The Greenhouse Effect: Damages, Costs, and Abatement

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Foreword

This Research Report resulted from a 1989 collaboration between Jörg Walter, a member of the Young Scientists Summer Program and Prof. Robert Ayres, then a member of the Technology, Economy and Society (TES) program at IIASA.

The work was stimulated by IIASA's growing involvement in global changes, in general, and by several papers presented at the International Energy Workshop, held in June 1989, in particular.

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Abstract

The buildup of so-called "greenhouse gases" in the atmosphere – CO_2 in particular – appears to be having an adverse impact on the global climate. This paper briefly reviews current expectations with regard to physical and biological effects, their potential costs to society, and likely costs of abatement. For a "worst case" scenario it is impossible to assess, in economic terms, the full range of possible nonlinear synergistic effects. In the "most favorable" (although not necessarily "likely") case (of slow-paced climate change), however, it seems likely that the impacts are within the "affordable" range, at least in the industrialized countries of the world. In the "third world" the notion of affordability is of doubtful relevance, making the problem of quantitative evaluation almost impossible. We tentatively assess the lower limit of quantifiable climate-induced damages at US$30 to US$35 per ton of "CO_2 equivalent", worldwide, with the higher level of damages being concentrated in regions most adversely affected by sea-level rise. The non-quantifiable environmental damages are also significant and should by no means be disregarded.

The costs and benefits of (1) reducing CFC use, and (2) reducing fossil fuel consumption, as a means of abatement, are considered in some detail. This strategy has remarkably high indirect benefits in terms of reduced air pollution damage and even direct cost savings to consumers. The indirect benefits of reduced air pollution and its associated health and environmental effects from fossil-fuel combustion in the industrialized countries range from US$20 to US$60 per ton of CO_2 eliminated. In addition, there is good evidence that modest (e.g., 25%) reductions in CO_2 emissions may be achievable by the USA (and, by implication, for other countries) by a combination of increased energy efficiency and restructuring that would permit simultaneous direct economic benefits (savings) to energy consumers of the order of US$50 per ton of CO_2 saved. A higher level of overall emissions reduction –

possibly approaching 50% – could probably be achieved, at little or no net cost, by taking advantage of these savings.

We suggest the use of taxes on fossil fuel extraction (or a carbon tax) as a reasonable way of inducing the structural changes that would be required to achieve significant reduction in energy use and CO_2 emissions. To minimize the economic burden (and create a political constituency in support of the approach) we suggest the substitution of resource-based taxes in general for other types of taxes (on labor, income, real estate, or trade) that are now the main sources of government revenue. While it is conceded that it would be difficult to calculate the "optimal" tax on extractive resources, we do not think this is a necessary prerequisite to policy-making. In fact, we note that the existing tax system has never been optimized according to theoretical principles, and is far from optimal by any reasonable criteria.

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1. Introduction

Human economic and industrial activity has reached a level of intensity that threatens the stability of the global atmosphere-biosphere system. One consequence to be expected is a significant warming of the climate. The proximate cause is a buildup of the concentrations of several trace gases in the atmosphere. The so-called Radiatively Important Gases (RIGs) are carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), tropospheric ozone (O_3), and chlorofluorocarbons (CFCs). Since pre-industrial times the first four gases have increased by 25%, 96%, 8%, and 0–25%, respectively (Ramanathan, 1988). CFCs are purely anthropogenic, having been invented in the early 1930s. They are used commercially as refrigerants, solvents, and foaming agents.

These greenhouse gases or RIGs are transparent to incoming short-wave (visible) radiation but they strongly absorb and reradiate long-wave thermal radiation. The net result is to change the radiative balance of the earth in such a way that more energy is trapped. *Table 1* shows the relative potency (absorptive power), atmospheric lifetime, and the contribution of different RIGs to global warming. Carbon dioxide is still the major contributing gas (about 50% of the total effect) and comes mostly from the burning of fossil fuels.

The expected increase of CO_2 and CO_2-equivalent concentrations is shown in *Figure 1*. Doubling of CO_2 equivalent gases (written as $2 \times CO_2$

Table 1. Global warming potentials for various greenhouse gases on mole and weight bases relative to CO_2.

			Molar basis		Weight basis	
Gas	Residence time (yrs)	Instantaneous forcing ($W\ m^{-2}\ ppm^{-1}$)	Cumulative forcing ($W\ m^{-2} yr\ Pmol^{-1}$)	Global warming potential	Cumulative forcing ($W\ m^{-2} yr\ Pg^{-1}$)	Global warming potential
CO_2	230	0.015	19	1.0	0.42	1.0
CO	(2.1)	(0.65)	26	1.4	0.94	2.2
CH_4	(14.4)	(0.65)	71	3.7	4.4	10
N_2O	160	3.8	3,400	180	77	180
HCFC-22	15	190	15,000	810	180	410
CFC-11	60	220	74,000	4,000	540	1,300
CFC-12	120	280	190,000	10,000	1,600	3,700

Source: Lashof and Ahuja (1990).

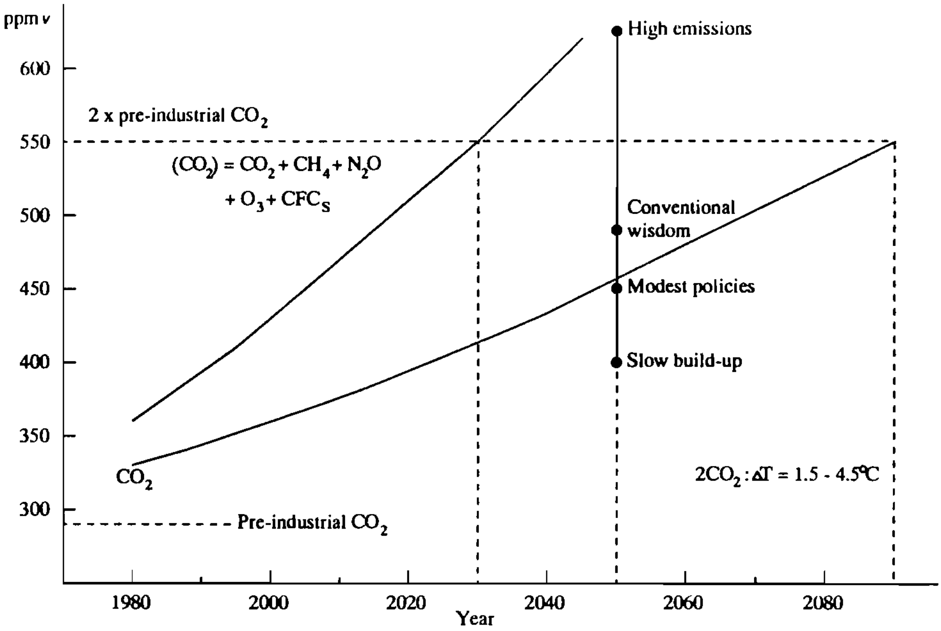

Figure 1. Expected increase of CO_2 and CO_2-equivalent concentrations.

for convenience) will occur between 2030 and 2090 according to conventional "high" and "low" emissions scenarios.

One of the major uncertainties in the system is ocean uptake. Today, it is generally believed that about 50% of anthropogenic CO_2 emissions are absorbed by the ocean, the remainder accumulating in the atmosphere. The accumulation (which is directly measurable), of course, leads to other effects. One of them is an increased rate of photosynthesis. However the rate of absorption (net of re-emission) by the oceans is still somewhat uncertain, and the exact role of the various actors in the system is still open to question.

Carbon dioxide is an essential input to photosynthesis by green plants. From laboratory experiments, it is estimated that a doubling of the ambient CO_2 concentration would cause a 10–50% increase in the yield of so-called C_3 crops (e.g., wheat, rice) and a 0–10% increase in yield of C_4 crops (e.g., corn). Depending on specific crop and growing conditions, the amount of water required to fix a unit of carbon is reduced, increasing yields in cases of growth limited by water availability (Bolin *et al.*, 1986). Leaf stomata, where gas exchange takes place (CO_2 in, O_2 and water vapor out) tend to decrease in size. Whether the effect of CO_2 "fertilization" will occur in open fields is uncertain. A few ambiguous multiple-year experiments reported suggest no permanent increase in the photosynthetic rate (Sedjo and Solomon, 1990). The possibility of biochemical surprises cannot be ruled out if the concentration of a major component of organic life is doubled. (By comparison, the ambient CO_2 concentration during the last Ice Age, 18,000 years ago was 25% lower than it is now).

A consequences of overall climate warming is likely to be changes in the temporal and spatial distribution of temperature, precipitation, evapo-transpiration, clouds, and air currents. All of these are simulated in so-called global circulation models (GCMs), although the detailed results of the simulations are not as yet a trustworthy basis for forecasting. (The next generation of such models should be considerably improved.) Computations carried out to date, comparing equilibrium for the $2 \times CO_2$ condition with control runs for current climate, show a very nonuniform response even to uniform change in RIGs. In effect, the regional effects are much more variable – and uncertain – than the global average projections. (For details see: Schneider, 1989a, 1989b, and 1989c; Schneider and Rosenberg, 1990; Bolin *et al.*, 1986; USEPA, 1988; Mintzer, 1987.) However, the nonlinear character of the system makes it likely that better GCMs will continue to exhibit significant regional variability.

The global mean temperature (GMT) is expected to rise between 2°C and 5°C for the $2 \times CO_2$ condition (Schneider and Rosenberg, 1990). This is remarkable compared to the last Ice Age extreme: 18,000 years ago GMT was about 5°C colder than today (Schneider, 1989a). The standard projection of global temperature evolution is shown in *Figure 2*. The regional averages change from –3° to +10°C with probable changes in seasonality and variability.

Global precipitation is likely to increase by 7–10% (high confidence); regional changes are projected to range from –20% to +20% (low confidence). The largest warming will occur in high latitudes and will be combined with large precipitation increases in winter. Higher temperatures will probably (high confidence) increase evapo-transpiration by 5–10% on global average. Soil moisture is controlled by precipitation, evapo-transpiration, and run-off. Regional changes are projected (medium confidence) to be in the range of plus or minus 50% (Schneider and Rosenberg, 1990).

