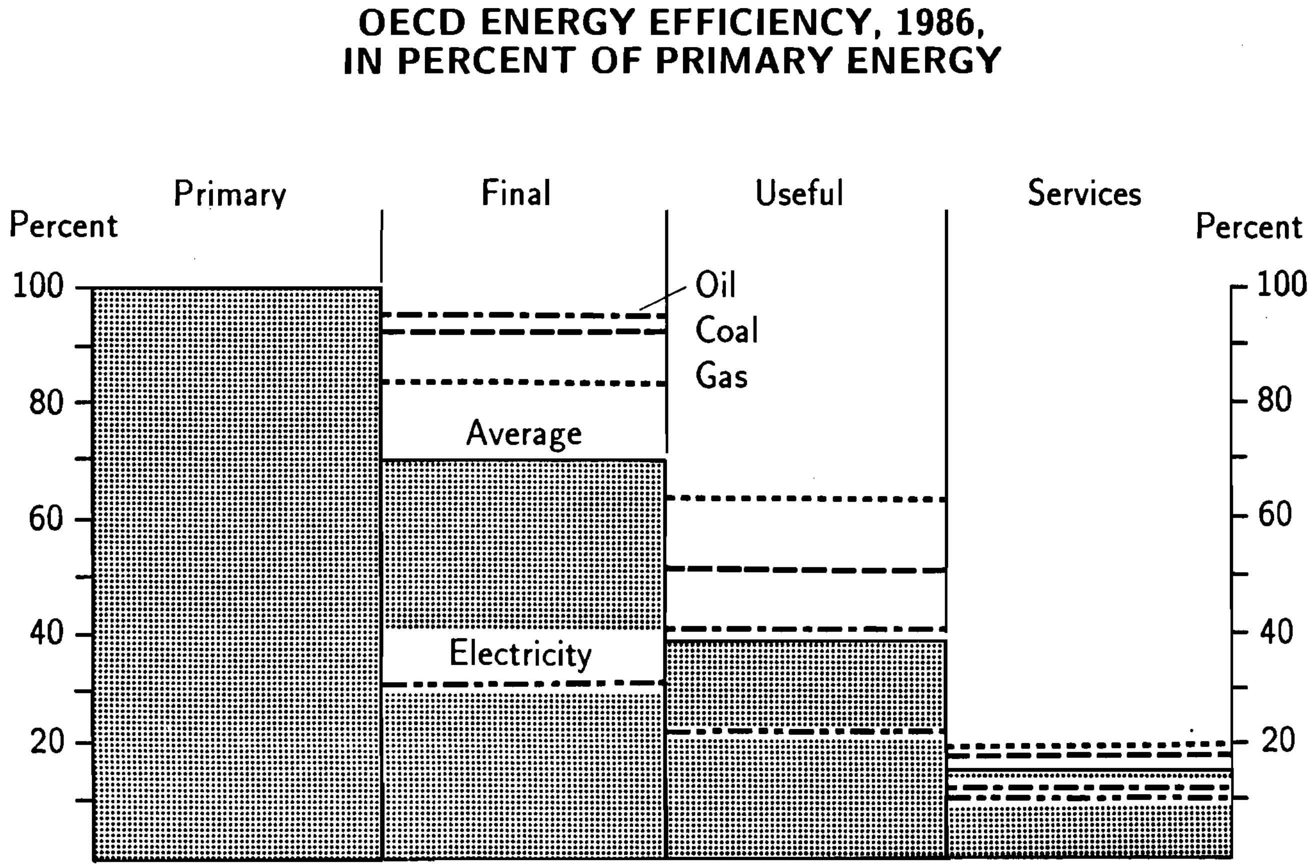
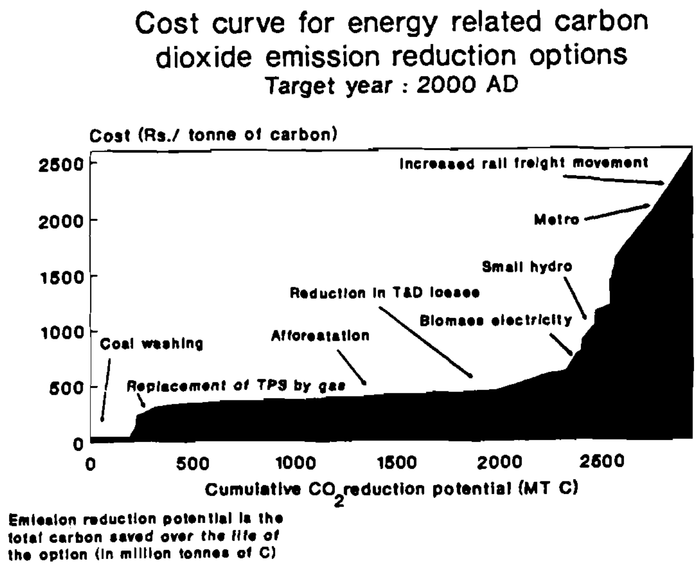


Figure 9. Exergy balances for the OECD countries in 1986 (in percent of primary exergy). A second-law analysis of the exergetic efficiency of the exergy (and energy) system in the OECD countries shows that while the efficiency in the provision of final exergy is already quite high, efficiencies at the 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 to only 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 cost and timing involved need detailed study.



