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Potential Contribution of the Clean Coal Program to Reducing Global Emissions of Greenhouse Gases

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INTRODUCTION

The U.S. Department of Energy's Clean Coal Program (CCP) is a government and industry co-funded effort to demonstrate a new generation of more efficient, economically feasible, and environmentally acceptable coal technologies. To demonstrate the feasibility of the various clean coal technologies (CCTs), several "showcase" facilities are being constructed at selected locations throughout the U.S. The best and most promising CCTs will then be advanced in terms of technical, environmental, and economic performance to the point where the private sector can introduce them into the commercial marketplace.

Environmental considerations of the CCP initially focused on reducing emissions of sulfur dioxide (SO_2) and nitrogen oxides (NO_x) to the atmosphere. However, it has also become apparent that some CCTs may contribute appreciably to reducing emissions of carbon dioxide (CO_2), thereby diminishing the rate of any global warming that may result from greenhouse effects. This is particularly true for CCTs involving replacement of a major portion of an existing facility and/or providing the option of using a different fuel form (the repowering CCTs).

Because the subject of global-scale climate warming is receiving increased attention, the effect of CCTs on CO_2 emissions has become a topic of increasing interest. The Final Programmatic Environmental Impact Statement for the Clean Coal Technology Demonstration Program projected that with full implementation of those repowering CCTs that would be most effective at reducing CO_2 emissions (Pressurized Fluidized Bed and Coal Gasification Fuel Cell technologies), the national fossil-fuel CO_2 emissions by the year 2010 would be roughly 90% of the emissions that would occur with no implementation of any CCTs by the same date. It is the purpose of this paper to examine the global effect of such a reduction in greenhouse gas emissions, and to compare that effect with effects of other strategies for reducing global greenhouse gas emissions.

THE GREENHOUSE EFFECT AND ITS CAUSES

Our atmosphere allows a large percentage of incoming solar radiation to pass through to the earth's surface. There, it is converted to heat energy (infrared radiation) which does not pass back through the atmosphere as easily. The result is that heat energy is "trapped" near the earth's surface. This phenomenon is commonly called the greenhouse effect because of a limited analogy between the atmosphere and the glass in a greenhouse.

The greenhouse effect can be understood in more detail by considering the wavelengths of the radiation involved. Incoming solar radiation is primarily in the wavelengths between 0.2 and 2 microns (1 micron = 10^{-6} meter). The visible spectrum of light lies within this range, between (shorter wave) ultraviolet radiation and (longer wave) infrared radiation. The earth radiates energy in the infrared portion of the electromagnetic spectrum, primarily between about 5 and 50 microns. Certain trace gases in the atmosphere, such as CO_2 and water vapor, can absorb some of this infrared radiation as it travels upward from the earth. The energy thus absorbed is eventually re-radiated in all directions including back down toward the earth. The effect is that heat is recycled through the lower atmosphere. This process is conventionally referred to as the greenhouse effect, and the infrared absorbing gases involved are often referred to as greenhouse gases. The analogy to a greenhouse is open to criticism because the main effect of the glass in a greenhouse is to keep the warm air inside from escaping and mixing with the colder air outside. Nonetheless, the terms greenhouse effect and greenhouse gas have stuck with us just as has the word climate, which comes from an ancient Greek word klima, which means inclination (originally, having to do with the inclination of the sun's rays with respect to the earth).

The naturally occurring greenhouse gases in the atmosphere are mainly water vapor and CO_2. Ozone (O_3) is also a strong absorber in a narrow wave band around 10 microns. These gases are only a small percentage of the earth's atmosphere, whether considered individually or collectively. However, their collective effect is to keep the temperature of the air in which we live about 33°C (59°F) warmer, on average, than the earth's surface would be if there were no atmosphere.

Each greenhouse gas has its own particular absorption spectrum, or set of wave lengths which it selectively absorbs. Water vapor absorbs radiation at wave lengths around 5 to 8 microns, and also at wave lengths greater than about 18 microns. CO_2 absorbs radiation of wave lengths around 12 to 18 microns. The natural component of the greenhouse effect is not particularly effective between 8 and 12 microns, except for a very narrow ozone absorption band around 10 microns. However, many greenhouse gases are emitted to the atmosphere each year as a result of agricultural or industrial activities, and some of these gases are effective absorbers in the 8 to 12 micron band -- the wavelengths at which they can add most effectively to the natural component of the greenhouse effect.