According to Schneider and Rosenberg run-off would increase globally and changes on a regional scale of –50% to +50% are expected. They are direct results of changes in evapo-transpiration (which is strongly influenced by temperature) and precipitation. Simulation studies on arid and semiarid river basins in the USA suggest that relatively small changes in temperature

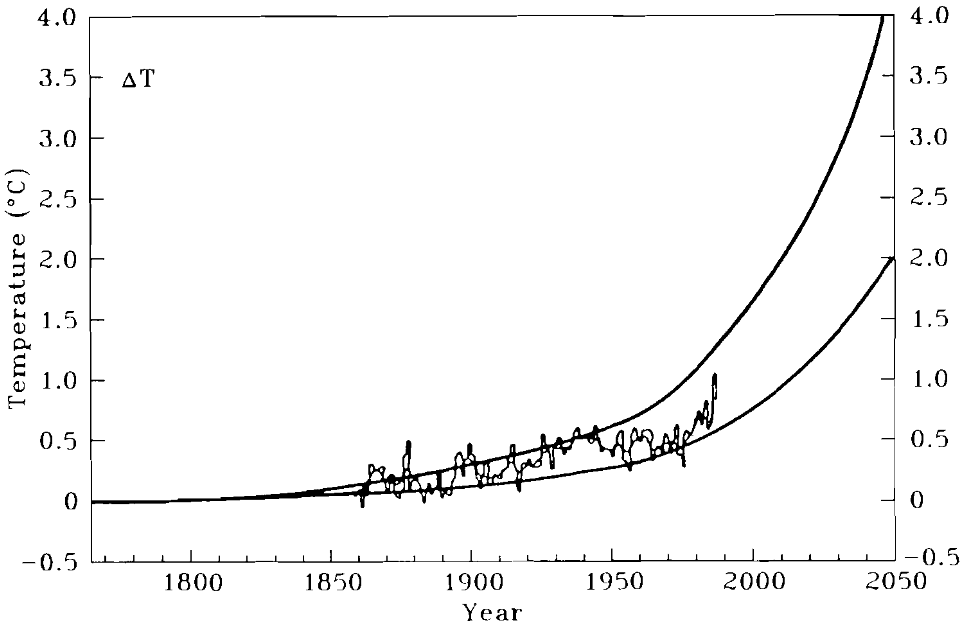

Figure 2. Expected temperature rise. Source: Wigley (1987).

and precipitation can have multiplier effects on run-off (see *Table 2*). There is evidence that run-off will increase in winter in high latitudes and decrease in summer in mid and low latitudes. These changes in run-off patterns "could greatly alter the likelihood of flooding and the availability of water during peak-demand periods such as irrigation seasons" (Frederick and Gleick, 1990, p. 133).

Thermal expansion of the ocean water will be the major cause of the expected sea-level rise (SLR) in the short term. Robin (1986) has estimated the SLR to be in the range of 0.2 to 1.65 meters. *Figure 3* shows a set of projections of SLR over time. The disintegration of the Western Antarctic Ice Sheet (Ross Sea) will take more than a century. An SLR of five meters is not out of the question. It can be regarded:

> ... either as the worst case that might occur during the next century or as an effect that might occur within three to five centuries. The fact that sea level has risen by 65 meters since about 10,000 B.P makes these numbers less fanciful than they would otherwise appear. (Hekstra, 1990, p. 56)

Table 2. Effects on runoff.

Basin-Study	Temperature change (°C)	Precipitation change (%)	Annnual runoff change (%)
Great Basin	+2	−10	−17 to −28
		+10	+20 to +35
Pease River	+3	−10	−50
		+10	+35
Sacramento	+2	−10	−18
		+10	+12

Source: Frederick and Gleick (1990).

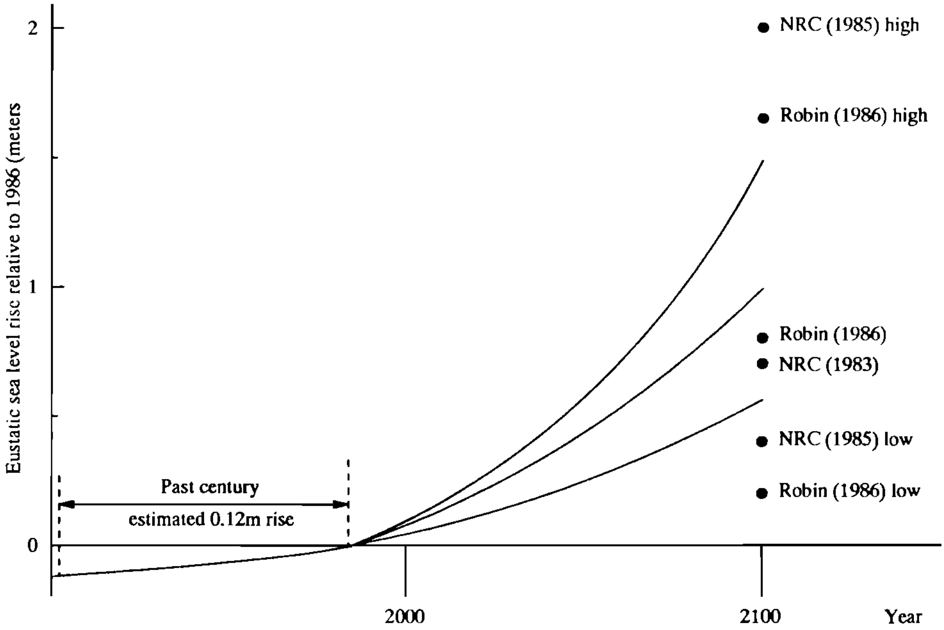

Figure 3. Projections of SLR over time.

Warming of the ocean is a delayed nonuniform process depending on local mixing rates. The feedback to climate will cause a transient phase which is so far not predictable with the current (equilibrium) GCMs. Impacts on ocean currents like a displacement of the Gulf Stream, or local SLR effects, are not taken account of by GCMs available to date. The major uncertainties of the current GCMs arise from inadequate knowledge of the air-ocean interface and the influence of cloud feedback. (For a detailed discussion of uncertainties and model validation, see Schneider and Rosenberg, 1990.)

2. Ecological Responses

The sensitivity of vegetation to climate has been investigated by (Emanuel *et al.*, 1985) and (Leemans, 1990) using the so called Holdridge classification. Since the broad scale distribution of terrestrial ecosystems is determined to a large part by the regional climate, one can relate the character of natural vegetation to climatic variables such as average annual temperature and precipitation. On the basis of interpolated data from about 8,000 meteorological stations a current world map of Holdridge life zones (grid resolution of $0.5^\circ \times 0.5^\circ$ latitude and longitude intervals) has been generated by Leemans and compared to a corresponding map computed for equilibrium $2 \times CO_2$ climate. The differences are quite significant.

The detailed maps cannot be reproduced here, but statistical analysis indicates that 48% of the global terrestrial surface would have to change its vegetation type. *Figure 4* shows results for the most productive life zones characterized by average annual temperature warmer than 3°C, and precipitation between 250 and 2,000 mm/yr. Total bar length corresponds to the total area of a current life-zone type (in terms of the Holdridge classification). The lower segment corresponds to the fraction of the area that would still belong to the same life-zone with a doubling of the CO_2 level. The middle segment reflects the fraction in which the current life-zone type is likely to be shifted to an *adjacent* category. The top segment reflects the area in which vegetation types can be expected to shift to a non-adjacent category.

Interpretation of these results is difficult because we have no experience with such rapid and broad scale changes in environmental conditions. The question that arises is not whether nature can adapt to changing climate in general (it can); the question is: *how fast can adaptation occur in a natural, unmanaged ecosystem, in response to global warming 10 to 60 times faster than any known to have occurred in the past?* (Schneider and Rosenberg, 1990). Solomon has calculated that the necessary migration rate of tree species to accommodate to $2 \times CO_2$ warming in 100 years (it could be even faster) has to be ten times higher than rates calculated for North America over the past 10 thousand years (Sedjo and Solomon, 1990).

Barriers, such as agricultural areas and urban areas, will tend to retard natural migration rates. As a result, a "rapid loss of tree species form landscape can be projected in the absence of massive reforestation programs" (Sedjo and Solomon, 1990, p. 108; also Solomon and West, 1985). As a result, a few tree species which have small, wind-dispersed seeds, easily transported over large distances, might dominate future landscapes.

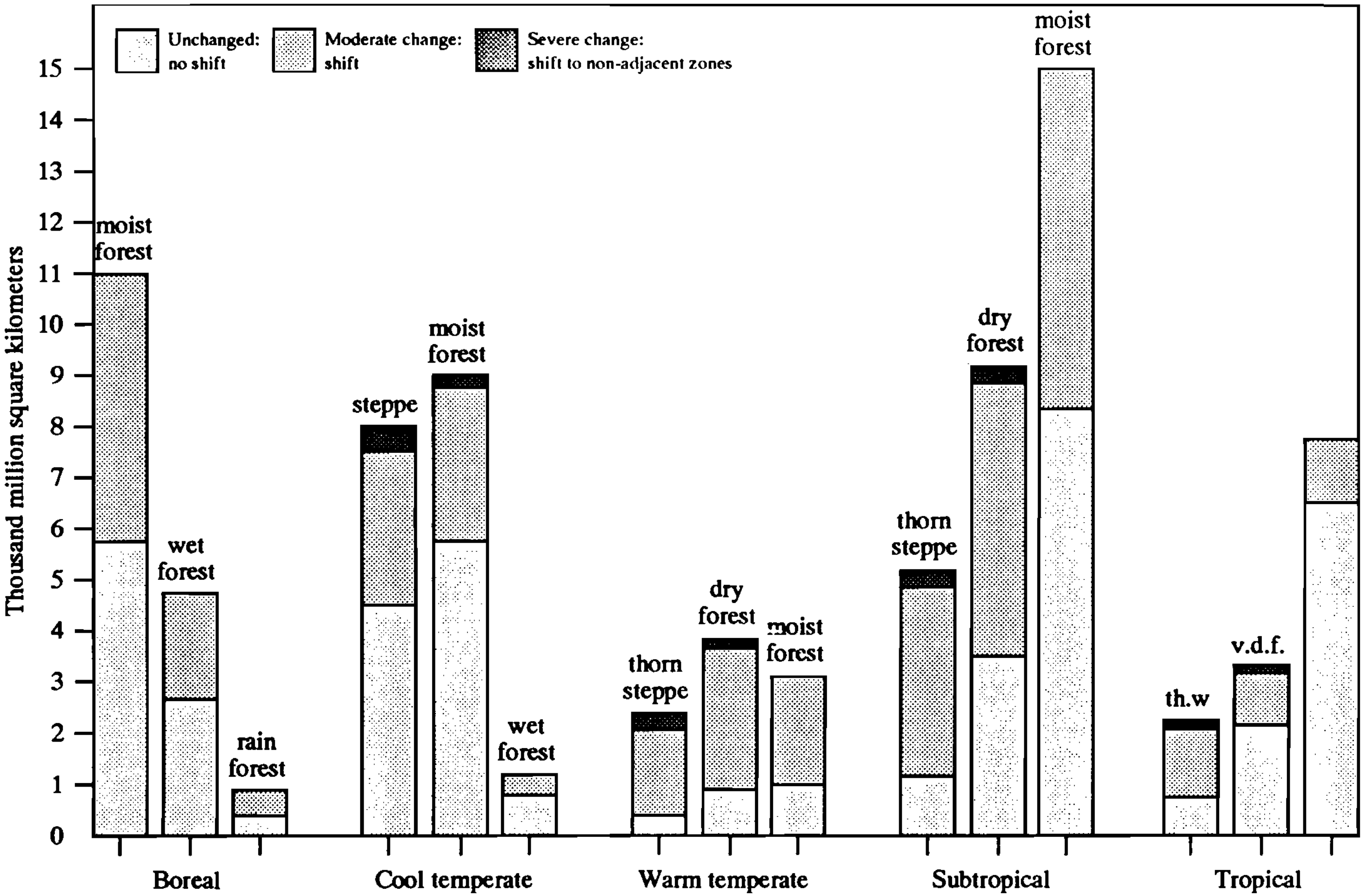

Figure 4. Shifts in life zones expected from doubling CO_2 level. Source: Adapted from Leemans (1990).