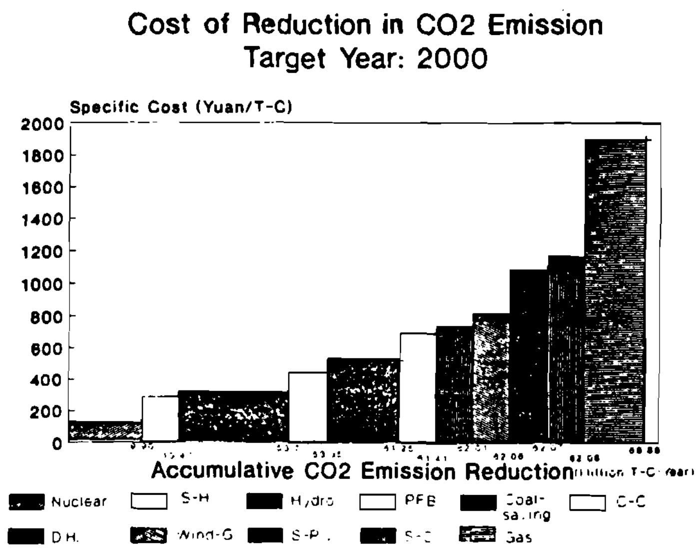


Figure 10. Cost curve for reduction of energy-related CO_2 emissions in India (TERI, 1991) in rupees (Rs) per ton of carbon (top) and China (Institute of Nuclear Energy Technology, 1991) in yuan per ton of carbon (bottom). Individual emission-reduction options are identified by arrows and as a step function, respectively. The curve illustrates the costs of lowering CO_2 emissions in India by the year 2000 as compared to a base case without mitigating measures. A number of very cost-effective options exist, particularly in the area of sustainable exploitation of biomass. However, capital shortages remain the most serious bottleneck for CO_2 avoidance measures in developing countries. In China the nuclear option appears to be most cost-effective followed by solar heaters and hydropower.

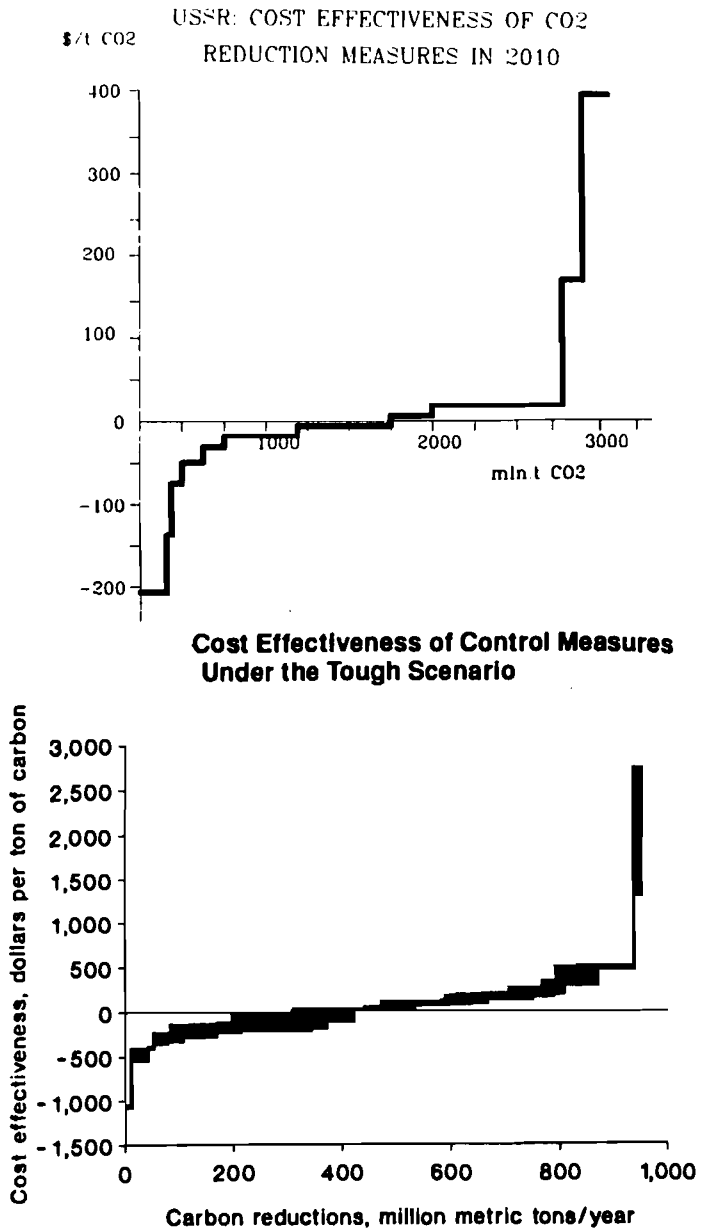


Figure 11. CO_2 emission reduction and avoidance costs estimates for the USSR (Sinyak, 1991) (top) and the US (OTA, 1990) (bottom). Emission-reduction costs are compared to a base-case scenario without any reduction measures. The time frames for the reference scenario are the year 2000 for the USSR and the year 2015 for the US. Negative mitigation costs indicate savings realized by energy-conservation measures compared to capacity expansion. Emission-reduction costs in the US refer to a reduction scenario with 0.9 Gt of carbon emissions in 2015 as compared to a business-as-usual scenario with 1.9 Gt of carbon emissions in 2015. Fuel savings are not included in the cost figures. Between one-third to one-half of the reductions in emissions between the two US scenarios either save money or are of very low costs.