In addition to water vapor, CO_2, and O_3, the greenhouse gases include methane (CH_4), nitrous oxide (N_2O), and several chlorofluorocarbons (CFCs, or freons). Notable among the CFCs are CFC11 ($CFCl_3$), and CFC12 (CF_2Cl_2). These compounds are the most common CFC species and account for most of the CFC production.[1] The atmospheric lifetimes of CFC11 and CFC12 are long, more than 50 years according to Ramanathan[2] and they have strong absorption bands in the 8 to 12 micron band[3], where infrared radiation from the earth is greatest and the natural component of the greenhouse effect is low. Although CFCs are greenhouse gases, they have counteracting influences on the greenhouse effect because they are particularly efficient destroyers of ozone in the stratosphere (where most of the atmospheric ozone is). Current thinking is that these counteracting influences on the total greenhouse effect have been roughly comparable over the last decade.[4].

Background Information on Individual Greenhouse Gases

Water Vapor. Water vapor is the most abundant greenhouse gas in the atmosphere. The variability in atmospheric concentration of water vapor is related to the short residence time of water vapor in the atmosphere -- about 8 days on average[5]. Other major greenhouse gases, except for ozone, have average atmospheric residence times of more than a year.[2] These time scales are large in comparison to the time it takes for winds to disperse these gases homogeneously throughout the atmosphere. Thus, concentrations of most major greenhouse gases do not vary appreciably from one region of the earth to the next.

Carbon Dioxide. After water vapor, the most abundant greenhouse gas in the atmosphere is CO_2. Measurement of the CO_2 content of air bubbles trapped in cores of polar and glacial ice[6,7] indicate that the "pre-industrial" CO_2 concentration in the atmosphere was between 275 and 285 parts per million per volume (ppm). Atmospheric CO_2 concentration has increased by about 25% over the last century. Recent (through 1990) CO_2 concentrations measured at several locations around the world were in the range of 351 to 357 ppm.[8,9,10] Most of the CO_2 increase in the last century has been attributed to the burning of fossil fuels. However, biomass burning may have contributed a substantial amount of CO_2 to the atmosphere. Estimates of the current annual contribution of CO_2 emissions contributed by biomass burning run as high as 50% of the fossil-fuel contribution.[11] However, these estimates are characterized by a wide range of uncertainty.

Methane. After water vapor and CO_2, the next most abundant greenhouse gas is methane, which is present in concentrations of about 1.6 to 1.7 ppm. Over the last decade it has increased by about 1% per year,[12] but during the last four years the rate of increase may have slowed to about 0.8% per year.[13] A large percentage of atmospheric methane is produced by bacteria breaking down organic matter in the absence of oxygen. Major sources include: wetlands, lakes, rice paddies, cattle and other cud-chewing animals, fossil fuel production, biomass burning, and landfills.[14]

Nitrous Oxide. Nitrous oxide is also a greenhouse gas. Its current concentration is about 0.31 ppm and has recently been increasing by about 0.2% per year,[15] although in the last four years that rate may have increased slightly to about 0.25% per year.[13] It is produced by biological processes in soils and in natural waters.[15] Increased nitrogen inputs to the soil, via fertilizers or in the form of acid rain, may be contributing to the natural processes by which N_2O is released to the atmosphere.

Ozone. Ozone is a greenhouse gas that varies in concentration from almost zero at night near the ground to as high as 10 ppm at about 12 miles (20 km) altitude. Most ozone is found in the stratosphere, which extends from about 8 to 30 miles altitude. There it is formed by chemical processes requiring the presence of ultraviolet radiation. In the troposphere, which extends from the ground to the stratosphere, O_3 is produced via different reactions involving nitrogen oxides and hydrocarbons in the presence of visible light.