Nonlinear response to changes in temperature and precipitation variability, as well as nonuniform biological response to increased CO_2 concentration, will cause shifts in the species composition of biomes. Alteration of several fundamental ecosystem processes, such as nutrient cycles, is to be expected. An increase in intensity and spread of wildfires due to higher midsummer dryness might occur. Moreover, plant diseases and insect outbreaks severe enough to kill dominant species over large areas may occur with greater frequency (Batie and Shugard, 1990, p. 125).

Conservation systems, such as parks, refuges, and preserves which are dedicated to protecting wildlife populations may fail under different climatic conditions, "By the mid-21st century, the climate that nurtures Yellowstone National Park could well be into Canada. The tundra of the Arctic National Wildlife Refuge could be pushed into the sea" (Kerr, 1988, p. 23).

The effects of climatic change will be superimposed on other changes, including a general increase in the intensity of land use, forest clearing, groundwater withdrawal, soil erosion, and air and water pollution. Acidity, of course, is a consequence of the emission of SO_x and NO_x due to fossil fuel combustion. Thus acidity and CO_2 "enrichment" of the atmosphere tend to increase together. Moreover, the environmental stresses due to acidity will tend to have a multiplier effect on the stresses of climate change. The combination will further weaken the ability of some species to survive. (The environmental acidification problem is already severe in some regions; it has been blamed for the drastic "dieback" of conifer forests in central and east-central Europe). The combination of climate change with other stresses on ecosystems could be more dangerous than any one of them taken by itself.

3. Sea Level Rise and Coastal Impacts

The impacts of sea-level rise (SLR) on coastal regions are potentially massive. Coastlines will move inland up to several hundred meters, in many places, depending on beach slope and the characteristics of the beach material (Hekstra, 1990). Salt water will also move upstream via rivers into lowland, freshwater pockets behind coastal dunes, and into groundwater aquifers. The effect will be magnified in some areas where intensive groundwater withdrawal has occurred (e.g., Long Island, New York).

SLR will cause enormous loss of biologically diverse coastal lowlands and wetland ecosystems (Wilson, 1989). For instance, Indonesia possesses 15% of all world coastline and it is the world's richest country in terms of wetland ecosystems quantity and diversity. Yet "at least 40% of its land surface is vulnerable to SLR of 1 m" (Wilson, 1989, p. 58). Worldwide, the land area that would be subject to inundation or made vulnerable by salt water intrusion is about 500 million hectares. This is only about 3% of all land area, but it constitutes over 30% of the most productive cropland area (Wilson, 1989, p. 60). As many as one billion people now live in the vulnerable areas, including some very large cities. Thus, as has been pointed out, as much as one-fifth of world market valued assets could be adversely affected (Crosson, 1990).

4. Damages: Summary

Many environmentalists distrust economic analysis and judge the generation of quasi-market prices as ill-suited for the study of economic impacts of global climate change, for instance. They tend to advocate notions such as "safe minimum standard" as a risk-averse, conservative criterion for the survival of species, habitats, and ecosystems, provided the costs are not "unacceptably large" (e.g., Batie and Shugard, 1990, p. 129). Yet, these "simple" policy instruments are often ineffective in practice, and they may even increase costs excessively in relation to benefits achieved.

In short, there is no real substitute for economic analysis, however unsatisfactory the present state of the subject. Nor do we distinguish (as some environmentalists do) between economic costs and "other" costs (such as eco-degradation), with the implication that the latter cannot be compared with (or traded off against) the former. To us, it is a question of defining the realm of economics broadly enough. All costs are economic if the economy is properly defined, but not all economic costs are automatically reflected in the marketplace (i.e., "market valued"). Nor are non-market-priced environmental assets (such as parks or ecosystems) included in the standard System of National Accounts (SNA).

Economists have developed a variety of tools and methods to monetize benefits of non-market amenities such as environmental preservation. One approach identifies three categories, namely, *use*, *option*, and *existence* value (see Greenley *et al.*, 1981; Batie and Shugard, 1990). The "use value" refers to the benefits of "using" the ecosystem as a recreation place, e.g., bird watching. The "option value" is what potential consumers are willing (in principle) to pay to preserve the amenity for possible later use (e.g., (Krutilla, 1967; Lindsay, 1969; Byerlee, 1971; Arrow and Fisher, 1974; Henry, 1974). Sometimes a category called "quasi-option value" is introduced (Conrad, 1980). It applies in cases of an irreversible decision on the future of the resource and the expectation of new growing knowledge about the usefulness of the resource. Bequest value is what someone in the current (living) generation might pay to be able to be assured of passing the amenity on to the next generation.

Actual numerical estimates for these values are normally obtained by one of three methods. One method is to measure differences in property prices (house prices, rents) in polluted and un-polluted areas for which all other factors that might contribute to price differentials are either known or equal (see Wicke, 1986; Schulz and Wicke, 1987). This is called the *hedonic* price approach. It is obviously limited in its applicability to a few cases where the (large) data requirements can be met.

Another econometric method applicable to valuation of parks, monuments, nature reserves, archeological or art objects is to assume that the value of the site or object is proportional to the actual time and money expenditures on tourist travel attributable to the site.

The third method is to ascertain "willingness to pay" (WTP) for an indicated improvement in environmental quality – such as visibility – by surveying a representative sample of the regional population, e.g., Bohm (1979). Refined sensitivity tests are needed to compensate for so-called "strategic behavior" (since those surveyed usually do not actually pay) (Bishop and Heberlein, 1979; Survey-type methods have been used for a number of years, with increasing levels of sophistication.[1] A fairly remarkable and robust result of such studies is that the non-use related value (option and existence value) can easily exceed the direct user benefits of recreation, for instance (Greenley *et al.*, 1981; Mitchell and Carson, 1989).

Notwithstanding the recent methodological progress in this area, the problem of quantitative measurement for non-market costs is still far from completely solved. In addition to methodological difficulties and ambiguities in applying the new indirect methods to assess damages likely to be associated with climate change some practical difficulties will also arise:

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[1] Such methods have been used, for instance, to estimate the benefits of improved water quality in the Merrimack River Basin in Connecticut (Oster, 1977), the South Platte River Basin of Colorado (Walsh *et al.*, 1978; Greenley *et al.*, 1988) and of the Tegeler See in W. Berlin, (Ewers and Schulz, 1982), as well as air quality in West Germany (Schulz and Wicke, 1987).

- The climate issue is not local, but regional and global. Hence there is an inherent problem with regard to assuring the representativeness of any sample survey.
- Changes will be nonlinear and some will be irreversible (i.e., species extinction).
- Interactions on several time-scales can cause numerous unforeseen consequences.

Due to the methodological and practical difficulties noted above, simpler approaches tend to be used in cases such as the present one. A rather typical example is summarized briefly below.

4.1 Nordhaus' estimates of damage costs

A recent study by William Nordhaus has attempted to estimate the economic costs of climate change (Nordhaus, 1989 and 1991). He began with a breakdown of the US gross national income or GNI[2] (for 1981) by sector and subdivided it further into *regimes* of sensitivity. The most climate-sensitive sectors were agriculture, forestry, and fisheries, amounting to 3.1% of total NI. Moderate sensitivity was attributed to sectors such as construction, water transport, utilities etc. These contributed 10.1% of the total. The rest (86%) comes from sectors affected negligibly by climate (e.g., mining, finance, manufacturing, etc.).

The results of this analysis were as follows:

(1) Agriculture damage costs (offset by the CO_2 fertilization effect) are estimated as plus or minus US$10 billion as an overall impact on all crops.

(2) Sea level rise (SLR) damages were estimated for land loss (15,540 square km) and protection of high-value property and open coasts by levees and dikes. The total market value of the property at risk is on the order of US$100 billion. Nordhaus converted this to an estimated annual equivalent loss of US$6.18 billion per year. (The capital value of property should reflect its continuing flow of benefits, thus reflecting tourism losses implicitly, at least so far as providers – hotel and motel operators and so on – are concerned. What is omitted is the loss of use and option value to users, who may not be able to find equivalent amenities elsewhere).

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[2] Gross National Income (GNI) differs from GNP by excluding indirect business taxes and capital set aside to replace depreciation.

(3) Greenhouse warming is expected to increase aggregate demand for airconditioning (US\$1.65 billion/yr) and reduce the demand for space heating (US\$1.16 billion/yr). Assuming average current prices for electricity and fuel, there would be a net annual extra cost to the economy of US\$0.46 billion (USEPA, 1988).

(4) No specific estimates were made by Nordhaus for other goods or services (either market-valued or otherwise). In effect, these were lumped together and included in the uncertainty of the overall estimate (see below).

Summarizing the quantified cost items above, the breakdown is as follows:

- 8% attributable to energy demand changes.
- 92% attributable to SLR (of which 85% is for coastal protection cost – levees, seawalls, etc. – and 7% is for loss of low-lying land).

The *bottom line* – the central (most likely) estimate of total annual economic damages, D, was US\$6.67 billion (1981 dollars), assuming the damages occurred in 1981. This is equal to 0.28% of US gross national income for that year. The error bounds were judged (by Nordhaus) to be quite a bit higher, due to the omitted unquantified items, but still less than two percent of national income.

Gross world income (GWI) in the year 2050 is likely to be more than US\$26 trillion (1981 dollars) (USEPA, 1989, low GNP case). This is 8.1 times more than US national income in 1981. Thus Nordhaus judged this scaling factor of 8.1 to be appropriate to extrapolate the US damage "snapshot" to global annual damages in 2050 (assuming similarity of income structures). In other words, annual world damages due to greenhouse warming are "most likely" to be about US\$54 billion (1981 dollars), with an upper limit of US\$520 billion. Based on expected emissions of 16.9 billion tons of CO_2 equivalents Nordhaus converted this to *marginal shadow damages of emission*, namely: central case: US\$ 3.3/ton (CO_2-equivalent); worst case: US\$ 36.9/ton (CO_2-equivalent).