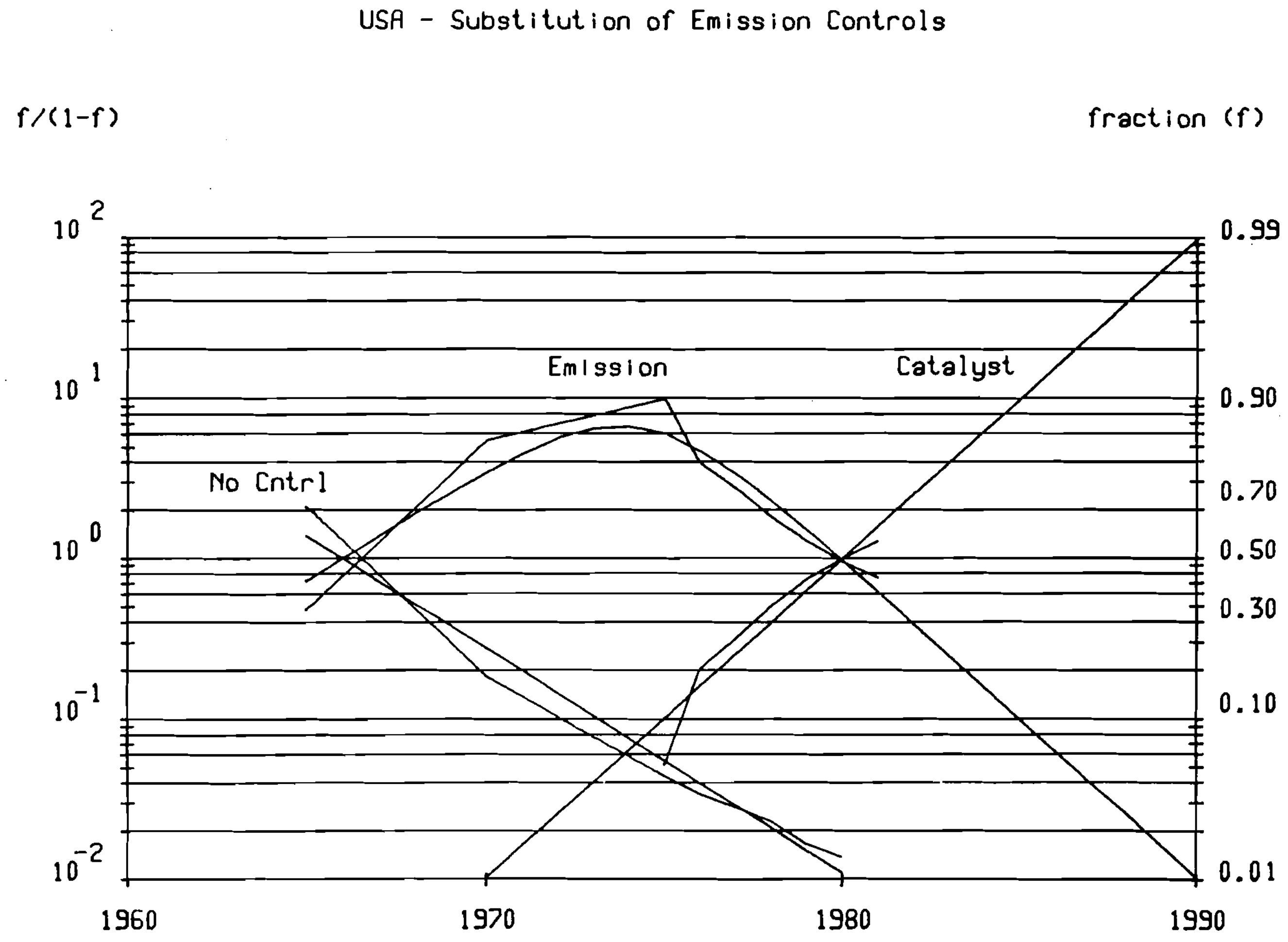


Figure 12. Substitution of automobiles with a catalytic converter and emission controls for older vehicles without any emission restraints in the US. The shares of each of three classes of vehicles are given in percent of the total fleet. The replacement of older vehicles by new types lasted about two decades in both cases. Similar duration of automobile fleet replacements can be also observed for other countries.