Chlorofluorocarbons. These gases are not a natural component of the atmosphere, but are entirely the result of human technology. They are currently present in the atmosphere in concentrations of less than one part per billion,[3] but are increasing at rates of 4 to 5 percent per year.[13,16] These relatively small concentrations can be deceptive because CFCs are particularly effective absorbers of infrared radiation. CFCs have long atmospheric lifetimes and eventually ascend into the stratosphere where they lead to the destruction of ozone. Their rate of increase is likely to be slowed as a result of international agreements made during the late 1980s (e.g., the Montreal Protocol of 1987) to limit their production. As noted above, CFCs can cause reductions in stratospheric ozone. These counteracting influences of CFCs on the total greenhouse effect appear to have been roughly comparable over the last decade.[4]

Relative Effects of Greenhouse Gases on Climatic Forcing

Carbon dioxide accounts for about 99%, by volume, of the greenhouse gases in dry air (water vapor being neglected because its concentration is variable and, on average, is many times that of CO_2). The contribution of CO_2 to the current greenhouse effect is also many times higher than the combined effects of other greenhouse gases except for water vapor. However, in terms of increasing the greenhouse effect, the relatively rare greenhouse gases are often much more effective on a molecule-by-molecule basis. This is largely because the CO_2 absorption bands in the electromagnetic spectrum are closer to radiative saturation. That is, there is enough existing CO_2 to absorb most of the radiation in these bands, so there is not much radiation left that could be absorbed by additional CO_2. By contrast, the absorption bands of CFC molecules are not saturated because CFCs are present in low concentrations and there is little overlap with absorption bands of other gases.[16] These are some of the reasons why the addition of one molecule of CFC12 can have the same greenhouse effect as the addition of 10,000 molecules of CO_2.[16] However, one CFC molecule can also cause the destruction of several molecules of ozone via mechanisms discussed by Panofsky[17] and Levi.[18]

Table I shows the breakdown of contributions of particular gases to greenhouse warming, as projected by Mitchell[16] for the year 2035. Ozone is expected to decrease, rather than to increase, because of the presence of the CFCs. If ozone depletion were to exactly cancel out the CFC increase, then the total greenhouse warming by year 2035 would be 2.45 W/m^2, and the CO_2 percentage of this would be about 73%. It should be noted, however, that even if the idea of mutual cancellation of CFC and ozone effects over the last decade is exactly correct, that is not likely to be the case in the future if CFCs to continue to increase while ozone decreases. Further, the effects of the Montreal Protocol and subsequent international agreements for reducing CFCs decreases are not known.

CARBON DIOXIDE TRENDS

The increase in atmospheric CO_2 concentrations over the last 100 years is well documented and reasonably well quantified. Measurements of atmospheric CO_2 concentrations at Mauna Loa, Hawaii, go back to March, 1958[9] and a less continuous record from the South Pole began in June, 1957.[10] Present and projected future anthropogenic source terms for atmospheric CO_2 are presented in Table II. Coal burning in the U.S. contributes about 8.4% of the global total. However, this percentage is projected to rise to about 11% by 2010.[19]

After reviewing studies of projected fossil-fuel growth, Mitchell[16] selected a value of 1.4%/yr for growth in global emission rates of CO_2. This leads to global CO_2 emissions of 32,286 tons/year from fossil fuels only by 2010. It is this value that is given in Table II. It will also be used for making comparisons of the expected global CO_2 emissions for 2010 with the reductions in CO_2 emissions that might be reasonably expected from successful commercialization of clean coal technologies. Note that unless otherwise indicated, weight units in this paper are short tons rather than metric tons.

CLEAN COAL TECHNOLOGIES AND REDUCTION OF CO_2 EMISSIONS

Environmental considerations of the Clean Coal Program initially focused on reducing emissions of sulfur dioxide (SO_2) and nitrogen oxides (NO_x) to the atmosphere. More recently, however, CO_2 and solid wastes have also been considered.[20] Atmospheric CO_2 is generally regarded as beneficial because it is an essential ingredient of the photosynthesis reaction and because it has contributed to making the earth warm enough for human habitation. However, recent concern about an increase in greenhouse effect possibly leading to a rapid climatic change, with a related rise in sea level and potential upsets to major ecosystems, has led to an attitude that it might be wise to also control CO_2 emissions. Clean coal technologies (CCTs) could thus have an added side benefit. By virtue of higher coal-use efficiency (more energy produced per unit of coal burned), certain CCTs could, with full commercialization, reduce U.S. CO_2 emissions from coal burning by 20% or more of what they would otherwise be and thereby reduce U.S. CO_2 emissions from all fossil fuel sources by around 10% of what they would otherwise be by the year 2010. The effects of the Clean Coal Technology Program on concentrations of other greenhouse gases are expected to be negligible. NO_x reductions from CCTs could lead to corresponding reductions in tropospheric ozone. However, most ozone is in the stratosphere. The contribution of tropospheric ozone to any "greenhouse warming" in the next few decades is expected to be negligible.