The above calculation (Nordhaus' numbers) is based on one fairly "heroic" (and technically incorrect) assumption with regard to physical damage: that future damage is simply proportional to RIG emission rates on a *current* basis, i.e., no accumulation of RIGs, and no damage dependence on rates of warming. Of course, the economic assumptions are equally strong, as already noted. For example, the pattern of energy use in the USA bears little relation to the rest of the world. The extrapolation to global scale assumes a similar balance between air-conditioning and space heating, which is somewhat implausible.

4.2 Modifications to Nordhaus' estimate

Bearing in mind the long list of potential adverse effects and costs, most of which have not been quantified - or even mentioned - by Nordhaus, many environmentalists will not be satisfied with the relatively simplistic sort of calculation exemplified above. To address these doubts it seems useful to examine Nordhaus' assumptions in more detail. We focus, first, on the implications of SLR, inasmuch as this item accounts for 92% of the total costs identified by Nordhaus.

With regard to SLR the major costs identified above are protection costs of valuable coastal land and beaches (via seawalls, dikes, and levees). The total US coast length is about 20,000 km. Average protection costs of about US$5 million per km coastline appears reasonable in view of the Dutch experience (e.g., Hekstra, 1990).

The coastline of the world amounts to between 0.5 million and 1 million km. To protect it to the same extent as projected in the USA, the total cost would be about US$2.5–US$5 trillion, or 10–20% of minimum GWI for 2050. Spread in proportion to GWI over 50 years, as Nordhaus did, this comes to about 0.2–0.4% of world GWI annually, or roughly what Nordhaus assumed. It is a rough magnitude of avoidance costs for the physical protection of "protectable" low-lying areas, estuaries and so on.

Nordhaus' estimate of land-loss cost of 1.55 Mha (million hectares) along the US coastline (19,924 km) is equivalent to 77 ha/km coastline. This is a factor of ten less than Hekstra's estimate of 500 Mha vulnerable land along 0.5–1.0 million km coastline, or 500-1000 ha/km (Hekstra, 1990). The land value assumed by Nordhaus (US$5000/ha) lies in between Hekstra's estimate for arable cropland in Bangladesh (US$3000/ha) and in the Netherlands (US$30,000/ha). Assuming Nordhaus' price of US$5000/ha, the total land value loss based on Hekstra's estimate of vulnerability, would be US$2.5 trillion. Spread over 50 years this would account for 0.3% of the world GWI, on average. This is still well within Nordhaus' range of error, of course.

Yet the methodology of estimating potential loss by attaching current values to submerged land is inherently suspect, even allowing for "scaling". In the first place, current monetary prices of land in different countries clearly reflect current levels of money income and exchange rates. In the second place, since the total amount of arable land will be reduced in absolute terms, it is clear that the price of the remaining land will rise along with the sea level. The gain in land values elsewhere could well outweigh the coastal losses. Yet one could hardly conclude that SLR might therefore be beneficial. Moreover, the remaining land would have to be cultivated more intensively to make up the shortfall, and food prices will rise, as Schelling noted. A gain for the (remaining) farmers, but a loss for consumers. (The same valuation problem arises if OPEC succeeds in raising the price of oil).

The use of land prices (based on current exchange rates) implies that coastal land in the USA or the Netherlands is more valuable than coastal land in Bangladesh or the Nile Delta. This conclusion makes no sense for a study of this kind. Land is more productive in Bangladesh or the Nile Delta than in the USA and probably no less productive than in the Netherlands. Land value should be related to its productivity in real terms for purposes of assessing long term costs of climate warming. On this basis, land losses in Bangladesh or Egypt should be evaluated at US$30,000/ha, rather than US$3000/ha. Using prices based on international exchange rates undervalues land in poor countries by an by an order of magnitude. Moreover (as Nordhaus noted) the USA derives little of its national income from coastal lands; the opposite is true in Bangladesh. A loss of 10% of the arable land of a country where 70% of the population lives on the land would (roughly) cut its real national income by at least 7%. It is the exchange rate that is artificial and misleading (being based on trade balances in a few portable commodities and manufactured goods). If the notion of marginal utility – rather than land price – were invoked, it would seem to follow that the utility loss to Bangladesh must be far greater, per capita, than the utility loss to the USA. Thus, the extrapolation from US calculations to the third world is unsatisfactory, to say the least.

Since the vulnerable low-lying lands are heavily populated, we must expect some environmental refugees. For example, more than 1,000 islands in the Maldive Atolls may be swallowed up by the sea. The deltas of the Brahmaputra River (Bangladesh) and the Nile River (Egypt) are densely populated. Assuming SLR of 0.79 m by the year 2050 and 2.17 m. by 2100, the homes and livelihoods of 46 million self-supporting people would be lost (Jacobson, 1989). Under "really worst case" assumptions, including widespread subsidence due to excessive groundwater pumping, the number threatened would be substantially higher. Bearing in mind Hekstra's estimate of one billion people potentially "affected" by SLR, it is not unreasonable to suppose that as many as 100 million people – mainly subsistence farmers with no urban experience or skills – may be displaced. They will have no place to go except to the already overcrowded cities.

How much does a refugee cost? It depends where the refugees are located and on their status and skills. Malawi's social cost per Mozambiquan refugee is reported as a mere US$24 per capita (*The Economist*, February 18, 1989). An inquiry by the UN High Commissioner for Refugees and the World Food Program sets the annual average expenditure of these two official institutions per assisted refugee at US$72 per capita, or about 20 cents per day; not too much. These costs reflect extremely bad conditions, such as those in camps for Palestinian refugees located in Lebanon and Jordan. On the other hand, the USA spends some US$4,000 per accepted refugee [US$362 million for 94,000 refugees arriving in 1988 (*The Economist*, September 24, 1988)].

These are just maintenance or resettlement costs. Since a refugee is obviously unproductive for some time, it would be sensible to assume one or more years of lost output (GNP/capita). In the case of the "low cost" Palestinian refugees, there is no resettlement program and the production loss is much more than a year or two – more nearly permanent. The social costs of repression, terrorism, regional political turmoil, and military/police responses to all of the above should be included also. These costs tend to dwarf the pure "subsistence" costs, although they are almost never properly allocated. Even in the case of refugees admitted to the USA or other industrialized countries, the period of adjustment is significant, especially is the refugees are uneducated. In order to get a crude magnitude of likely social costs for resettling economic refugees from the poorer countries (within the same country) we assume a modest two year period of lost output at US$250/yr, or US$500/capita at 1981 income levels. (Comparable GNP/capita figures for 1985 were: India US$270, Bangladesh US$160, Egypt US$760 (WRI, 1989, p. 236). Altogether, this adds up to US$250 billion, over 50 years. Assuming significant economic growth in these areas, resettlement costs and losses rise in proportion; it would not be unreasonable to double or even quadruple this figure.

A revised set of SLR costs, based on the above reasoning is as follows: coastal protection cost: US$2.5-5 trillion; coastal land loss: US$15 trillion; costs of resettling 100 million refugees at US$1,000 each: US$1.0 trillion; total: US$18.5-21 trillion.

This is a total for the world as a whole, spread over 50 years as Nordhaus did, and therefore comparable to his numbers. Annualized, it comes to around 2.1–2.4% gross world income (GWI), or nearly 10 times higher than Nordhaus "central" estimate for total costs, and slightly outside his range of error. For reasons discussed previously, we think US$30-35 per tonne of CO_2 (equivalent) is more realistic than US$3.30, just to take account of the effects of SLR on countries like Egypt and Bangladesh.

Of course many indirect effects are still omitted, that have completely unknown shadow costs. One of the most obvious is the implicit assumption that there is empty land available somewhere to resettle the refugees. In fact, there is no likelihood of such resettlement. Displaced persons will crowd into cities creating squatter settlements that tax the available city services to the limit. These shanty towns are already prime reservoirs of frustration and disaffection, and a breeding ground for violence, crime, and civil unrest. What are the true social costs of uprooting people, taking into account the breakdown of traditions and family relations, and the resulting social problems for the rest of society? We do not know, except that the costs are not zero.

Moreover, large numbers of refugees in Southeast Asia would augment the immigration pressure to the more highly developed countries in a dramatic way. The *boat people* from Vietnam may be only the vanguard of an enormous migratory wave the world in general (and Australia, in particular) is ill-prepared to cope with. So far, the USA has not succeeded in integrating its black population, after 125 years of struggle. Britain has not solved its problem with the commonwealth immigrants, France has difficulties with the North African immigrants, while West Germany is finding its small Turkish minority quite indigestible. Lacking adequate "social technologies" most countries will, instead, end up spending more money on internal and external security.

In summary, there is good reason to believe that "when the winners and losers have been identified, there will be little interest on the part of the winners to alter their status in order to compensate the losers" (Glantz, 1988, p. 409). In short, there is increasing risk of tensions, frictions, and conflicts threatening political stability.[3] Yet, it is impossible to put a convincing number on these indirect effects, if only because the causes of social tensions and disruptions are multifarious and the *greenhouse effect* contribution is likely to be relatively minor compared to other factors. All things considered, Nordhaus' estimates seem too optimistic by a considerable margin.

Before moving on to consider abatement strategies and costs, it must be pointed out once again that Nordhaus' estimates of losses and costs exclude

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[3] See, for instance, the Brundtland Report (Brundtland, 1987, pp. 291–294, p. 300); also Renner (1989, pp. 141–144); and Myers (1989a and 1989b).

all losses to final users of environmental assets, as well as option and bequest value losses. What is the option value of the last Redwood forest or the large shade trees on urban streets and in urban parks? Old, slow-growing trees like oaks, elms, maples, and beeches are clearly vulnerable to climate change (*cf.* the work of Leemans and Solomon, cited earlier) and are highly valued. Since fully grown trees cannot be moved, there is no actual market for them; however the retail prices of relatively young trees (around 20 years old) range up to US$500. It is quite normal for suburban property owners in the USA to spend several hundred dollars per year for tree care.

If this can be taken as an indicator of the value of the underlying assets, then one would have to impute a value of at least several thousand dollars to each mature shade tree in a built up area. The number of such trees is unknown, but it probably exceeds the number of people (at least in the USA and Western Europe). If the life expectancy of shade trees is reduced from 200 years to 50 years by rapid climate change, there will be a major loss of amenity value, and a sharp increase in expenditure on landscaping (the rate of tree-planting would have to increase by 4-fold, for instance). Other costs of maintaining parks and gardens will also rise sharply. This would translate into significant annual costs for both individual homeowners and cities. We do not attempt to take the calculation further, except to note that annual expenditures by suburban homeowners of the order of 2% or 3% of income to maintain trees and shrubs are by no means uncommon today. (Averages are smaller, of course.) Still, an annual average expenditure for this purpose in the next half century (including indirect outlays) attributable to the higher costs of compensating for effects of climate change, would not be implausible. In summary, we suspect that the sum total of potential losses of this type greatly exceeds the items that Nordhaus has actually quantified.