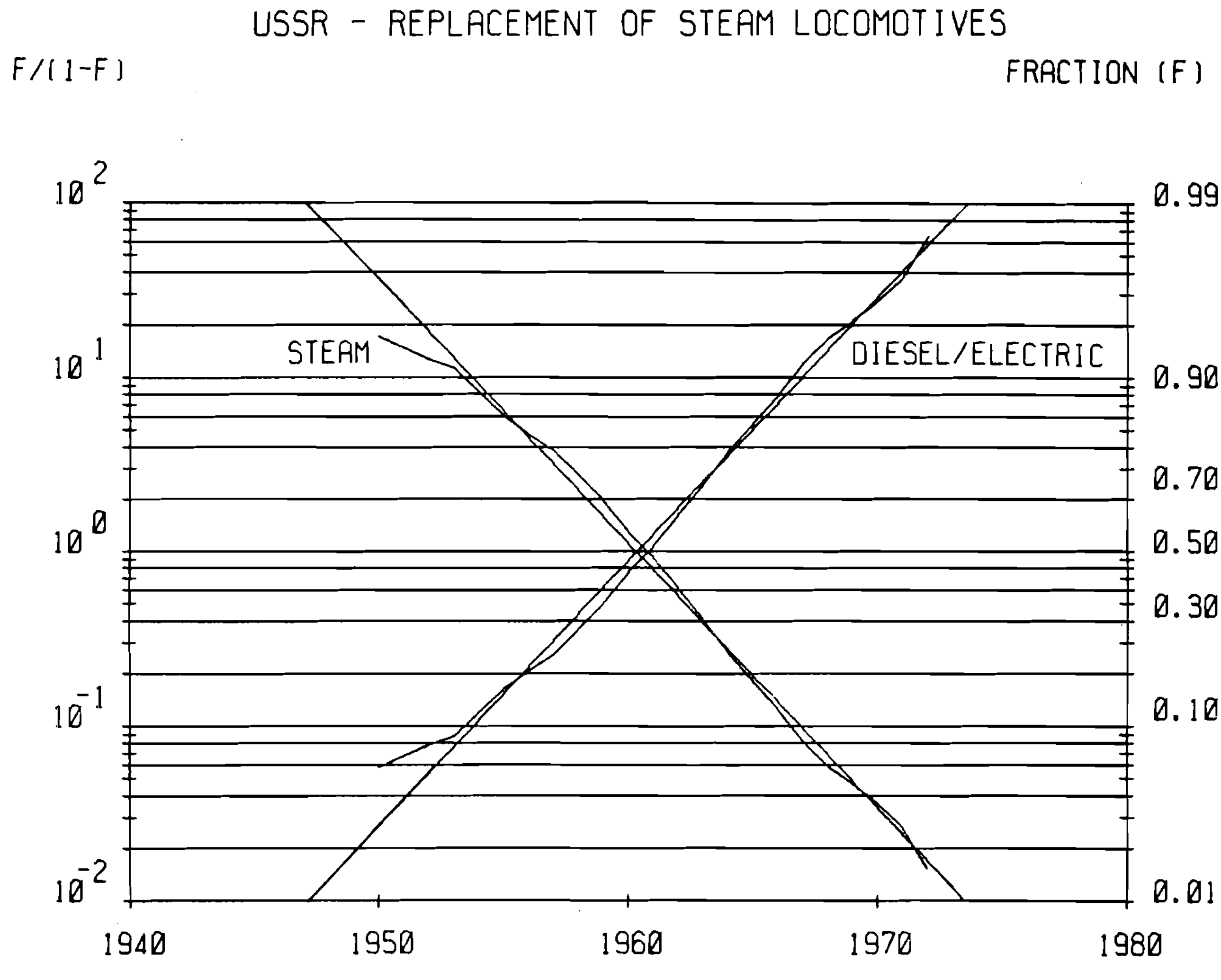


Figure 13. Substitution of steam by diesel and electric locomotives in the USSR. The shares of the two classes of locomotives are given in percent of the total number of locomotives in use. The replacement process lasted about two decades. Similar duration for replacement of the rolling stock and locomotives can also be observed for other countries.

Age distribution of capital stock for USSR and FRG

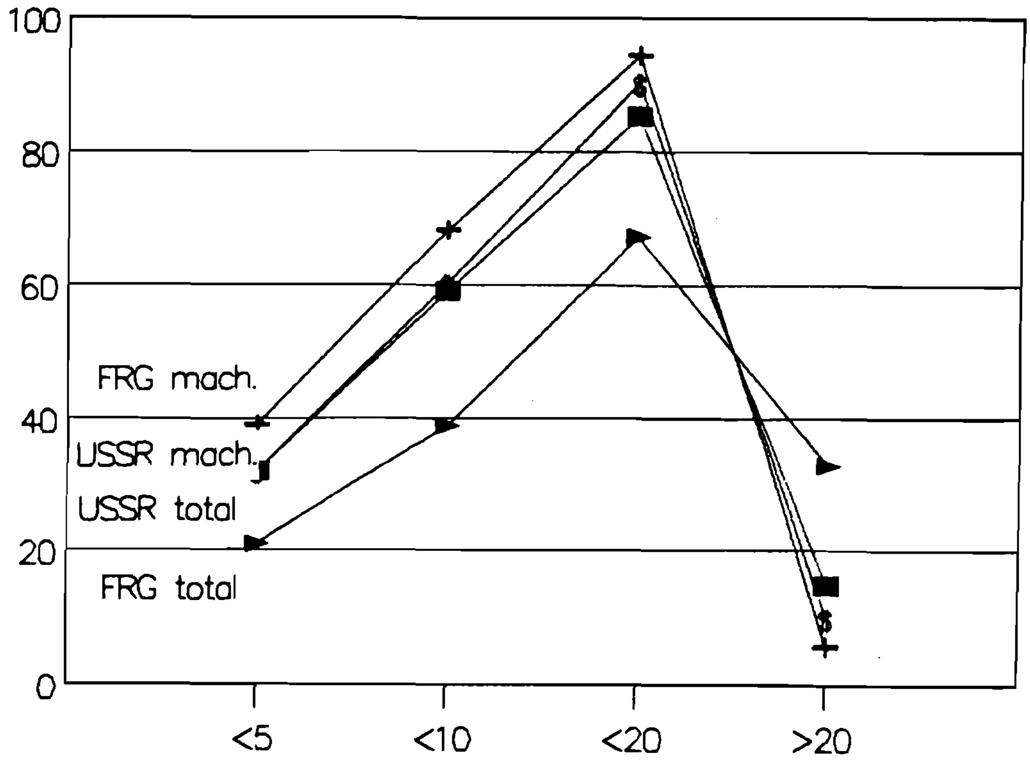


Figure 14. Age distribution of capital stock for USSR and FRG. It gives different vintage categories in percent of total capital stock and that of the manufacturing sector. The vintage structure is similar in the two countries. About 80 percent of the capital stock is newer than two decades. The other 20 percent is of older age. Given the same dynamics, the majority of the capital stock in the industrialized countries is in principle replaceable during the next decades.