Clean Coal Technologies

Clean coal technologies (CCTs) may be divided into two categories: repowering and retrofitting. Repowering technologies replace a major portion of an existing facility and provide the option of using a different fuel form. They can achieve significant emissions reductions (for NO_x, SO_2, and CO_2) and may also increase facility capacity, extend facility life, or improve system efficiency.[20] Retrofit technologies reduce emissions by modifying existing facilities or their present feedstock or by using new fuel forms.[20]

Repowering technologies include: (1) Circulating Atmospheric Fluidized-Bed Combustion (CAFB), in which the low combustion temperature limits NO_x formation and optimizes the sulfur capture by the limestone that is mixed with the coal; (2) Pressurized Fluidized-Bed Combustion (PFB) in which the combustor operates at very high pressure, most of the sulfur emissions are captured in the combustion process, and lower operating temperatures reduce NO_x emissions; (3) Integrated Gasifier Combined Cycle (IGCC), in which coal is converted into a fuel gas which is then cleaned and used to fire a gas turbine generator, and the exhaust heat is then used to produce steam and drive a steam turbine generator; and (4) Coal Gasification Fuel Cell (FC) in which a coal gasifier supplies the fuel gas for electrochemical conversion of the chemical energy in the fuel to electrical energy, thus eliminating a large heat engine and its inherent efficiency limitations.

Retrofit technologies include advanced combustors, advanced flue gas desulfurization, combined SO_2 and NO_x control, and advanced NO_x control. Retrofit technologies are divided into three classes in terms of the ability to meet new source performance standards (NSPS). These classes are: NSPS capable, partial NSPS capable, and new fuel forms. The NSPS capable technologies includes those that can control SO_2 and NO_x emissions to levels equal to or below the NSPS limits. The partial NSPS capable class includes technologies that, when applied singly, will control either SO_2 or NO_x to NSPS levels. New fuel forms technologies physically or chemically alter the coal so as to reduce emissions of SO_2 and/or NO_x.

Effects of Clean Coal Technologies on CO_2 Emissions

To comply with the National Environmental Policy Act (NEPA), a comprehensive Programmatic Environmental Impact Statement (PEIS) was prepared to address potential environmental consequences of CCTs by the year 2010.[20] The PEIS compared potential consequences of widespread commercialization of CCTs with a no-action alternative which assumed that CCTs were not adopted and that conventional coal-fired technologies and conventional flue gas desulfurization would continue to be used for new plants or refurbishment of existing plants.

Changes in emissions of SO_2, NO_x, and CO_2 projected to result from full implementation of CCTs are compared with the no-action alternative in Table III. The numbers given represent the percentage change in national emissions if each technology were applied independently to 100% of its respective applicable market. That is, the percentages in the table are not additive, there is some overlap inherent in the construction of the table, and the figures represent the maximum projected changes in the environmental parameters of interest for each particular technology. The environmental costs of producing clean coal (e.g., the CO_2 produced by converting coal to fuel gas for the Integrated Gasification Combined Cycle Technology) have been factored into the calculations. Because the retrofit technologies are seen to have close-to-negligible effects on CO_2 emissions, the following material applies mainly to repowering technologies that are capable of reducing CO_2 emissions substantially by increasing the amount of energy produced per unit of coal burned.

