Impact of energy production on atmospheric concentration of greenhouse gases

Energy systems must be restructured to reduce emissions of carbon dioxide

by E. Iansiti and F. Niehaus

The earth receives energy radiated by the sun, with the temperature of the earth’s surface established by the balance between the energy received and that radiated back into space. Without the greenhouse effect of the atmosphere, the equilibrium would be reached at the global average surface temperature of -19 degrees Celsius. However, greenhouse gases — such as water vapor, including clouds, carbon dioxide (CO\(_2\)), methane (CH\(_4\)), nitrous oxide (N\(_2\)O), ozone (O\(_3\)), and chlorofluorocarbons (CFCs), as well as other less important trace gases — capture infrared radiation escaping from the earth’s surface. This is not too different from what happens in a greenhouse where the glass panes let solar radiation enter but trap a substantial part of the outgoing infrared radiation, increasing the temperature inside the greenhouse. This is the reason for the name of the phenomenon that has maintained the average surface temperature of the earth at 16 degrees Celsius and which has allowed life to develop.

Global warming: “Greenhouse effect”

Since the industrial revolution, the concentration of greenhouse gases has been steadily growing. There is now a reasonable consensus that this will produce an increase in the heat trapped in the atmosphere and consequently a global climate change. The more likely changes are shifting of climatic zones and a rising sea level.* Changes in rainfall patterns and more extreme weather conditions are also considered possible. This would seriously affect life in many countries and in particular world food production.

At the moment there are major uncertainties as to the sources and “sinks” which make up the budget of greenhouse gases, not so much for CO\(_2\) and CFCs as for nitrous oxide, ozone, and methane. Moreover, the warming of the atmosphere from the growing concentration of greenhouse gases is somewhat disguised by the variability of the climate due to several natural causes, many of which are not yet known in a quantified way.* (See accompanying figure.) Other important uncertainties arise from the feedback of factors that might counteract or amplify the effects of the greenhouse gases.


Reconstruction of atmospheric carbon dioxide concentration and relative temperature variations


These trends were reconstructed using data from ice core samples at the USSR Vostok station in Antarctica. Temperatures were estimated using the deuterium method.

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Features

These include cloud cover, even greater industrial production of greenhouse gases, and ocean processes. Such uncertainties do not facilitate policy-making for reducing emissions of greenhouse gases. They indeed might suggest that decisions should be held back until the feedback becomes clearer and analytical models are further validated. Unfortunately, the lifetime of greenhouse gases in the atmosphere and associated compartments (ocean, biosphere) is very long, and unless drastic reduction of present release rates are achieved their concentration will continue to increase. Moreover, the oceans and other feedback mechanisms introduce a delay of up to 100 years in effective changes of temperatures and other climate variables caused by emissions of greenhouse gases. Thus, changes introduced now are clearly irreversible. It is possible, therefore, to speak of a commitment to future climate changes because of greenhouse gases that have already been released into the atmosphere.

It is for this reason that in many international meetings recommendations have been made to take action as soon as possible in national programmes so as to reduce emissions.

The production of energy, in particular the burning of fossil fuels, accounts for an important part of industrial releases of greenhouse gases. This has prompted discussion on the role that nuclear energy could play in reducing the production of greenhouse gases. Annually the burning of fossil fuels emits about 20 billion tonnes of carbon dioxide. A nuclear plant produces electricity without releasing CO$_2$ or other greenhouse gases. One 1000-megawatt plant thus allows avoidance of about 6 million tonnes of CO$_2$ emissions per year that would be released by a coal-fired station producing the same amount of electricity. All nuclear plants operating worldwide today enable avoidance of about 1.6 billion tons of CO$_2$ per year.

Main greenhouse gases

Two categories of gases are connected with the greenhouse effect: Greenhouse gases — such as CO$_2$, methane, nitrous oxide, and CFC11 and CFC12 — capture heat escaping from earth’s surface and send it back, thereby warming the earth. (Ozone also absorbs energy in the direct solar and infrared radiation field.) Chemically interactive gases — such as nitrogen oxide, carbon monoxide, and hydroxyl radical — affect the concentration of these greenhouse gases.

Following are brief descriptions of the main greenhouse gases, which are responsible for more than 95% of global warming. In assessing emissions of greenhouse gases, clear distinctions have to be made between the natural equilibrium cycles and the anthropogenic emissions that disturb this equilibrium. Comparatively small man-made emissions can significantly disturb the natural balance of flow rates.