5. Optimal Abatement

Let us now introduce an hypothetical relationship between emissions damages and abatement costs (*Figure 5*). Assume we know all damages $D(z)$ as a function of annual emissions z of greenhouse gases, incorporating present and future values, priced and unpriced (see discussion above). Further, assume

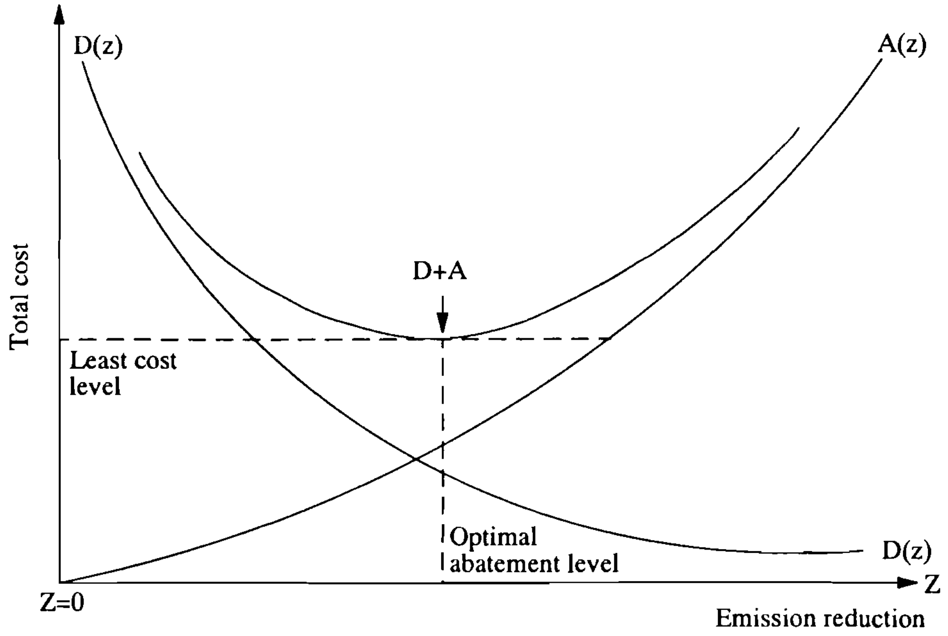

Figure 5. Abatement in economic equilibrium.

we know the cost function of abatement $A(z)$ for all levels of emissions. By assumption $A(z)$ describes the total cost to an economy of abating the next increment of greenhouse emissions by the most cost-effective available means. If reducing fossil fuel combustion is the chosen strategy, then the cost curve would reflect the costs of introducing energy-conserving technologies or providing alternative fuels, for instance.

The shape of $A(z)$ is usually derived from two general axioms in economic theory, namely, (i) that the economy is always in (or nearly in) an equilibrium state, and (ii) declining marginal cost-effectiveness of abatement with increasing levels of abatement. Given these assumptions, abatement costs are zero at the *laissez-faire* point of uncontrolled emissions and increase as a function of increasing abatement (CO_2-equivalent reduction). Because of declining marginal cost-effectiveness, the real cost of abatement $D(z)$ can be expected to increase at an increasing rate, as shown.

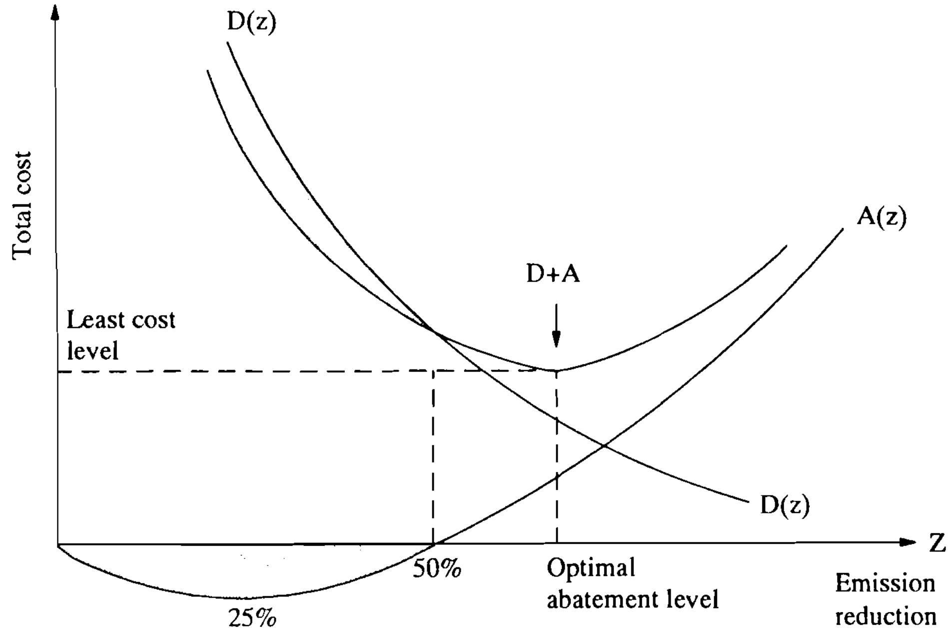

Figure 6. Optimal abatement in economic disequilibrium.

The optimal level of abatement is the minimum of the sum $D(z)+A(z)$, which has by definition a slope of zero. Both less and more reduction would lead to reduced welfare benefit. In other words: the optimal point is characterized by the equality of the absolute first derivatives (marginal costs) of A and D. Evidently, the *marginal benefit* of abatement is obtained from the slope of the damage cost curve, $D(z)$. The marginal cost of abatement is the slope of $A(z)$, where z is measured in percentage of CO_2-equivalent reduction.

Figure 6 contrasts with the usual version (*Figure 5*) with a rather different form of the abatement cost curve. It is inconsistent with one of the two key assumptions underlying *Figure 5* (the equilibrium assumption), but we think it comes much closer to reflecting reality. It reflects the view that, in fact, there exists a considerable opportunity to enjoy *negative abatement costs* (i.e., profits) by investing in selected technological "fixes", largely in the area of energy conservation.

The implication, of course, is that, for a variety of reasons – including massive market failures – the economy has become "locked in" to a suboptimal state of excessive energy/resource dependence.[4] We defend this proposition in more detail below. Of course, the optimum degree of abatement is still the point where $D(z)+A(z)$ is minimal. However, it will be noted that the optimal point is significantly to the right of the corresponding point in the case where $A(z)$ is monotonically increasing (*Figure 5*) and – more important – the optimal abatement level is far greater.

6. Abatement Strategies

Before analyzing the costs and benefits of alternative strategies to cope with the *greenhouse effect*, let us consider the principal different kinds of policy responses that have been proposed. There are two extreme cases:

(1) No response: unfettered emission, no policy to prevent greenhouse warming and adapt to a warmer climate.
(2) Halt the buildup of RIGs (responsible for warming) "immediately".

Clearly all realistic policies lie between these extremes. For example, the recent proposal to agree to reduce greenhouse emissions by 25% over the next decade would not halt warming, but would slightly reduce its rate of increase.

As regards strategies, there are many options, at least in theory, some are listed below:

(a) Reduce energy consumption (and resulting CO_2 emissions).
(b) Reduce CO_2 emission/energy unit e.g., shift to natural gas, because of its lower carbon content per energy unit (Ausubel *et al.*, 1988), or increase the use of nuclear energy.
(c) Halt deforestation and accelerate reforestation.
(d) Reduce CFC emissions, e.g., by shifting to less harmful substitutes.
(e) Divert CO_2 from entering the atmosphere (e.g., by pumping into the ocean).

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[4] The classic example of the "lock-in" phenomenon is the QWERTY typewriter keyboard, which is known to be inefficient but which is so well established that it seems unchangeable (David, 1985). Another example might be the persistent use of the so-called "English system of weights and measures." For a theoretical discussion of positive returns to scale and self-reinforcing mechanisms in economics see (Arthur, 1983 and 1988; Arthur *et al.*, 1987a and 1987b).

(f) Remove CO_2 from the atmosphere.
(g) Reduce other RIG emissions (e.g., methane).
(h) Offset climate effects, e.g., by painting roads and roofs white (albedo change) or by climate engineering (e.g., injecting submicron particles into the stratosphere).

Some of the items on this list are clearly beyond present technological capabilities, and have been included only for the sake of completeness. In this category we include all the above items, recognizing, however, that future technological advances might alter this conclusion. It is recognized that CFCs and other RIGs are much more potent than CO_2 per unit mass, and that energy-related activities do not account for more than about half of the total greenhouse emissions. However, the virtual elimination of CFCs is already recognized (by Nordhaus, and others) to be both feasible and cost-effective, and we see no need to discuss it in the present context. The sources of methane and nitrous oxide are not yet well understood, but they appear to be largely biological.[5] A major source of CO_2, as well, is from deforestation. Thus, a significant part of the greenhouse problem lies in the domain of agriculture, forestry, and land use. We do not consider this domain further in the present paper.

In the following discussion we focus mainly on the costs and benefits of CO_2 emission reduction by energy conservation and, where feasible, fuel substitution (items a, b). Nordhaus also considered two other possibilities: reforestation (item c) and CFC reduction (item d). We review the latter two options briefly in Appendices A and B, respectively.

7. Costs of Combustion-Related Emission Reduction

Ranking various alternative sources of energy and possibilities for switching to less carbon-rich fuels in terms of cost-effectiveness enables one to construct an abatement cost curve such as $A(z)$ in *Figures 5* or *6*. Assuming

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[5] The difficulty in reducing methane emissions is that, so far as is now known, most of the increase in atmospheric methane in the last two centuries is due to increased cultivation of paddy rice and (to a lesser extent) the buildup in numbers of cattle and sheep. Barring a major breakthrough in genetic engineering, it will be very difficult to reduce these sources of emissions. The increasing substitution of natural gas for coal (e.g., in Europe) will also increase the leakage which constitutes the third largest source of methane emissions.

the energy supply/conversion and industrial component of the economy "optimizes" quickly to adjust to changing prices (hence, it is always in or near its instantaneous equilibrium) such models can be used to estimate cost curves for various policy assumptions. Nordhaus has, for example, estimated the costs of achieving a given energy output with successively lower amounts of CO_2 production (Nordhaus, 1973 and 1976). He found that shadow costs could be expressed by a quadratic function of percentage emission reduction. A similar result was later obtained econometrically (Nordhaus and Yohe, 1983). Nordhaus used this function (updated to 1989 prices) in his recent work (Nordhaus, 1989 and 1991).

