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_2O), 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.

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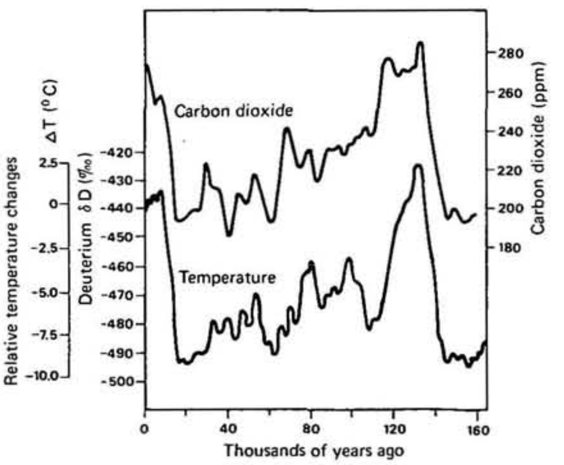
* *The Greenhouse Effect, Climatic Change, and Ecosystems*, (SCOPE 29), published on behalf of the Scientific Committee on Problems of the Environment (SCOPE) of the International Council of Scientific Unions, with support of the United Nations Environment Programme and World Meteorological Organization (May 1988).

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.

* *Schutz der Erdatmosphäre, eine Internationale Herausforderung*, Zwischenbericht der Enquete-Kommission des 11. Deutschen Bundestages, Bonn (1988).

Reconstruction of atmospheric carbon dioxide concentration and relative temperature variations



Source: *Schutz der Erdatmosphäre, eine internationale Herausforderung*. Zwischenbericht der Enquête-Kommission des II. Deutschen Bundestages, Bonn (1988).

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

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.

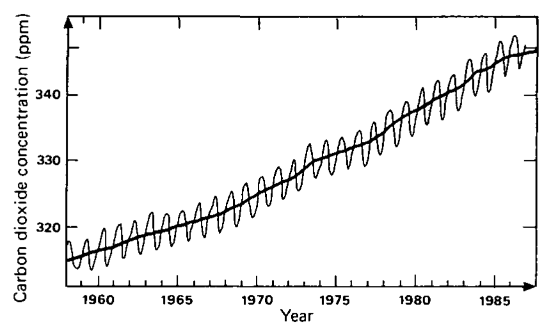
Main greenhouse gases

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.*)

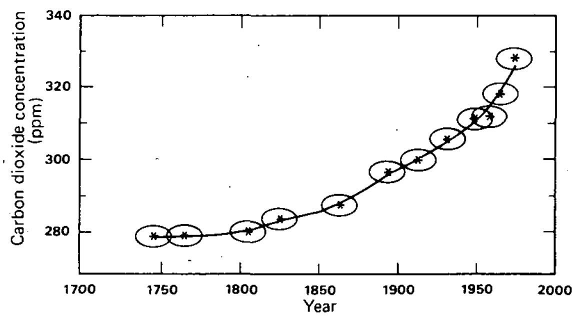
Atmospheric carbon dioxide concentration, 1958–86



Source: *Schutz der Erdatmosphäre, eine internationale Herausforderung.* Zwischenbericht der Enquête-Kommission des II. Deutschen Bundestages, Bonn (1988).

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

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



Source: Neftel et al, 1985, as cited in "How much CO_2 will remain in atmosphere?", by B. Bolin, *The Greenhouse Effect, Climatic Change, and Ecosystems* (SCOPE 29) (May 1988).

* See previously cited, *The Greenhouse Effect, Climatic Change, and Ecosystems* (SCOPE 29).

Annual global budget of carbon dioxide

Natural sources	*10^9 tonnes per year*	*Percent*
Gross from ocean	~376–390	~60
Gross from land	~ 32–440	~36
Total natural sources	~619 (408–830)	~96
Man-made sources		
Fossil fuel use	~ 16–20	~ 3
Land use conversion	~ 0–10	~ 1
Total man-made sources	~ 22 (16–30)	~ 4
Total sources	~642 (424–860)	100
Sinks		
Ocean gross uptake	~389–396	~64
Land net primary production	~183–257	~36
Total sinks	~612 (572–653)	100

Sources: Based on *A primer on greenhouse gases,* US Department of Energy (March 1988) and "Energy, climate, environment", *Energy and climate change: What can Western Europe do?,* Directorate General for Environmental Protection, Netherlands (February 1988).