Carbon dioxide. The concentration of CO$_2$ in the troposphere has now increased to an annual average 350 ppmv (parts per million by volume). In the Northern Hemisphere, an annual cycle of up to 15 ppmv occurs. (See accompanying figure.) The differences are primarily due to the regular variation in terrestrial photosynthesis and to a lesser degree to the annual variation of the sea surface temperature, which influences the solubility of the gas in the sea. The variation of photosynthesis in the sea also has a small effect. The concentration in air has been traced back in time by the analysis of the air trapped in ice. The general trend shows that before the industrial revolution and the expansion of agricultural activity, the concentration was 275 ± 10 ppmv; the present increase of carbon dioxide is 1.5 ± 0.2 ppmv, or 0.4% per year.* (See accompanying figure.)


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Atmospheric carbon dioxide concentration, 1958–86


Monthly and annual averages, as observed at Maunahoe, Hawaii, indicate that variations are linked with seasonal factors such as photosynthesis and sea-surface temperatures.

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Atmospheric carbon dioxide concentrations measured in glacier ice over past 200 years

The cycle of CO$_2$ is very complex and the natural sources and sinks are much larger than those due to man-made activities. (See accompanying table.) Carbon is the key element for the life on earth. The residence time in the atmosphere and strictly coupled compartments (upper ocean, biosphere) is very long, on the order of many centuries. Only 40-50% (airborne fraction) of the total emission of CO$_2$ remains in the atmosphere under present conditions.

Doubling the concentration of CO$_2$ would increase the global average equilibrium surface temperature by 1.5 to 4.5 degrees Celsius, based on current models (in which many of the feedback factors have to be better validated). Recent analysis suggests, however, that there is sufficient evidence to call for policy decisions. At present about 50% of global warming is attributed to the anthropogenic addition of CO$_2$. The percentage might be even higher considering some amplifying feedback mechanisms; for example, the natural production of methane.

**Methane.** Methane concentration in 1985 was 1.7 ppmv in the Northern Hemisphere and 1.6 ppmv in the Southern Hemisphere. The current atmospheric trend is a growth of $1.1 \pm 0.1\%$ per year (calculated between 1951 and 1983). (See accompanying graphs.) The long-term trend has been obtained from air bubbles trapped in the ice sheet of Greenland and Antarctica. Methane is mainly released by microbial activities during the mineralization of organic carbon under strictly anaerobic conditions; for example, in waterlogged soils and within the intestines of herbivorous animals. It is also released by man-made activity such as exploitation of natural gas, biomass burning, and coal mining. (See accompanying table.) The total global annual production of methane due to man-made activities is estimated between 135-395 million tonnes per year; this range is an important uncertainty. The main sink of methane is in the reaction with hydroxyl radical in the troposphere. Other sinks are transported into the stratosphere by oxidation. The lifetime of methane in the atmosphere is 7-10 years.

An important fact is that methane is 32 times more effective per molecule as a greenhouse gas than carbon dioxide. It is estimated that about 19% of present global warming can be attributed to methane.

**Nitrous oxide.** Nitrous oxide concentration has been observed since the late 19th century from the measurement of air trapped in ice cores of Antarctica. The concentration in 1985 was 0.31 ppmv and the trend reflects an increase of 0.2-0.3% per year. Nitrous oxide’s atmospheric lifetime is very long, on the order of 150 years. It is naturally released into the atmosphere primarily by microbial action in soil and water as part of the nitrogen cycle. Man-made sources are fossil fuel
Methane: Past and present atmospheric concentrations

*Tropospheric methane mixing ratios in Northern Hemisphere*

| Year | Data were obtained from measurements carried out on aircrafts (circles), on ships (squares), and at different land based stations during clean air conditions (triangles). The figure includes data (dots) measured by Rowland and colleagues (see Blake, 1984) at similar latitudes in air from the Pacific Ocean. |

Methane mixing ratios measured in air trapped in ice cores

| Time (years before present) |

Dots and filled triangles are data taken from Rasmussen and Khalil (1984) and represent values obtained from ice cores in Greenland and Antarctica, respectively. Open circles are data published by Craig and Chou (1982) and squares are data published by Robbins et al. (1973).