Another instance of this *macro* approach is found in the work of Manne *et al.* (1979).[6] This is a major modeling effort linking a macro-economic model and an energy supply-conversion optimization model of the "activity" type. There are three underlying assumptions (1) that the economy is always in a quasi-equilibrium state, (2) that it "finds" the optimum supply mix for a given demand more or less instantaneously, and (3) that energy consumption is both an input (factor), a cost of production, and a claim on resources. The former assumption means that energy appears as an input in a production function. When the production function is econometrically fitted to past data on energy consumption, energy prices, and total output of goods and services, it is possible to estimate the reduction in output. This can be interpreted (somewhat loosely) as the economic "cost" of reducing energy inputs by a given amount.

The interpretation of "lost gross output" as "cost of change" is justified for most economists by the notion that GNP is a measure of aggregate social welfare. This interpretation has been criticized, for various reasons. However, we do not propose to review the arguments *pro* and *con* here.

Engineers and businessmen think of costs in a somewhat different and more traditional way. A businessman would try to compute cost as the annualized net additional capital and operating costs of investing in and using a new technology. It can happen, of course, that little or no new investment is needed or that the result of the substitution results in a net saving, rather than a net cost.

For a business or a householder, a "net saving" translates into a profit, or a return on investment. The usual standard of comparison is money invested in high quality government bonds or, simply "money in the bank". In other

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[6] For an early review paper see Manne *et al.* (1979); also Manne (1981); Edmonds and Reilly (1985a and 1985b); Manne and Richels (1991).

words, if a given investment produces a greater return (assuming equal risk) than money invested at the current rate of interest, it is "profitable" in the above sense. If the rate of return is less than the interest rate, the investment is a loser. The usual target rate of return-on-investment (ROI) for business investments – which tend to be fairly risky, and which must allow for taxes on the profits – is typically around 30% per annum. If the best return that can be realistically expected is only 15%, a prudent businessman will not make the investment. On the other hand, for a government (which does not have to pay taxes and can borrow money at lower rates than a private business), an 8% or 10% expected rate of return is probably adequate justification.[7] (This is sometimes equated roughly with the social discount rate, although the latter is usually taken to be in the range of two to four percent in real terms.)

Given that capital is scarce, it is rational to invest in the most profitable ventures first. Thus, a business run by a profit maximizer should try to rank order the various proposals for capital spending (in order of expected ROI) and go down the list until either the available money for investment runs out or the minimum target rate-of-return threshold is reached. In principle, government should do the same. In an equilibrium economy, there should be just enough capital to fund all of the most promising projects, i.e., all the projects with expected ROI above the appropriate threshold level. It follows that the really promising (i.e., profitable) projects should be funded as soon as they are identified. In an equilibrium economy there should be very few opportunities capable of yielding returns far above the average. By the same token, capital should not be available at all for projects with below-threshold ROIs. *The existence of a class of under-funded projects with high ROIs, while another class of over-funded projects consistently yields below-norm ROI, is an indication of significant economic disequilibrium.*

In this context, it is relevant to note that most large-scale energy *supply* projects (e.g., hydroelectric or steam-electric plants) yield a long-term real net rate of return between 5% and 10% (*The Economist*, January 6, 1990, p. 59). Since this is below the threshold level for a rational tax-paying profit maximizer, it is difficult not to suspect that non-economic factors are involved in diverting capital into such investments.

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[7] Many projects are evaluated in terms of *payback time* rather than return. The two concepts are closely related. A project with a payback time of one year corresponds to 100% return on investment. A project that pays for itself in six months has an annual return of 200%, and so on.

On the other hand, there is ample evidence of under-utilization of profitable opportunities for conserving energy (e.g., Hirst and Hannon, 1979; Williams *et al.*, 1983; ACEEE, 1984; Berman, 1985; Geller, 1985 and 1988; Goldemberg *et al.*, 1987a and 1987b; Akbari *et al.*, 1988; Lovins, 1988; Rosenfeld and Hafemeister, 1988; Nelson, 1989). In a major study carried out by the Italian energy research institute ENEA it was shown that technological "fixes" exist with payback times of one to three years – well below the typical threshold for most firms and several times faster than investments in new supplies (e.g., d'Errico *et al.*, 1984).

Even more convincing evidence comes from the experience of the Louisiana Division of Dow Chemical Co. in the USA. In 1981 an "energy contest" was initiated, with a simple objective: to identify capital projects costing less than US$200,000 with payback times of less than one year (Nelson, 1989). In its first full year (1982), 38 projects were submitted, of which 27 were selected for funding. Total investment was US$1.7 million and the 27 projects yielded an average ROI of 173%. (That is, the payback time was only about seven months). Since 1982, the contest has continued, with an increased number of projects funded each year. The ROI cutoff was reduced year-by year to 30% in 1987, and the maximum capital investment was gradually increased. Nevertheless, in the year 1988, 95 projects were funded, for a total capital outlay of US$21.9 million and – surprisingly – an average ROI of 190%! The average submitted ROI for 167 audited projects over the entire seven years was 189%, while the actual (post-audit) average was 198%. *Table 3* summarizes the results of the Dow experience.

It is important to note that, although the number of funded projects increased each year, there is (through 1988) no evidence of saturation. Numerous profitable opportunities for saving energy, with payback times well below one year, apparently still exist at Dow even after the program has been in existence for seven years. One would have to suspect that the program could still be expanded many-fold before reaching the 30% ROI threshold. Furthermore, it is important to emphasize that these opportunities exist even at relatively low US energy prices. Should taxes or a new energy crisis force US prices higher (i.e., toward world levels), the number of such opportunities would be multiplied further.

At the macro-level, it has been argued in a study by the Mellon Institute that a "least-cost" strategy for providing energy services for the USA in 1978 would have utilized much less primary energy, and in a very different manner, than that which was actually observed. In economic terms, the "least-cost" strategy would have saved US$800 per family (17%) or US$43

Table 3. Summary of Louisiana division contest results – all projects.

	1982	1983	1984	1985	1986	1987	1988
Winning projects	27	32	38	59	60	92	95
Capital, US$MM	1.7	2.2	4.0	7.1	7.1	21.8	21.9
Average ROI (%)	173	340	208	124	106	77	190
ROI cutoff (%)	100	100	100	50	40	30	30
Savings, US$M/yr							
Fuel gas[a]	83	-63	1506	2498	798	2550	10790
Capacity						1197	2578
Maintenance	10	45	-59	187	357	2206	583
Miscellaneous						19	-98
Total savings	1590	3838	5341	7353	6894	11944	18023

[a] All fuel gas savings are based on 1988 incremental fuel gas value.
Source: Nelson (1989, Table 1).

billion in that year alone (Sant, 1979). Taking the year 1973 as a standard for comparison, such a strategy would have involved a sharp reduction in the use of centrally generated electricity (from 30% to 17%) and a reduction in petroleum use from 36% to 26%. The only primary fuel to increase its share would have been natural gas (from 17% to 19%). Interestingly, the Mellon study suggested that "conservation services" would have increased their share from 10% to 32% in the optimal case (see *Figures 7* and *8*).

What the Mellon study showed, in fact, is that (at 1978 energy prices) conservation, up to a point, would not have cost more (as *Figure 5* implies) – it would have cost *less* (as in *Figure 6*).[8] Between 1973 and 1978 "conservation services" reduced actual energy consumption by 10% compared to

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[8] It should be noted that the Mellon study was thoroughly critiqued by a group at MIT, at the request of the Department of Energy (Berndt *et al.*, 1981). The critique was extensive and detailed, and a number of significant substantive and methodological criticisms were offered. One criticism was directed at the study's implication that a "least-cost" solution would be achieved automatically if the economy were truly competitive. The authors of the critique asserted that competition does not necessarily yield an optimal result and that regulation might be more effective. The critique also noted that some of the projected savings were "imposed" on the study, rather than being derived endogenously. The examples cited in this regard included projected savings by the use of variable-speed electric motors, co-generation of electric power and industrial process heat, and dieselization of the bus fleet. In retrospect, the benefits of variable speed motors were certainly exaggerated somewhat. However, in defense of the study, it should be noted that there is no way technological shifts such as the ones noted could be generated endogenously by any economic model. Moreover, a large number of other specific but minor opportunities for

the 1973 baseline pattern; but a 32% reduction would have been not only possible, but cheaper! The differential between actual and potential is 22%. The greatest potential savings were to be found in the so called "buildings" sector (23%), but nontrivial savings (10%) were also available in the industrial sector. Significant opportunities also existed in industry, notably by avoiding (or in other words, using) waste heat by means of heat-cascading, heat pumps, and co-generation (of electricity and process heat). Assuming the Mellon Institute's figures to be roughly correct, the 22% unachieved but possible energy savings in 1978 would have reduced carbon dioxide production by at least 25% as compared to actual emissions. This amounted to around 275 million tons. The monetary savings to energy consumers would have been US\$43 billion, as noted, or about US\$65 per ton of CO_2 saved. This point would define the low point of the (negative) marginal cost of abatement curve in *Figure 6*.

If the curve in *Figure 6* is symmetric on both sides of this point, it follows that a gross reduction in fossil energy use and CO_2 emissions of roughly 50% should have been achievable (in 1978) at zero net cost to the economy as compared with the actuality. Clearly the optimum abatement level would be somewhat further to the right, perhaps around the 60% level, depending on the value of reducing emissions.

Admittedly the 1978 disequilibrium might have been reduced somewhat in the last decade, and energy prices have (temporarily) dropped. The above calculation is illustrative, at best. Still, an increase in energy prices (via taxes) would merely increase the already clear benefits of investing in energy conservation. Others have arrived at similar conclusions (see, for example, Lovins *et al.*, 1981). There is growing evidence supported by numerous examples that many investments in energy conservation can pay for themselves in reduced operating costs in a few months to a few years, even at present (lower) energy prices.