Annual global budget of methane

Natural sources	*10^6 tonnes per year*	*Percent*
Wetlands	~ 60–160	~24
Termites	~ 5 -45	~ 5
Oceans	~ 7–13	~ 2
Wild animals	~ 2–8	~ 1
Lakes	~ 2–6	~<1
Tundra	~ 1–5	~<1
Others	~ 0–80	~ 9
Total natural sources	~197 (77–317)	~43
Man-made Sources		
Cattle	~ 40–110	~16
Biomass burning	~ 30–110	~15
Rice paddies	~ 40–100	~15
Natural gas and mining losses	~ 25–75	~11
Total man-made sources	~265 (135–395)	~57
Total sources	~462 (212–712)	100
Sinks		
Reaction with hydroxyl radical in troposphere	~250–450	~85
Reaction with hydroxyl radical, chlorine, oxygen in stratosphere	~ 30–70	~12
Uptake by micro-organisms in soils	~ 5–15	~ 3
Total sinks	~410 (285–535)	100

Source: Based on A primer on greenhouse gases, US Department of Energy (March 1988) and "Energy, climate, environment", *Energy and climate change: What can Western Europe do?,* Directorate General for Environmental Protection, Netherlands (February 1988).

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 ± 0.1% per year (calculated between 1951 and 1983). *(See accompanhing 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 transport into the stratosphere followed by oxidation. The lifetime of methane in the atmosphere is 7–10 years.

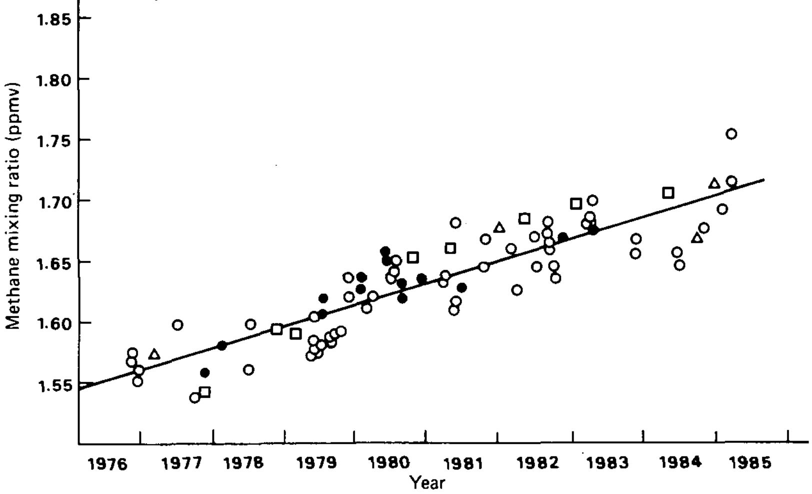
An important fact is that methane is 32 times more effective per molecule as a greenhouse gas than carbon dioxide.* It is estimated that about 19% of present global warming can be attributed to methane.

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

* *Schutz der Erdatmosphäre, eine Internationale Herausforderung,* Zwischenbericht der Enquete-Kommission des 11. Deutschen Bundestages, Bonn (1988).

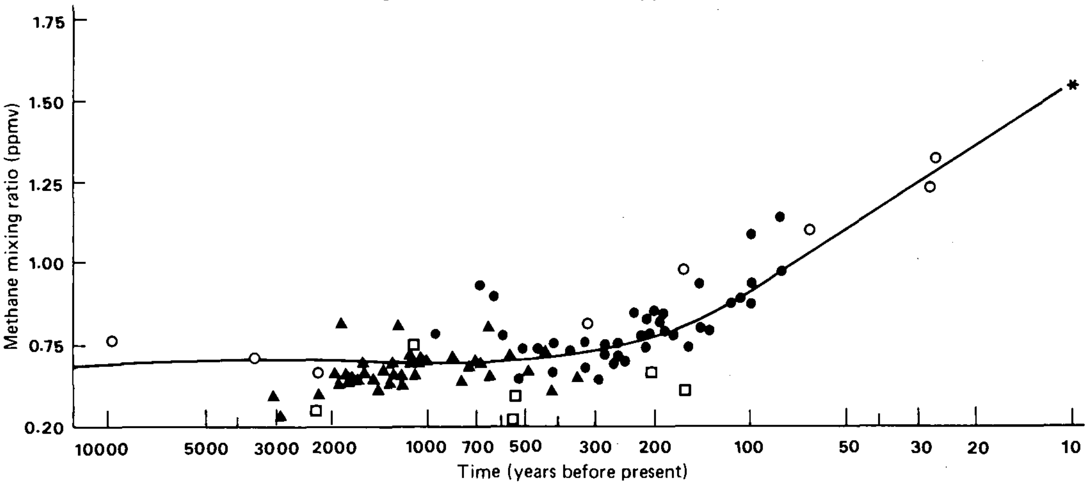
Methane: Past and present atmospheric concentrations

Tropospheric methane mixing ratios in Northern Hemisphere



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



Source: "Other greenhouse gases and aerosols", by H.-J. Bolle, W. Seiler, and B. Bolin. *The Greenhouse Effect. Climatic Change, and Ecosystems* (SCOPE 29) (May 1988).