**Features**

Combustion and cultivation of soils. (See table on page 16.) The main sink is stratospheric photolysis and reaction with oxygen. It is estimated that about 4% of present global warming is attributed to nitrous oxide.

**Chlorofluorocarbons.** The main chlorofluorocarbons are CFC$_3$ (CFC11) and CF$_2$Cl$_2$ (CFC12). There are no natural sources. They are all produced by man-made activities, mainly as refrigerants, fluids, aerosol propellants, and in the foaming of plastics. There are no sinks in the troposphere and the CFCs are dissociated in the stratosphere where they contribute to the process of ozone depletion. Atmospheric lifetimes are about 75 years for CFC11 and about 110 years for CFC12. In 1983, the concentration of CFC11 was 200 ppbv (parts per billion by volume) and of CFC12, 310 ppbv. The annual growth is estimated to be about 5%.

During 1987, an international agreement (the Montreal Protocol) was introduced because of the role of CFCs in stratospheric ozone depletion. The agreement
Aims at reducing the use of CFCs by industrialized nations 50% by the year 2000. More recently, international objectives have been directed at abolishing their use.

Per molecule, CFC11 is 14,000 and CFC12 is 17,000 times as effective as a greenhouse gas compared to carbon dioxide.* It has been estimated that at present about 5% of global warming can be attributed to CFC11 and 10% to CFC12. Between 5-10% of the releases are indirectly related to energy, e.g., they originate from the production of insulation materials used to conserve energy.

Ozone. Ozone is a major absorber of solar and infrared radiation. Tropospheric ozone is derived in part from the transport from the stratosphere and in part from tropospheric photochemical reactions. Stratospheric ozone is produced primarily through photodissociation of molecular oxygen followed by a combination of the resulting oxygen atoms with O<sub>3</sub> in the presence of a catalyst. Destruction of ozone comes through recombination with oxygen atoms and catalytic reactive processes. The lifetime of ozone in the troposphere is very short (hours to days); there is therefore a large local variability of its concentration and it is difficult to detect trends. In the troposphere, an average concentration value of 0.02 to 0.1 ppmv is given in the literature, while for the stratosphere the values range from 0.1 to 10 ppmv. Satellites and ground-based measurements suggest that its concentration is decreasing in the stratosphere and growing in the troposphere. At present about 8% of global warming is attributed to ozone.

Energy production

Estimates of the contribution of energy production to emissions of greenhouse gases reflect a broad range. (See the table below and pie chart on page 17.)

Global carbon dioxide emissions by fuel. Since 1950, there has been a steady increase of CO<sub>2</sub> emissions with peaks after the oil crises in 1975 and 1979. (See accompanying figure.) While the 1979 oil crisis led to a stabilization of oil consumption, natural gas consumption continued its upward trend. Coal consumption showed a significant increase even above its historical trend. It thus assumed the lead role in CO<sub>2</sub> emissions that it had before the late 1960s. This resulted in a record level of CO<sub>2</sub> emissions in 1986. This actual development stands in sharp contrast to all recommendations of the scientific community to reduce CO<sub>2</sub> emissions. Present plans for increasing coal consumption will worsen the situation dramatically.

It should be noted that, if present forecasts for the year 2000 come true, China alone would use more coal than all the countries of the Organisation for Economic Co-operation and Development (OECD) do today. The projected world increase of 40% is roughly equal to the present consumption of OECD countries or about twice the consumption of the United States. (See table below.)

Country-specific carbon dioxide emissions. Since 1950, there has been a rapid increase in CO<sub>2</sub> emissions from developing countries and a relative decrease of the contribution from industrialized countries. (See figure, page 17.) With very few exceptions, per caput

Percentage of greenhouse gas production from energy

<table>
<thead>
<tr>
<th>Percentage due to energy compared to all:</th>
<th>Natural sources</th>
<th>Man-made sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon dioxide</td>
<td>2-4</td>
<td>65-98</td>
</tr>
<tr>
<td>Methane</td>
<td>10-30</td>
<td>16-48</td>
</tr>
<tr>
<td>Nitrous oxide</td>
<td>18-38</td>
<td>65-100</td>
</tr>
<tr>
<td>CFCs</td>
<td>n/a</td>
<td>5-10*</td>
</tr>
</tbody>
</table>

* Indirectly due to energy conservation.