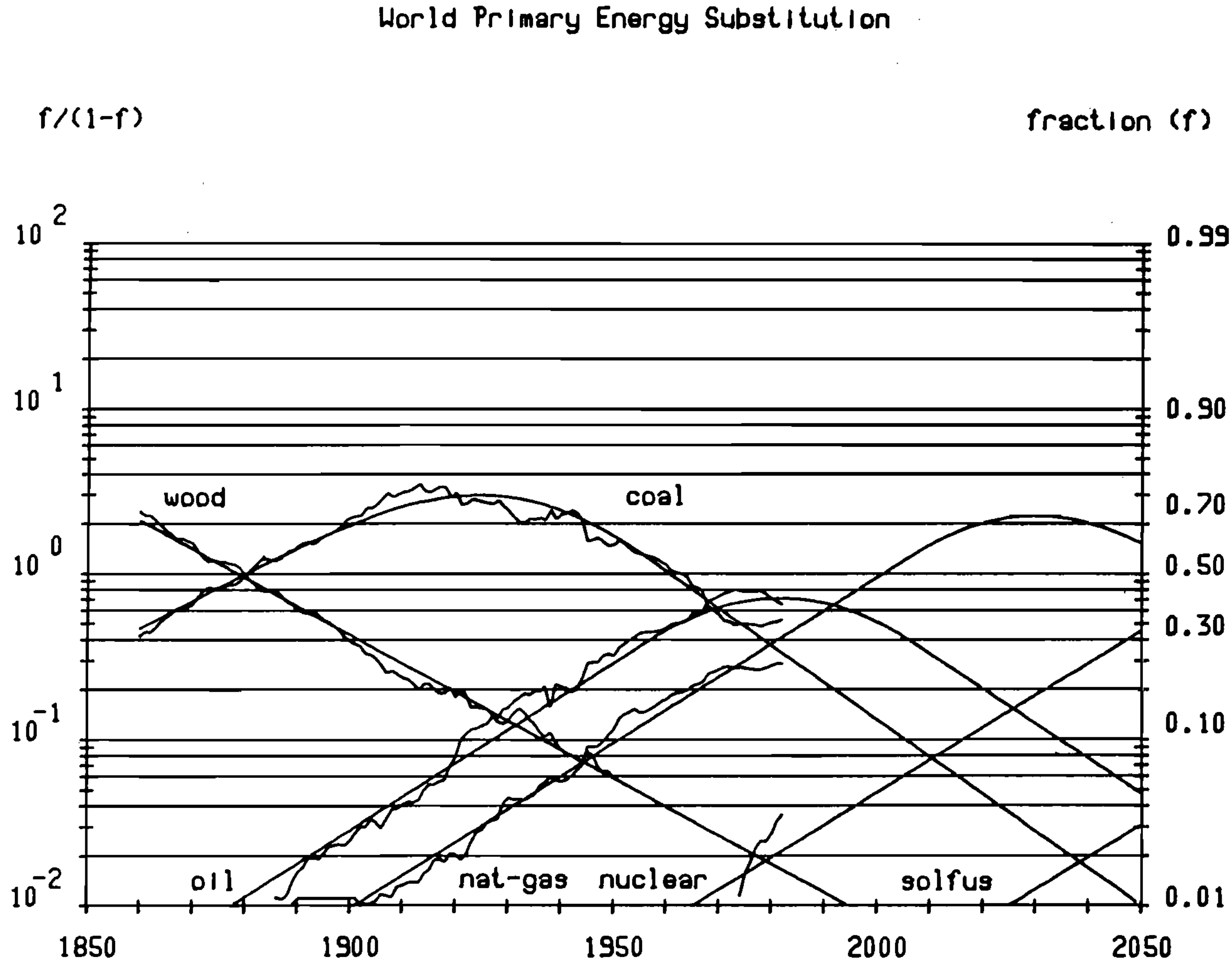


Figure 15. World primary energy substitution. Shares of primary energy sources in global consumption. Smooth lines represent model calculations, and jagged lines are historical data. "Solfus" is a term employed to describe a major new energy technology, for example solar or fusion (Marchetti and Nakićenović, 1979; Nakićenović, 1990). It shows that the diffusion of new sources of energy is a very long process lasting many decades. Replacement of other infrastructures, such as that of transport systems is also a long process.

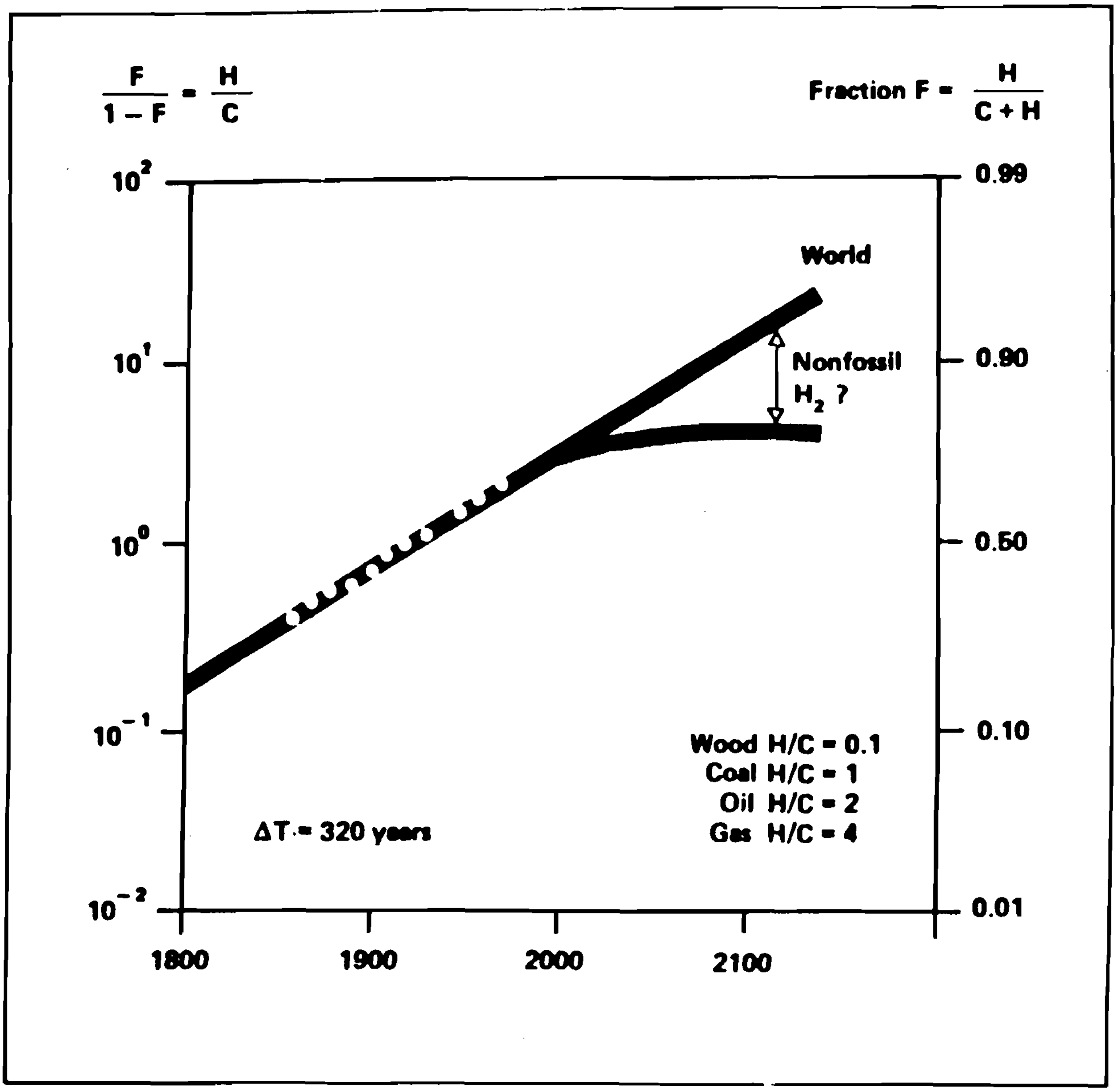


Figure 16. Evolution of the ratio of hydrogen (H) to carbon (C) in the world fuel mix. The figure for wood refers to dry wood suitable for energy generation. If the progression is to continue beyond methane, production of hydrogen fuel without fossil energy or with carbon removal is required (Marchetti, 1985).