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).

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 $CFCl_3$ (CFC11) and CF_2Cl_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

Annual global budget of nitrous oxide

Natural sources	*10^6 tonnes per year*	*Percent*
Natural soils	~ 9–31	~42
Oceans and estuaries	~ 3–9	~13
Total natural sources	~12–40	~55
Man-made sources		
Fossil fuel combustion	~ 9–16	~26
Cultivation of natural soils	~ 3–6	~ 9
Fertilization of soils	~ 2–3	~ 5
Biomass burning	~ 2–3	~ 5
Total man-made sources	~22 (16–28)	~45
Total sources	~48 (28–69)	100
Main sink		
Stratosphere photolysis and reaction with oxygen	~24–42	~100
Total	~33 (24–42)	

Sources: Based on A primer on greenhouse gases, US Department of Energy (March 1988) and "Energy, climate, environment", *Energy and climate change: What can Western Europe do?,* Directorate General for Environmental Protection, Netherlands (February 1988).

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_2 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.

* See previously cited. *The Greenhouse Effect, Climatic Change, and Ecosystems (SCOPE 29).*

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_2 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_2 emissions that it had before the late 1960s. This resulted in a record level of CO_2 emissions in 1986. This actual development stands in sharp contrast to all recommendations of the scientific community to reduce CO_2 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_2 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

	Percentage due to energy compared to all:	
	Natural sources	*Man-made sources*
Carbon dioxide	2–4	65–98
Methane	10–30	16–48
Nitrous oxide	18–38	65–100
CFCs	n/a	5–10*

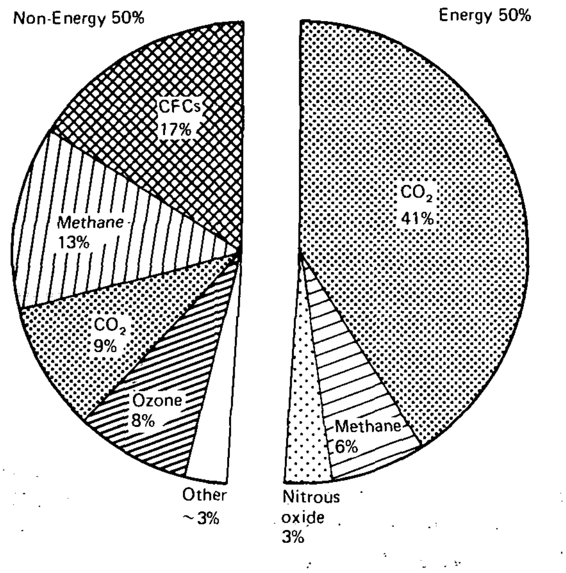
* Indirectly due to energy conservation.

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

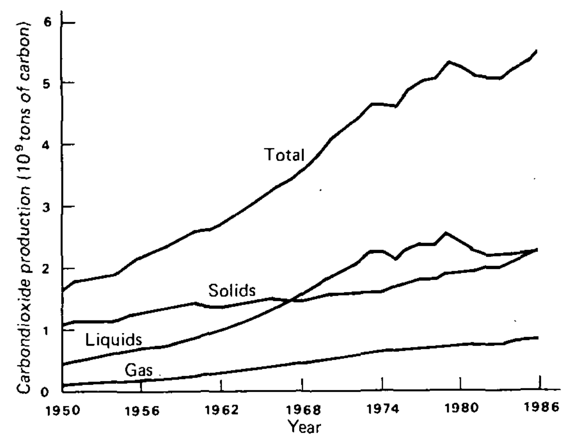
	1985–86	2000	Increase
China	700	1400	+100%
USA	680	900	+ 32%
Australia	43	62	+ 44%
India	140	440	+214%
World total	3200	4500	+ 40%
OECD share of total	1200	1640	+ 37%