Before moving on to other issues, it is worthwhile commenting on the evident discrepancy between actual behavior and optimal behavior. Consumer behavior with regard to energy conservation is sometimes dismissed as "stupidity-limited" (Schipper, 1989). However, what appears to be "stupidity" at first glance can be resolved into two other phenomena. One of the probable explanatory factors is inadequate information. (Information is

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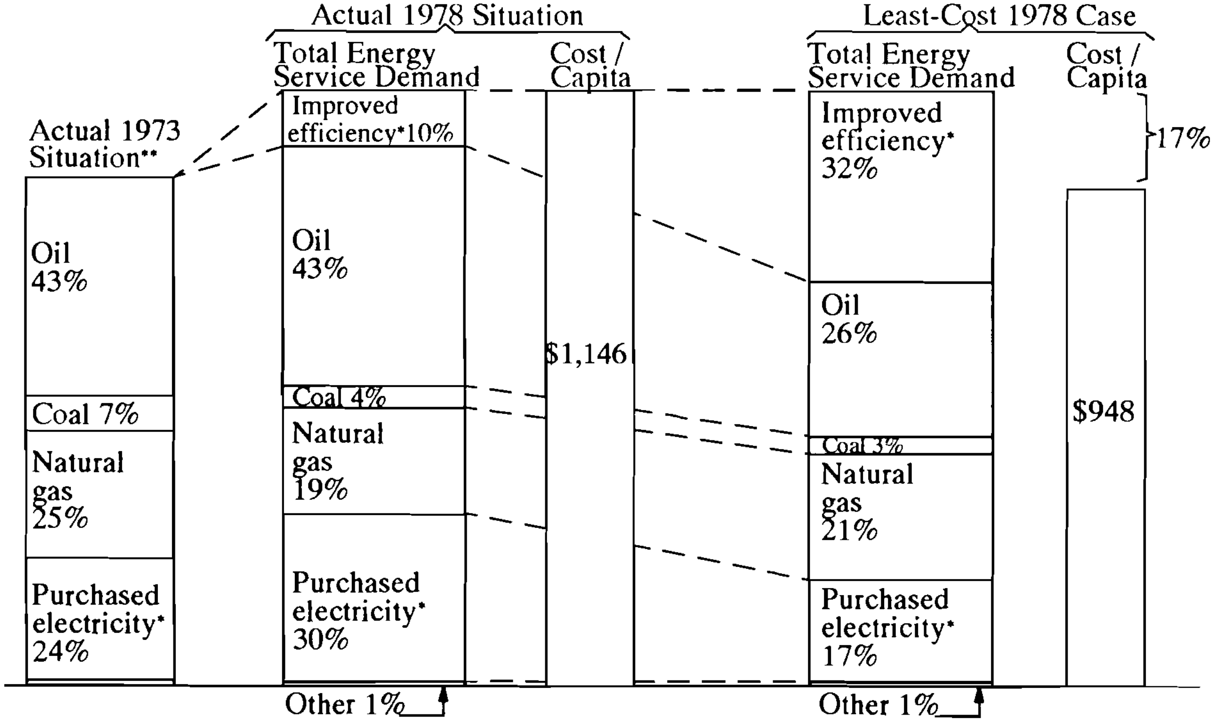
saving energy via the use of available technology were necessarily overlooked, simply because the authors had limited time and resources available to them. Thus, it is more likely that the extent of the conservation opportunities were underestimated than conversely.



(*) In terms of primary fuel (**) Primary fuels demand in 1973 was 74.6 quads.

Figure 7. Energy sector market shares of various technologies. Note: The primary fuel equivalent of service demand in 1978 was 79.0 quads, plus 9.2 quads of improved efficiency (calculated against a base of stock and equipment in place in 1973) or a total of 88.2 quads. Actual service depends on the conversion efficiency of fuels and equipment utilized. 1 quad = a quadrillion = 10^{15} BTU. Another means of visualizing a quad is one million barrels per day of oil equivalent = 10^{15} BTU (quads) per year. Source: Sant (1979).

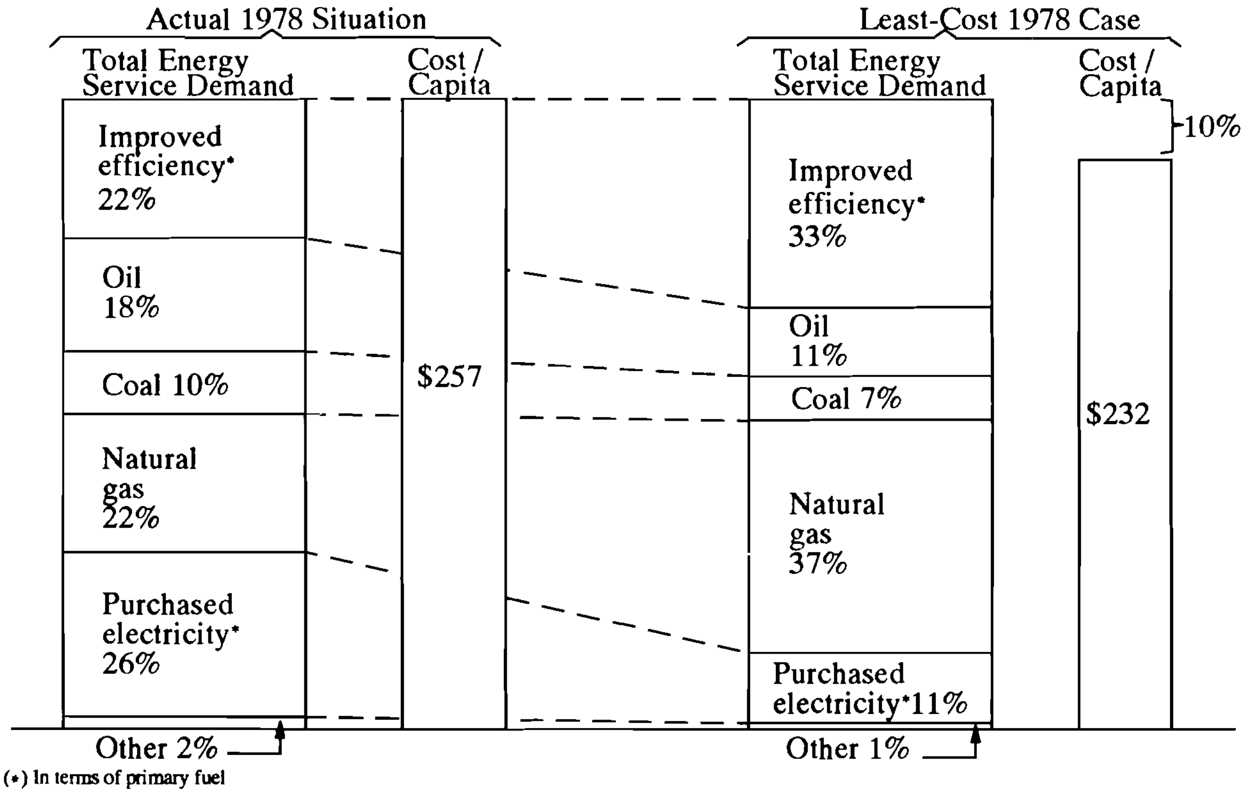


Figure 8. Industry energy service market shares of various technologies. Note: The primary fuel equivalent of service demand in 1978 was 28.2 quads, plus 7.9 quads of improved efficiency and 0.8 quads of biomass (calculated against a base of stock and equipment in place in 1973) or a total of 88.2 quads. Source: Sant (1979).

Table 4. Estimated discount rates using mean population estimates.

Income class	Number of observations	Implied discount rate
US$6,000	6	89.0%
US$10,000	15	39.0%
US$15,000	16	27.0%
US$25,000	17	17.0%
US$35,000	8	8.9%
US$50,000	3	5.1%

not costless, in the real world.) It has been remarked that lack of awareness by the consumer is a major impediment to increasing conservation in the end-use sector. Consumers focus today mainly on product color, size, and features and only a small amount on energy consumption during the appliance's lifetime. To some extent this can be countered by public information and awareness campaigns and government-sponsored information programs, such as "green labeling".

The other phenomenon, which deserves more study, is that individuals seem to display extremely high *discount rates* in their personal financial affairs. To put it simply, people will not voluntarily pay much extra or wait very long for promised savings in future operating costs of houses, automobiles or appliances. One study, based on detailed survey data on household appliance purchases, has inferred the average discount rate for consumers to be 20% (Hausman, 1979). It is strongly income dependent, however, as shown in *Table 4*. Note that much higher discount rates are observed for households with very low incomes (89% for the poorest category). Translated into payback times, consumer behavior among the lowest income group in the USA seems to correspond to personal "payback times" of the order of one year (or even less).

Any investment that pays for itself in much less than twenty years would be an unambiguous economic gain at the macro-economic level. (This follows from the fact that the average growth rate of the economy corresponds in a doubling time of the order of 20 years.) Businesses are generally happy to invest in moderately risky projects that will pay for themselves in five years if they are successful. The existence of numerous opportunities for paybacks of one or two years, with almost no risk, is clear evidence of a nonequilibrium situation.

Many economists have trouble with these implications. They ask: if, indeed, such opportunities really exist, why don't entrepreneurs operating in the competitive market place find and exploit the opportunities? The fact that this does not seem to be happening suggests that the opportunities are not real, after all; according to this view, there must be "hidden costs".

We have no authoritative answer to the question. We think, however, that the basic answer is related to two facts: (1) The opportunities for energy conservation are mostly incremental; they require many small investments, rather than a few massive ones. This is difficult for industry because of the second fact. (2) Large firms are central planners; they do not operate *internally* like competitive markets. Internal operations are bureaucratic, hierarchical, and "rule driven" rather than competitive. People with entrepreneurial instincts generally find it very difficult to function in bureaucracies or large firms. By the same token, large firms find it very difficult to induce their employees to behave entrepreneurially. The reasons for this must be sought in the incentive systems that function in bureaucracies.

8. Secondary Economic Benefits of CO_2 Reduction

As noted above (*Figures 5* and *6*), the economic benefit of emission reduction is equated with the corresponding damage reduction. A simple approximation to damage reduction in the present case can therefore be obtained by dividing total "greenhouse" damages by total carbon dioxide. It was suggested by Nordhaus that the most probable cost of such damages would be US$3.30 per ton of CO_2 eliminated, with an upper limit of US$37/ton (Nordhaus, 1989). We argued above that the first figure may be too low by a factor of ten, not even allowing for unquantified items such as loss of recreational and ecological assets. For reasons discussed previously we take the direct "greenhouse" benefits of eliminating CO_2 to be at least US$30 per ton.

However, except for the deforestation component, carbon dioxide is almost entirely produced by the burning of fossil fuels. This, in turn, generates emissions of air pollutants such as SO_x, NO_x, CO, and so on. It is literally impossible to eliminate combustion-related CO_2 without cutting down on the other pollutants, even in the unlikely case that all of the reduction is accomplished at the expense of the most benign of the fossil fuels, natural gas. In economic terms, greenhouse gases and conventional air pollutants are *co-products.* Hence the benefits of CO_2 emission reduction must be equated to the full set of benefits of reduced fossil fuel (at least, coal and oil) combustion, whether it be achieved by regulation, conservation or taxation. The latter, in turn, include all of the health and environmental benefits of air pollution reduction. (It is important to observe that air pollution benefits due to reduced fuel consumption will be in addition to and independent of any benefits achieved by emission controls.)

Of course, the air pollution and health costs of fossil fuel use depend on the specific fuel. They are much greater for coal, for instance, than for natural gas. One can monetize these benefits by a procedure that was first used for evaluating the social costs of road traffic and energy consumption in West Germany (Grupp, 1986; Hohmeyer, 1988). The major air pollutants cause damages at very different concentration levels. Relative weighting factors in the German studies were chosen as follows: Particulates = 100; SO_2 = 100; NO_x = 125; VOC = 100; CO = 1.