Repowering technologies and their corresponding projected reductions in gaseous emissions are listed in Table IV. Fuel cell technology is seen to be most effective in reducing CO_2, and Circulating Fluidized-Bed Combustion is seen to be least effective. In the following discussion, an optimistic assumption of a 10% reduction (as compared to the no-action alternative) in total U.S. fossil fuel CO_2 emissions (from all sources) by the year 2010 will be made to represent an approximate best case result for market penetration of CCTs. Because the U.S. contribution to global fossil-fuel CO_2 emissions is projected to be about 22% of the total in the year 2010, a 10% reduction in the U.S. contribution by that year is equivalent to a 2.2% reduction in global emissions, as compared to the no-action alternative. This is equivalent to reducing CO_2 emissions by about 700 million (short) tons per year by 2010. The 2.2% figure above only applies to global CO_2 increases contributed by fossil fuels. Because biomass burning also contributes CO_2 to the atmosphere, this percentage may be even lower. It should also be noted that CO_2 is expected to contribute about 50% to 75% (depending upon the net contribution of the CFCs) of the increase in greenhouse effect experienced by 2010. Only negligible reductions in emissions of industrially produced greenhouse gases other than CO_2 are expected from CCTs. Therefore, full implementation of CCTs in the United States would be expected to decrease human-induced global warming by only about 1% to 1.5%, depending on the extent to which CFCs and corresponding ozone depletion cancel each other out in terms of greenhouse effect. Even if CO_2 from biomass burning could be reduced to zero and the net effect of CFCs were zero, the decrease in any human-induced global warming due to full implementation of CCTs in the U.S. would be, at most, about 2%.

PERSPECTIVE

The contribution of CCTs to reducing human induced greenhouse warming would be only about 1% to 2%, even assuming favorable market penetration by repowering CCTs. This percentage might at first seem insignificant. However, significance (like truth and beauty) is often in the eye of the beholder. The following paragraphs consider the role of CCTs in reducing greenhouse gas emissions in the context of other possible mechanisms to accomplish the same purpose.

Because the residence time of CO_2 and most other greenhouse gases in the atmosphere is long compared to the time required for global dispersion by wind patterns, emissions from any location on the face of the earth contribute to the global average concentrations. The current buildup of CO_2 and other greenhouse gases is therefore the result of contributions by many technologies within a variety of industries or practices serving virtually all sectors of society in every inhabited region of the world. Even in the largest CO_2 producing countries, no single technology or application of a technology produces more than a few percent of the global fossil-fuel CO_2. Therefore, a significant reduction, or even elimination, of any single fossil-fuel technology in any particular country would have little effect on the overall amount of global fossil-fuel consumption and resulting CO_2 emissions.

For example, Wolff and Frosch[21] have estimated that a complete elimination of U.S. vehicular exhaust sources would result in a 3.5% reduction in the anthropogenic component of the greenhouse effect. Their percentage accounts for CO_2 emissions from the production of motor fuel as well as from its consumption. They noted that it could be argued that the elimination of all U.S. vehicles would have only a negligible effect on global greenhouse forcing. Other examples of the same concept are readily available from CO_2 emission data,[22] and some of these examples are shown in Table V. There is probably no single CO_2 source in any country of the world for which drastic reduction or elimination of emissions would realistically be expected to reduce worldwide CO_2 emissions by as much as 5% (or to reduce the anthropogenic component of the greenhouse effect by as much as 2% to 3%). Reduction of global CO_2 emissions is, therefore, a "nickel and dime proposition" in which steps can only be taken in increments of a few percent at most.

On a more positive note, CO_2 reductions could be achieved by simultaneous measures that would have a nontrivial cumulative effect. Several options are available to reduce CO_2 emissions in the next generation. These include alternative (non-fossil) energy sources and energy conservation, as well as CCTs. It should be noted that these alternative energy sources and energy conservation may lead to a reduction in coal use, so that by 2010 the actual amount of coal burned may be less than the projections given in Table II. In that case the CO_2 savings due to CCTs would be less, because those savings are determined by the amount of coal that is actually used in CCTs.

In any case, the repowering CCTs add one more option to the list of ways to reduce future CO_2 emissions to the atmosphere. The CCTs are comparable quantitatively with other individual measures considered specifically for reducing CO_2 emissions, although CCTs were initiated for a different purpose. Further, CCTs would have less drastic effects on people's life styles than would some of the other measures that have been considered for reducing CO_2 emissions. Finally, this analysis considers only the potential implementation of CCTs in the United States. The extent to which such technologies could penetrate the international market could represent an amplification of their potential effectiveness in reducing global CO_2 emissions.

CONCLUSIONS

Clean coal repowering technologies, if fully implemented, could reasonably be expected to reduce U.S. fossil fuel CO_2 emissions by as much as 10% of the amount that would occur without these technologies.

Because only 22% of global fossil fuel CO_2 emissions come from the U.S., the reduction of CO_2 resulting from full implementation of CCTs would be about 2.2 percent of the global total.