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

Global warming sources



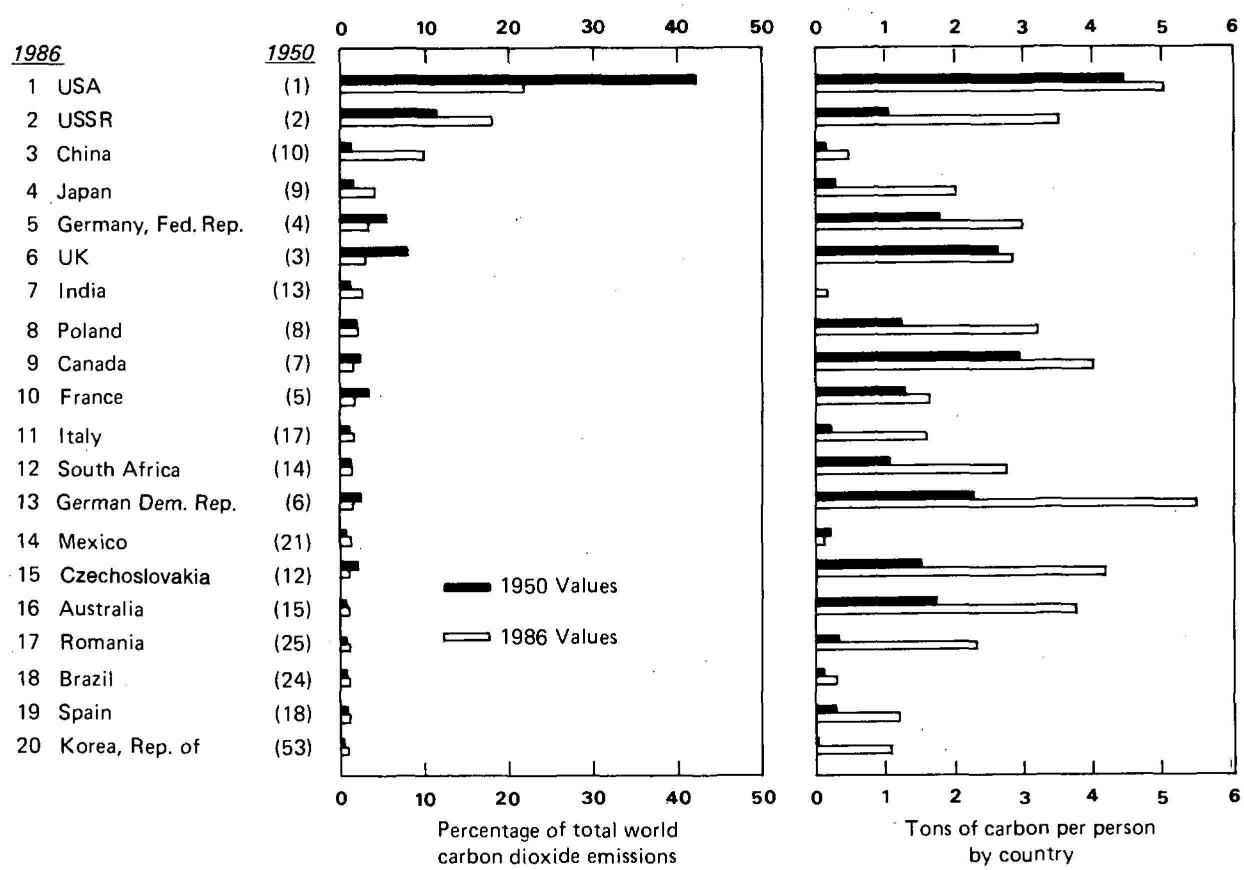
Global total emissions by fuel type, 1950–86



Note: Total includes emissions from natural gas flaring and cement manufacturing.

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.

Emissions of carbon in 1984, by region and economic sector

	Percentage (rounded values)					Total
	Industry	Transport	Others	Electricity	Own use* (energy sector)	(10^6 tonn
Asia	38	11	21	26	3	642.5
Africa	28	20	11	40	1	136.31
Latin America	23	32	12	19	15	203.6
OECD	23	24	17	28	8	2622.0
CMEA	21	8	17	43	11	1378.9
Total	24	18	17	32	8	4983.4

* 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.

Sources: Energy balances and electricity profiles, United Nations (1982) for Africa, Asia, and Latin America data; *Energy balan 1970–85,* Organisation for Economic Co-operation and Development (OECD) for OECD data; *Energy balances for Europe and N America 1970–2000,* UN Economic Commission for Europe, for data on Council for Mutual Economic Assistance (CMEA) countri

Source: T. Müller (consultant), IAEA Planning and Economic Studies Section, Division of Nuclear Power.