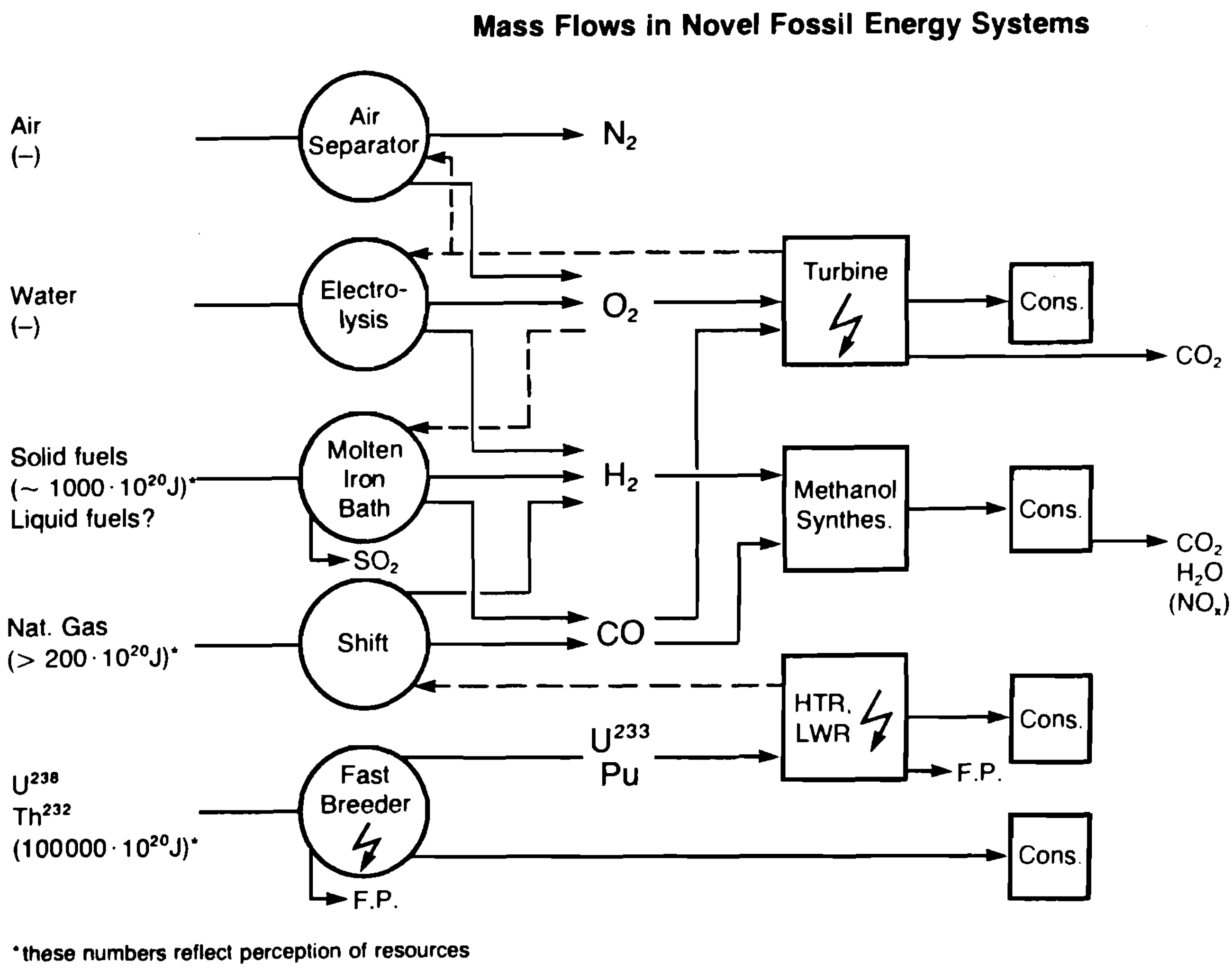


Figure 17. Schematic illustration of the novel integrated energy system (IES) concept that utilizes fossil fuels but allows for separation and removal of resulting emissions. The basic idea is to decompose and purify the fossil fuels before combustion, to integrate these decomposed (clean) products and allocate them stoichiometrically to produce required energy carrier. Resulting CO_2 can be collected and removed into a permanent storage.