Forecasts of coal consumption (million tons of oil equivalent per year)

<table>
<thead>
<tr>
<th>Country</th>
<th>1985-86</th>
<th>2000</th>
<th>Increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>700</td>
<td>1400</td>
<td>+100%</td>
</tr>
<tr>
<td>USA</td>
<td>680</td>
<td>900</td>
<td>+32%</td>
</tr>
<tr>
<td>Australia</td>
<td>43</td>
<td>62</td>
<td>+44%</td>
</tr>
<tr>
<td>India</td>
<td>140</td>
<td>440</td>
<td>+214%</td>
</tr>
<tr>
<td>World total</td>
<td>3200</td>
<td>4500</td>
<td>+40%</td>
</tr>
<tr>
<td>OECD share of total</td>
<td>1200</td>
<td>1640</td>
<td>+37%</td>
</tr>
</tbody>
</table>

Sources: International Energy Agency of the Organisation for Economic Co-operation and Development 1986 (USA, Australia data); World Energy Conference 1986 (World total data).
Features

Global warming sources

Non-Energy 50%

Energy 50%

Global total emissions by fuel type, 1950–86

Source: Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, USA.

Carbon dioxide emissions, 1950–86

Source: Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, USA.

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Emissions of carbon in 1984, by region and economic sector

<table>
<thead>
<tr>
<th>Percentage (rounded values)</th>
<th>Industry</th>
<th>Transport</th>
<th>Others</th>
<th>Electricity</th>
<th>Own use* (energy sector)</th>
<th>Total (10^6 tonm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asia</td>
<td>38</td>
<td>11</td>
<td>21</td>
<td>26</td>
<td>3</td>
<td>642.5</td>
</tr>
<tr>
<td>Africa</td>
<td>28</td>
<td>20</td>
<td>11</td>
<td>40</td>
<td>1</td>
<td>136.31</td>
</tr>
<tr>
<td>Latin America</td>
<td>23</td>
<td>20</td>
<td>12</td>
<td>19</td>
<td>15</td>
<td>203.61</td>
</tr>
<tr>
<td>OECD</td>
<td>23</td>
<td>24</td>
<td>17</td>
<td>28</td>
<td>8</td>
<td>2622.01</td>
</tr>
<tr>
<td>CMEA</td>
<td>21</td>
<td>8</td>
<td>17</td>
<td>43</td>
<td>11</td>
<td>1378.91</td>
</tr>
<tr>
<td>Total</td>
<td>24</td>
<td>18</td>
<td>17</td>
<td>32</td>
<td>8</td>
<td>4983.41</td>
</tr>
</tbody>
</table>

* Distribution and conversion losses secondary energy.

Notes: Africa region includes 17 countries plus Iran (1982 data) and Algeria (1982 data). Asia region includes 15 countries plus Ch (1980 data) and Taiwan, China (1984 data). Latin America includes 16 countries plus Mexico (1982 data). OECD data cov 25 countries; CMEA data 7 countries. Some countries were not considered or only partly considered: Algeria, Liberia, Libyan A Jamahiriya, South Africa, Iran, Democratic People's Republic of Korea, and Syria.


Emissions have drastically increased since 1950. The large differences in today's per caput emissions also indicate how difficult it would be to reach an agreement among countries to reduce CO₂ emissions; for example, to meet the goal set by the Toronto Conference in 1988 of reducing CO₂ emissions by 20% by the year 2005. It is obvious that any stabilization of CO₂ emissions can only be reached if all countries contribute. However, different strategies are necessary depending on the status of technological capabilities of countries and the availability of alternatives.

Carbon dioxide emissions by sector. Another important aspect of CO₂ emissions is their distribution by sector of economy. Electricity production plays an important role. (See accompanying table.) For the world, roughly one-third of CO₂ emissions are due to electricity production; one-quarter to industry; less than one-fifth to transport and other activities (including services, agriculture and households) and less than one-tenth to conversion losses and uses of processing industries. The percentage from electricity production varies between 19% for Latin America and 43% for countries of the Council for Mutual Economic Assistance (CMEA).

The importance of electricity production has increased at a much higher rate than gross national product (GNP) or energy production. In OECD countries, total energy production over the period 1973-1985 has increased by only 4% whereas electricity production has grown by 39%. For the world, electricity production has increased by 57% during that time. (See table below for details.)