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 CO_2 emissions; for example, to meet the goal set by the Toronto Conference in 1988 of reducing CO_2 emissions by 20% by the year 2005. It is obvious that any stabilization of CO_2 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 CO_2 emissions is their distribution by sector of economy. Electricity production plays an important role. (*See accompanying table.*) For the world, roughly one-third of CO_2 emissions are due to electricity production; one-quarter to industry; less than one-fifth each 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

Growth in gross domestic product, energy, and electricity 1973–85

	GDP	Energy	Electricity
World	42%	29%	57%
OECD	33%	4%	39%

product (GNP) or energy production. In OECD co tries, total energy production over the period 1973- has increased by only 4% whereas electricity product has grown by 39%. For the world, electricity product has increased by 57% during that time. *(See table belo*

Policy options to control carbon dioxide emissio

In view of such trends, there is consensus that we no longer afford to continue the global experiment increasing atmospheric greenhouse gases, in partic CO_2 for which the greatest source, by far, is burning fossil fuels. It is important to keep in mind that the c mercial development of energy systems shows defi historical trends that are rather mildly interrupted by turbances such as an oil crisis. To change histor trends in short time periods is not possible (and also desirable), considering, for example, the lifetime energy investments and their relationship to indust and economic development.

A solution to the CO_2 problem can only be achie if a set of measures is taken immediately that com ment each other. Such a combination of measures, e contributing a fraction to the solution of the problem also more flexible and less disturbing to econo development. The benefit of such measures is multip if the steps are correct for other reasons as well example, to lower emissions of other greenhouse g and atmospheric pollutants, or to reduce productior waste).

However, it should be noted that stabilizing er sions of greenhouse gases (that is, continuing to them to the atmosphere at the present rate) will not vent an increase in atmospheric concentrations. H 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_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_2 are emitted when supplying a unit of energy services.

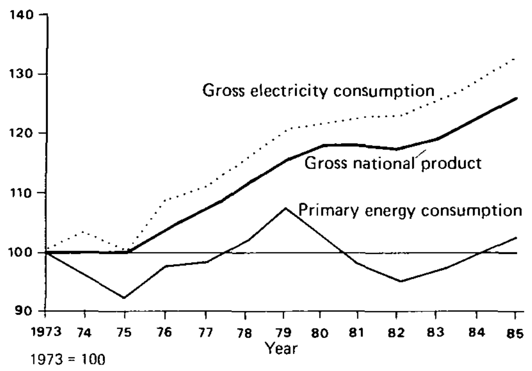
The basic options for doing so are:

• 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_2. Such "fuel switching" would also lead to a reduction of environmental pollution. However, the impact on greenhouse gases other than CO_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_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_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_2 emissions have been stable over the past 15 years. Per unit of economic output, the CO_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.

Trends in the Federal Republic of Germany's primary energy consumption, gross electricity consumption and the gross national product, 1973–85



Source: *Energy Report of the Government of the Federal Republic of Germany*, Federal Ministry of Economics, Bonn (1986).

This development took place with the objective of minimizing costs and environmental impacts but without a stated policy in mind to minimize CO_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_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.

* "Energy and the greenhouse effect", Science Concepts, Inc., Washington, DC (March 1989).

* Based on data reported in SCOPE 29 (see earlier reference) and *Energy Report of the Government of the Federal Republic of Germany*, Federal Ministry of Economics, Bonn (1986).

• *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 CO_2 emissions. Yet they demonstrate the potential for reducing CO_2 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 CO_2, they, therefore, have a special responsibility to "over-proportionally" reduce CO_2 emissions. In favourable climatic conditions, developing countries should make use of renewable energy sources.

Nuclear power can make a significant contribution to solving the CO_2 problem. Each 1000-megawatt-electric reactor prevents the emission of about 6 million tonnes of CO_2 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 CO_2 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 CO_2 from the atmosphere depending on climatic conditions. Therefore, between 3000 and 6000 square kilometres of forests would be needed to absorb the CO_2 emissions already prevented by one 1000-megawatt nuclear plant compared to a comparable coal-burning plant. Thus, the 1.6 billion tonnes of CO_2 *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 CO_2.

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 CO_2 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 CO_2 emissions must be based on its technological capabilities, economic wealth, alternative energy options, and the amount by which it has polluted the atmosphere with CO_2 in the past.

• Apart from their positive impact on CO_2 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 CO_2 emissions. This could be very cost-effective where technologies with low CO_2 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.