Because CO_2 from non-fossil sources (e.g., biomass burning) and gases other than CO_2 are likely to be responsible for a substantial fraction of any increase in greenhouse effect that may occur by 2010, full implementation of CCTs in the U.S. would be expected to reduce the overall effects of greenhouse gas increases by only about 1% to 1.5%.

Global increases in atmospheric CO_2 and many other greenhouse gases result from a large number of "nickel and dime" contributions, so that the largest reduction in global CO_2 emissions that could be realistically expected from any single technological innovation or national policy change within the next 20 years is almost surely less than 5%. Therefore, several measures must be implemented simultaneously if CO_2 emissions are to be reduced appreciably.

Potential measures for reducing CO_2 emissions include non-fossil energy sources and energy conservation. CCTs, which were initiated to reduce NO_x and SO_2, provide an additional option that compares quantitatively with some other individual measures that have been suggested specifically for reducing CO_2 emissions.

The extent to which CCTs penetrate the international market would amplify the effects considered in this paper, which only considered the implementation of CCTs in the United States.

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Table I. Relative effects of projected increases in greenhouse gases on global warming from 1985 to 2035.[16]

Gas	Estimated contribution to radiative forcing of greenhouse warming (W/m^2)
Carbon dioxide	1.8
Methane	0.5
Nitrous oxide	0.15
CFC11	0.35
CFC12	0.69
TOTAL	3.49

Table II. Recent and projected sources of atmospheric CO_2 in millions of (short) tons. (Parentheses indicate the percentage of the world fossil fuel total due to each particular source category.)

Year	1986	1989	Projected 2010
Coal Only, USA	1763[20]	2014[22] (8)	3637[19] (11)
All Fossil Fuel, USA	4803[20] 4867[22]	5370[22] (22)	7100[20] (22) 6990[19] (22)
Coal Only, Global	9104[22]	9665[22] (40)	NI[a]
All Fossil Fuel, Global	22,430[22]	24,111[22]	32,286[b]

[a]No information.
[b]Calculated assuming a 1.4% per year increase in global CO_2 emissions, as per Mitchell.[16]

Table III. Comparison of the consequences of full implementation of clean coal technologies with consequences of the no action alternative.[20]

Clean coal technology category	Consequences of clean coal technologies (vs no action)			
	SO_2	NO_x	CO_2	Solid Waste
Repowering technologies	-29 to -48	-14 to -17	-5 to -12	-15 to +8
Retrofit technologies				
NSPS capable	-30 to -45	-11 to -33	0 to <-1	-22 to +19
Partial NSPS capable	0 to -48	0 to -15	0 to <-2	-2 to +9
New fuel forms	<-1 to -26	-3 to +4	0 to +1	0 to +23

Table IV. Projected reductions in U.S. fossil-fuel CO_2 emissions by 2010, for implementation of the repowering CCTs.[20]

Clean coal technology category	Applicable market (quadrillion Btu)	Consequences of clean coal technologies (vs no action)			
		SO_2	NO_x	CO_2	Solid Waste
CAFB	27.4	-44	-17	-5	+8
PFB	27.4	-48	-17	-8	-4
IGCC	27.4	-37	-17	-6	-5
Fuel cell	27.4	-29	-14	-12	-16

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Table V. Comparison of the potential effect of clean coal technologies with effects of other scenarios for reduction of global emissions of CO_2. (Units are millions of short tons of CO_2, per year, injected into the atmosphere.)

Scenario for year 2010	Millions of Tons of CO_2
Favorable market penetration of repowering clean coal technologies in the U.S.	700
Reducing U.S. oil consumption by 30%[a]	700
Reducing U.S. coal burning by 35%[a]	700
Reducing U.S. coal burning by 20%[b]	700
Reducing coal burning in the Peoples Republic of China by 33%[a]	700
Reducing coal burning in the USSR by 40%[a]	700
Completely eliminating all oil consumption in Japan (using 1988 data for Japanese oil consumption)	600
Reducing world oil consumption by 5%[a]	500
Completely eliminating all oil consumption in Germany (using combined data on FRG and DDR oil consumption for 1988)	350

[a]Percentage refers to the amount for 1989.[22]
[b]Percentage refers to the amount projected for 2010.[19]