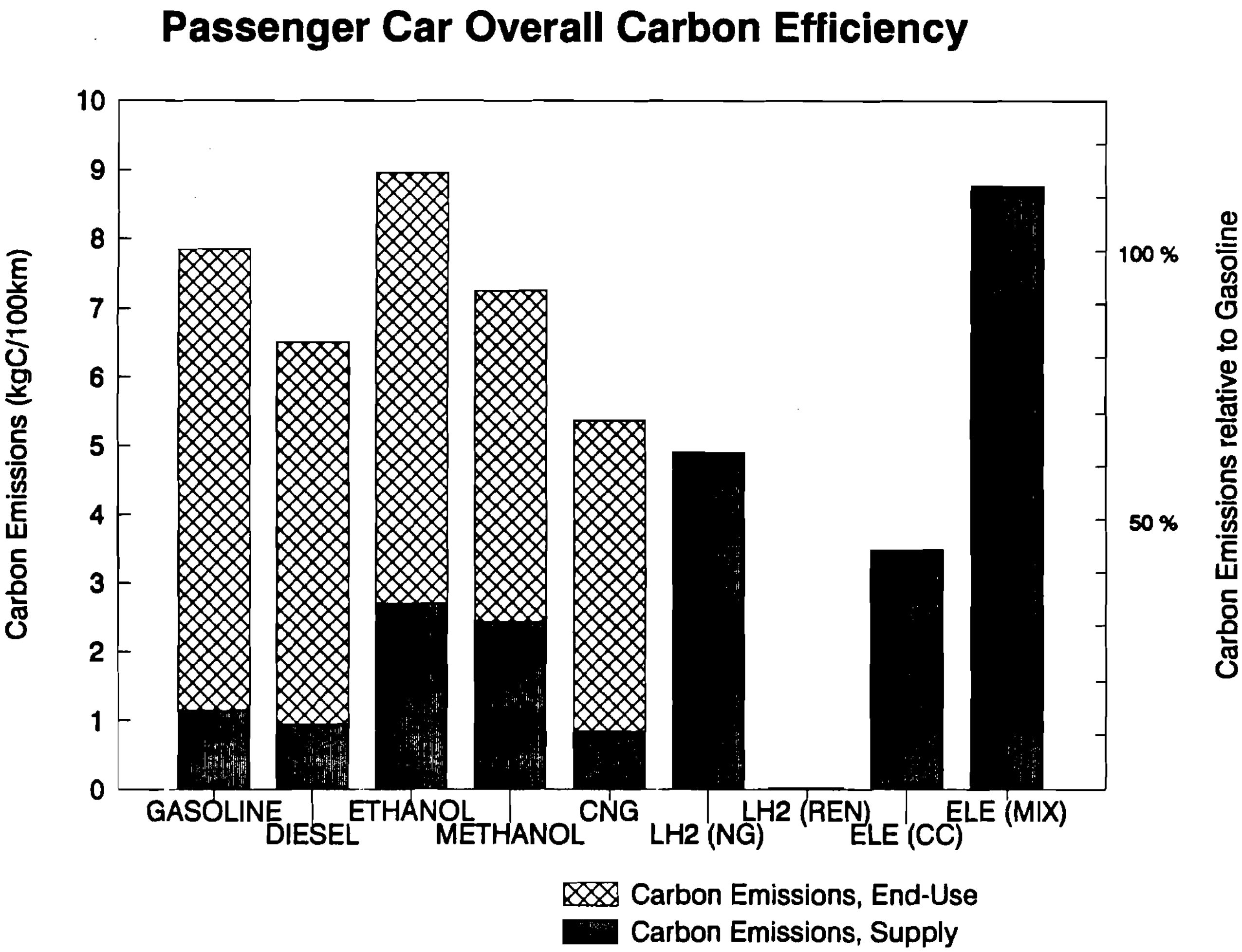


Figure 18. Carbon emissions for different transportation fuels. Gasoline, diesel, CNG: compressed natural gas, ethanol is assumed to be produced from sugarcane, methanol and hydrogen derived from natural gas (SR-NG: autothermal steam reforming of natural gas), LH2 (REN): liquid hydrogen from renewables, ELE (CC): electric vehicle with electricity from a natural gas fired combined cycle power plant and ELE (MIX) from an average power plant with the current US fuel mix.