Policy options to control carbon dioxide emissions

In view of such trends, there is consensus that we no longer afford to continue the global experiment increasing atmospheric greenhouse gases, in particular CO₂ for which the greatest source, by far, is burning fossil fuels. It is important to keep in mind that the commercial development of energy systems shows definite historical trends that are rather mildly interrupted by disturbances such as an oil crisis. To change historic trends in short time periods is not possible (and also desirable), considering, for example, the lifetime energy investments and their relationship to industrial and economic development.

A solution to the CO₂ problem can only be achieved if a set of measures is taken immediately that complement each other. Such a combination of measures, contributing a fraction to the solution of the problem, will enable a more flexible and less disturbing to economic development. The benefit of such measures is multiplied if the steps are correct for other reasons as well (for example, to lower emissions of other greenhouse gases and atmospheric pollutants, or to reduce production waste).

However, it should be noted that stabilizing emissions of greenhouse gases (that is, continuing to add them to the atmosphere at the present rate) will not prevent an increase in atmospheric concentrations. Any much increase in concentration can be tolerated is...
known at this time. It is thus of overriding importance to slow down the increase and to introduce changes in lifestyles, industrial development, and energy production which would provide for flexible response strategies, considering the inertia of the system. Such strategies could be reinforced and accelerated with greater understanding of the problem. In this connection, the Inter-Governmental Panel on Climatic Change (IPCC) is exploring the implications of scenarios which would lead to an equivalent doubling of atmospheric CO\textsubscript{2} concentration by the years 2030, 2060, and 2090, with no increase for the last scenario.

It is necessary to restructure the energy system in such a way that lower levels of CO\textsubscript{2} are emitted when supplying a unit of energy services.

The basic options for doing so are:

- More efficient use of carbon-based primary energy. This would also lead to lower emissions of all energy-related greenhouse gases.
- Switching from coal to fuels emitting less CO\textsubscript{2}. Such "fuel switching" would also lead to a reduction of environmental pollution. However, the impact on greenhouse gases other than CO\textsubscript{2} is rather small. Switching to natural gas will lead to larger emissions of methane (losses are generally estimated to be fractions of 1% in distribution). Per molecule, however, methane is 32 times more effective as a greenhouse gas than CO\textsubscript{2}.
- Use of nuclear power. Nuclear power leads to no emissions of greenhouse gases. In addition to production of electricity, future applications might be extended to production of process heat for industrial and other purposes and production of special fuels for transport which do not produce greenhouse gases.
- Use of renewable energy sources (such as solar, wind, and biomass). Renewable energy sources do not emit greenhouse gases. Presently, these techniques are not available at economic costs and unless major technological breakthroughs are made, their use is limited to small-scale decentralized applications. These, however, add up to significant amounts in countries with favourable conditions.
- Pursuing mitigating strategies. They include such diverse measures as reforestation or dumping of CO\textsubscript{2} into deep ocean water or depleted oil or gas fields.

Which combination of measures a country should take, and with which emphasis, strongly depends on its degree of technological development and the available alternatives.

**Analysis of sample cases.** In the United States, for instance, total CO\textsubscript{2} emissions have been stable over the past 15 years. Per unit of economic output, the CO\textsubscript{2} "emission efficiency" has increased by about 20%; that is, specific emissions have decreased from 470 000 to 350 000 metric tonnes per billion dollars of GNP (1982 US $).* This has mainly been achieved by increasing energy efficiency, increased use of electricity, and a substantial increase in nuclear power.

This development took place with the objective of minimizing costs and environmental impacts but without a stated policy in mind to minimize CO\textsubscript{2} emissions specifically.

A similar development can be observed in the Federal Republic of Germany.* During the time period 1973–85 GNP increased (+26%) while carbon dioxide emissions decreased (−11%). This development was caused by the following changes in energy production and use.

- More efficient use of energy. With some deviations, total primary energy consumption has stayed nearly constant in spite of a significant increase in GNP. (See accompanying figure.) This development was accompanied by a steep increase in electrical energy demand. (This trend toward electrification reflects developments worldwide and notably in OECD countries.) Energy savings were realized in industry, by a shift to more efficient products and services, and in room heating and petrol consumption. The increase in electricity consumption occurred in spite of more efficient use of electricity.

- **Fuel switching.** In 1973, specific CO\textsubscript{2} emissions from all fuels were 13% lower than they would have been if coal had been used to supply all the energy. This difference was increased to 24% in 1985 by using less oil and coal and by increasing the share of natural gas and nuclear power.

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• Use of nuclear power. The share of nuclear power in primary energy production was increased from 1% to 11%.

Again these changes occurred without intending to minimize CO₂ emissions. Yet they demonstrate the potential for reducing CO₂ emissions if such a basic policy would be pursued and enforced.

Policy implications and the role of nuclear power

It is clear, however, that a policy derived from the examples of the United States and Federal Republic of Germany is more suitable for industrialized countries and applies to a lesser degree to developing countries. Developing countries will need and are planning to significantly increase primary energy consumption primarily based on fossil fuels. Since industrialized countries are responsible for the lion’s share of the increase in atmospheric CO₂, they, therefore, have a special responsibility to "over-proportionally" reduce CO₂ emissions. In favourable climatic conditions, developing countries should make use of renewable energy sources.

Nuclear power can make a significant contribution to solving the CO₂ problem. Each 1000-megawatt-electric reactor prevents the emission of about 6 million tonnes of CO₂ per year when compared to the same amount of electricity produced by burning coal. Collectively, the world’s 430 nuclear power plants are preventing some 1.6 billion tonnes of CO₂ emissions; that is, 8% of all present emissions. This is not an insignificant amount considering that it is roughly equal to 40% of the reduction goal suggested by the Toronto Conference. To reach the same effect with reforestation would need very large areas. In the Federal Republic of Germany, for example, forests fix about 3 tonnes of carbon per hectare and year in growth of trunks and branches of the trees. It could be twice the value under more favourable conditions. Thus, one hectare of forests absorbs between 10 and 20 tons of CO₂ from the atmosphere depending on climatic conditions. Therefore, between 3000 and 6000 square kilometres of forests would be needed to absorb the CO₂ emissions already prevented by one 1000-megawatt nuclear plant compared to a comparable coal-burning plant. Thus, the 1.6 billion tonnes of CO₂ not released by all nuclear power plants today are equivalent to about 1 to 2 million square kilometres of forest area, or 4–8 times the area of the Federal Republic of Germany. This does not take into account the fact that mature trees have to be buried and sealed from air forever to avoid oxidation into CO₂.

In many countries, though not in all, there is still a significant potential to increase the use of nuclear power for electricity production, considering the rapid growth of electricity consumption. However, increase of nuclear power beyond, say, doubling the present capacity will mean new challenges for nuclear safety, fuel cycle facilities, and the international safeguards system. In addition, principle changes will be needed to make nuclear power more attractive to developing countries, including financing and better international co-operation in various steps of the nuclear fuel cycle.

Considering the special responsibility of industrialized countries to the CO₂ problem and their technological capabilities, it is their duty to make extended use of existing type of reactors, and to make advanced reactors more rapidly available in smaller sizes, based on simpler and standardized technology and enhanced use of passive safety features. A variety of such designs, including high-temperature reactors, are being developed and will be available in some years. Ultimately it might be necessary to develop very different designs based on different technologies and fuel-cycle features in reconsideration of aspects of waste disposal, availability of fuel, and proliferation. Such a policy might also help overcome the problem of public acceptance at least partly.

Conclusions

• Because of the significance of the problem, there is the need to take actions now, in particular those which are cost-effective and which are correct for other environmental and economic reasons.

• Options should be selected which reinforce current positive trends and thus are least disruptive to societal development.

• All countries, but in particular industrialized countries, should follow a strict policy of efficient use of carbon-based primary energy, fuel switching, use of nuclear power where applicable, and the use of renewable energy sources under favourable conditions.

• The effort each country should make to reduce CO₂ emissions must be based on its technological capabilities, economic wealth, alternative energy options, and the amount by which it has polluted the atmosphere with CO₂ in the past.

• Apart from their positive impact on CO₂ emissions, the efficient use of energy, fuel switching, and the use of nuclear power are desirable for other environmental reasons.

• No final word can be said on global warming. The problem could be more or less severe than estimated today. It is then of utmost importance to adopt a strategy now which allows options in the future. In particular, this refers to nuclear power, since it might be necessary to build a large number of reactors in the future. Thus, industrial countries should give high priority to making advanced nuclear technology available.

• Industrial countries should help developing countries in efforts to economize on CO₂ emissions. This could be very cost-effective where technologies with low CO₂ efficiency are used.

• Reducing emissions of greenhouse gases from energy production has to be complemented by measures to avoid releases of greenhouse gases from other sources.