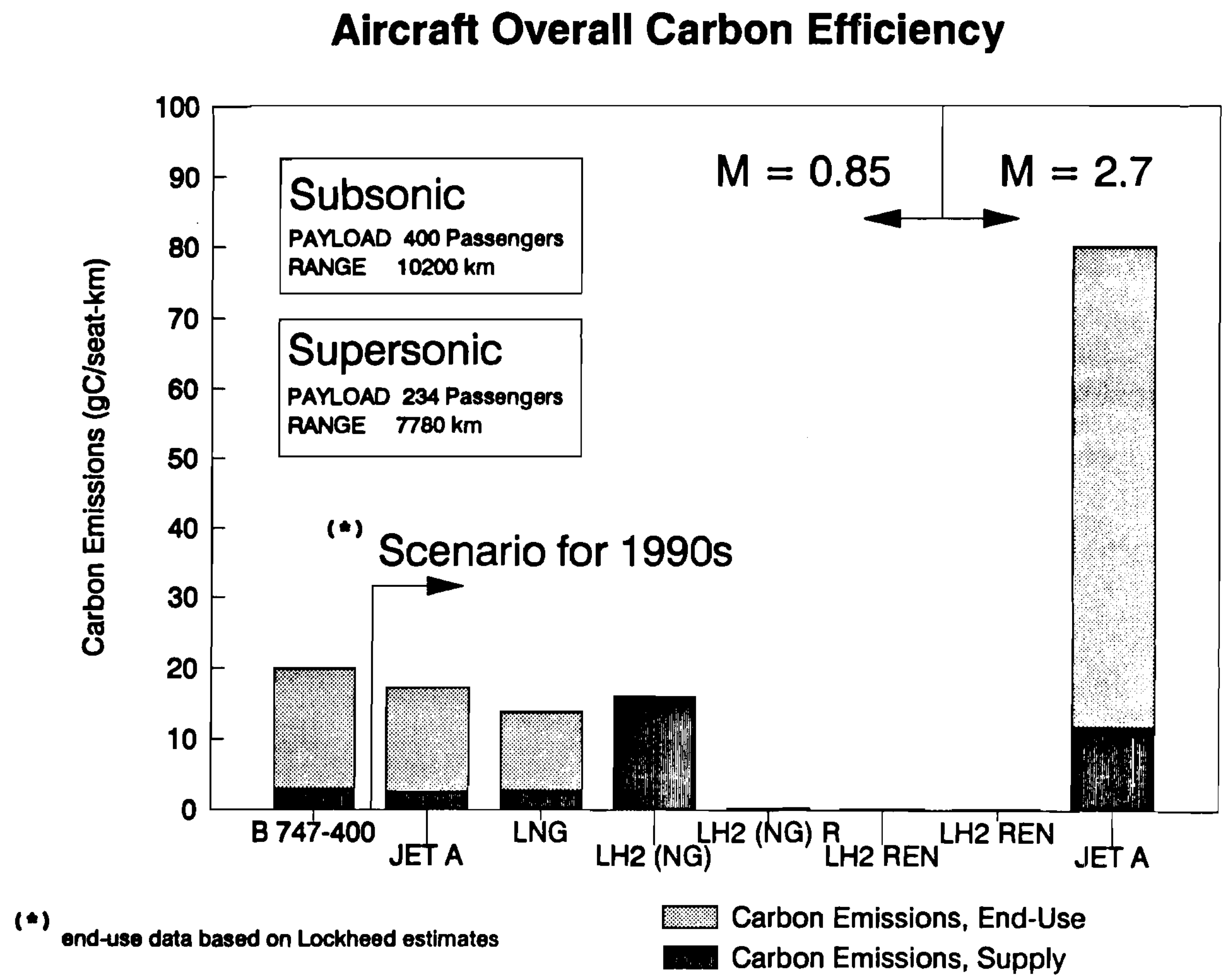


Figure 19. Carbon emissions for different transportation fuels. Boeing 747-400 powered by Jet A. Advanced subsonic aircraft: Jet A, LNG: liquefied natural gas, LH2 (NG) and LH2 (NG) R: liquefied hydrogen derived from natural gas by autothermal steam reforming and subsequent shift reaction of natural gas with carbon removal of the latter (R), LH2 (REN): liquid hydrogen from renewables. Supersonic aircraft powered by liquid hydrogen and Jet A.

ENERGY EFFICIENCY AND DECARBONIZATION

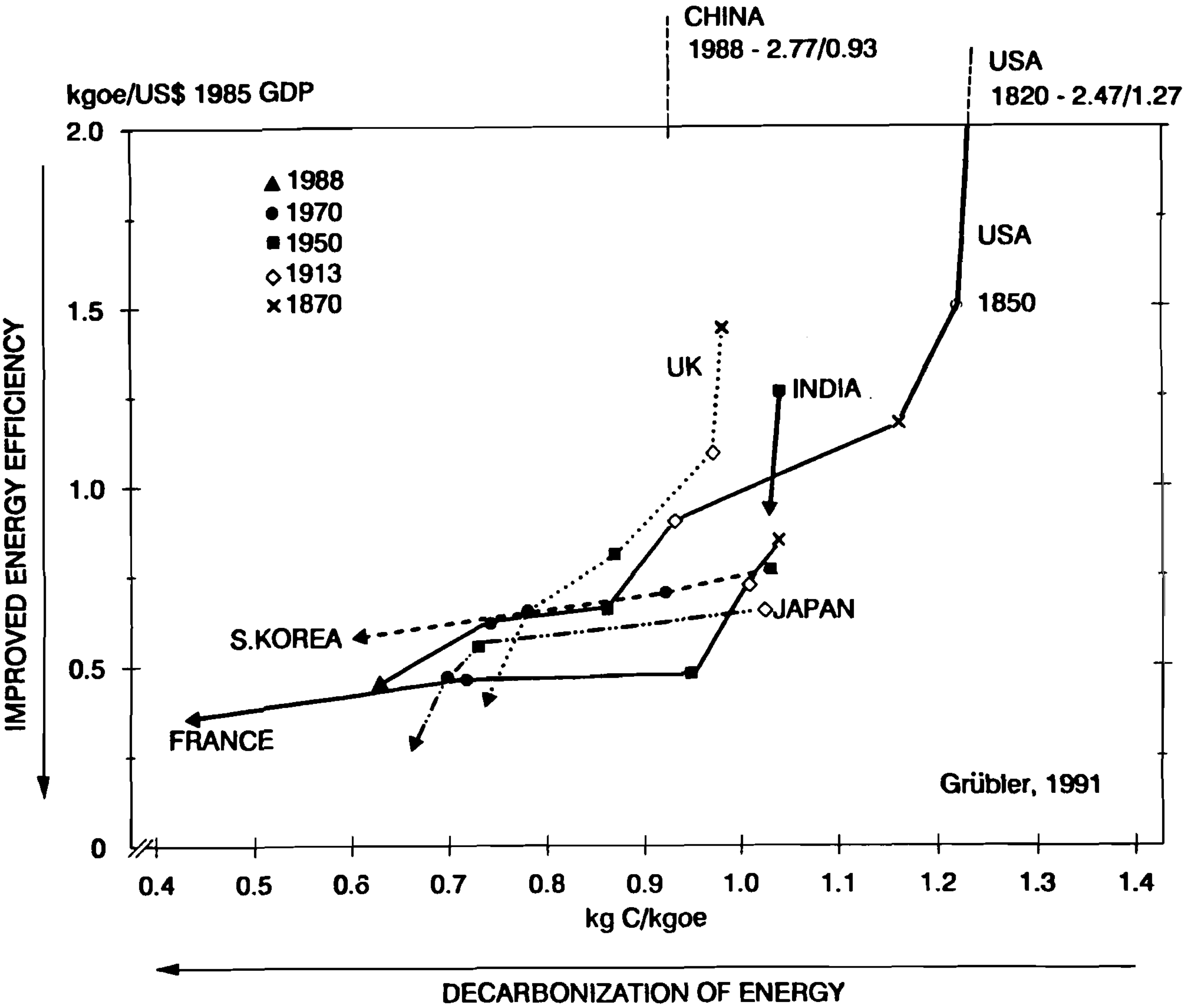


Figure 20. Historical trends in energy (kgoc per 1000 US$ GDP) and carbon intensity (kg C per kgoc) of various countries. Improved energy efficiency (lowering the energy intensity) and interfuel substitution (lowering the carbon intensity of energy use) are two important options for lowering carbon emissions. The graph shows the diverse policy mix and strategies followed in different countries over the time horizon considered. France appears to follow a decarbonization strategy, whereas Japan mostly an efficiency improvement strategy. All countries shown achieved improvements in both domains. The objective of research at IIASA in the area of Energy and the Environment is to assess the conditions that would direct the future development trajectories of most countries further toward the origin of this figure.