Since these toxicity weightings are derived mainly from animal experiments, the extrapolation to impacts on vegetation and materials remains questionable. However we know that SO_2 and NO_x contribute roughly equally to acidification, while CO, NO_x, and the hydrocarbon components take part in photochemical reactions (leading to ozone production) in a rather complicated and interrelated manner. Since most of the monetized damages are linked to human health, these assumptions seem to be a defensible compromise.

We also assume that the flow of annual damages from pollution (exclusive of the greenhouse effect) is approximately proportional to current emissions. This means no accumulation effects are considered. Since the scope of our concern is global, no complex trans-border transport of pollutants need be considered.

Table 5 shows emissions of traditional air pollutants in the FRG and the USA in the years 1975 to 1985, from all sources [including mobile sources (MS) and power plants (PP)]. These two categories account for most of the coal and petroleum, although some gas is used in electricity production and some oil is used for home heating. In effect, we are neglecting the pollutant effects of natural gas consumption. Weighting the data with the (toxicity) factors given above yields the results in *Figure 9*. *Table 6* shows the result in relative shares for mobile sources and for the power plant sector in total air pollution for the FRG and USA. *Table 7* gives total annual CO_2 emission in these two sectors for each country. In effect *Table 6* states that 39.5 percent of all (1985) air pollution damages in the FRG are attributable to

Table 5. Air pollutant emissions by sector (1000 t/yr).

	FRG			USA		
	1975	1980	1985[a]	1975	1980	1985[a]
Particulates						
All	813	696	576[a]	10600	8500	7000[a]
MS	61	64	70[a]	1300	1300	1400[a]
PP	179	151	127[d]	3036	2125	1750[b]
SO_2						
All	3325	3187	2345[a]	26000	23900	21600[a]
MS	132	107	94[a]	700	900	900[a]
PP	2062	1976	1426[d]	16829	16102	14768[c]
NO_x						
All	2532	2935	2924[a]	19100	20300	19800[a]
MS	1297	1594	1718[a]	8900	9200	8800[a]
PP	709	813	719[d]	4929	6101	6463[c]
HC						
All	2545	2486	2371[a]	22800	2300	20300[a]
MS	1164	1249	1196[a]	10200	8200	6700[a]
PP	25	16	24[d]	222	230	203[b]
CO						
All	13014	11708	8804[a]	81000	76100	64300[a]
MS	10148	8808	6301[a]	62000	52600	45200[a]
PP	521	471	352[a]	3380	3044	2572[b]

[a] OECD (1989).
[b] Adjusted from Benkovitz (1982).
[c] Adjusted from NAPAP (1990).
[d] Adjusted from Hohmeyer (1988).

vehicles and 27.4 percent to electric power generation. For the USA the corresponding figures were 27.5 percent and 33.4 percent.

The highest costs of external effects of air pollution are health-related.[9] Respiratory diseases, for instance, lead to costs of medical treatment, increased morbidity (loss of working time plus direct costs of illness), and an increased risk of mortality. Many epidemiological studies have attempted to

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[9] Losses of quality of life are still not monetized, hence not included in any of the estimates.

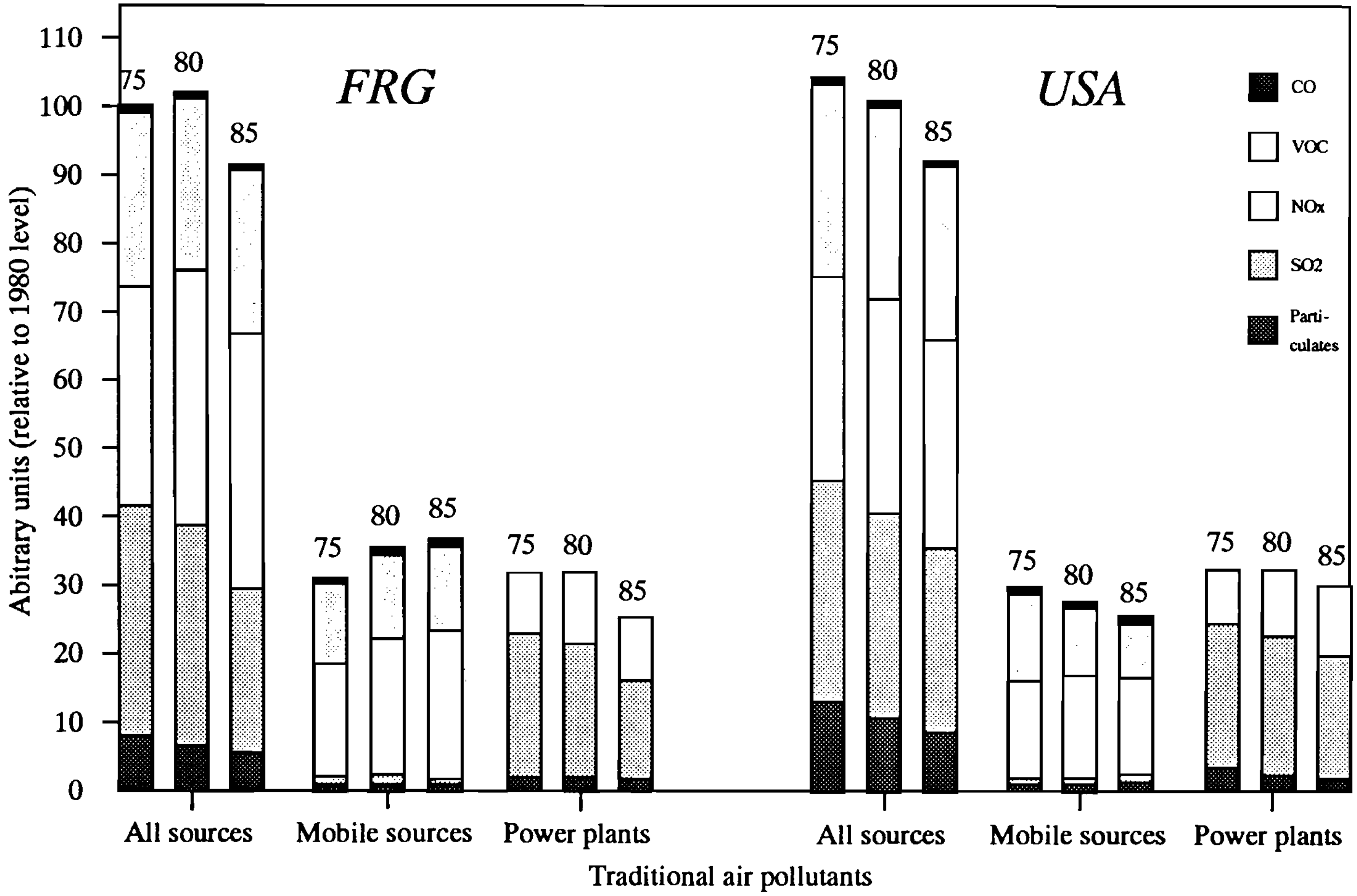

Figure 9. FRG and USA: Weighted emissions 1975–1985. Source: Adapted from OECD (1989) and others.

Table 6. Air pollution damages (% of total) from weighted emissions by sector.

	1975	1980	1985
FRG mobile sources	30.9	34.5	39.5
Power plants	31.6	31.2	27.4
USA mobile sources	28.5	27.5	27.5
Power plants	31.3	32.0	33.4

Source: OECD (1989); NAPAP (1990)(II); Hohmeyer (1988).

Table 7. Energy consumption and related CO_2 emissions – 1985.

	Conversion factor	Electricity		Transportation	
	tCO_2/toe	Mtoe	$MtCO_2$	Mtoe	$MtCO_2$
FRG					
Coal	3.556	44.18	157.11		
Oil	2.707	1.42	3.84	42.08	113.93
Gas	2.140	4.22	9.03		
Total		49.82	169.99	42.08	113.93
USA					
Coal	3.556	357.37	1270.86		
Oil	2.707	25.12	68.01	445.75	1206.85
Gas	2.140	72.66	155.49		
Total		455.15	1494.36	445.75	1206.85

Source: OECD/IEA (1988).

establish a relationship between ambient pollutant concentration and the incidence of acute and chronic diseases. Based on such studies (especially Lave and Seskin, 1971), Myrick Freeman estimated a pollution-mortality elasticity of 0.05, which means a 0.5% decrease in mortality for a 10% pollution reduction (Freeman, 1979; Freeman, 1982). He concluded that a 20% air pollution reduction in the USA would save between 2,780 and 27,800 lives per year. (Freeman's work is old, but has not been superseded.)

The next step is to impute the monetary valuation of morbidity and mortality benefits. While this is a highly controversial topic, it is unavoidable. In many policy areas it is necessary to balance the value of saving human life (by investing in risk-reduction) against other benefits, implicitly if not explicitly. Freeman used a value of US$1 million per statistical life saved, based on individuals' apparent willingness to pay to reduce risk of mortality

(Freeman, 1979). More recent US studies put the value of a statistical life at US$3 million (Portney, 1990). Others have used the loss of expected net future domestic income per capita to estimate the damages to society which range from US$0.3 to US$10 million per human life (e.g., Gaines *et al.*, 1979; Grupp, 1986; Wicke, 1986).

Freeman's best point estimate for the annual human health benefits of a 20% reduction in air pollution for the USA was US$17 billion in 1978 prices (Freeman, 1979). Assuming linearity, this implies total damages of US$85 billion per year. A more recent study for the EPA suggests that the annual benefits might be greater than Freeman's figure, but it is difficult to derive an annualized figure from the method used (Mathtech, 1983; OECD, 1984).

For the FRG, one study estimates the annual total costs of respiratory diseases (assuming 29% to 50% are due to air pollution) to range from DM 2.3 to DM 5.8 billion (Wicke, 1986). Another estimate ranges from 6.8 to 27.2 billion DM/yr (Grupp, 1986). Still another study yields damage estimates ranging from 1.6 to 40.3 billion DM/yr (Hohmeyer, 1988), based on figures given by (Euler, 1984).

Air pollution also causes accelerated corrosion and weathering of materials. For instance surface corrosion rates of zinc are five times higher in polluted areas than in clean-air regions, causing slow but significant damages to steel construction (Isecke, 1986). The need to enhance surface protection (of cables, for instance) increases costs in ways that are difficult to specify precisely. Further sources of damages include corrosion of natural stone used in buildings and outdoor works of art such as sculptures (The Statue of Liberty and Cologne Cathedral, for example).

Freeman estimated the benefits of a 20% reduction of air pollution for the USA to be about US$0.9 billion in the field of materials; this implies total damages (assuming linearity) of US$4.5 billion. In earlier times, when coal-burning was more widespread, Parrish found the total annual damages to be some US$6 billion a year (Parrish, 1963).

For the FRG annual damages from corrosion have been estimated by various people. One study set the figure at about 2.3 billion DM (Wicke, 1986), based on updated studies by (Heinz, 1986). Grupp estimated annual costs of 3.2–4.2 billion DM (not including damages to cultural property and monuments, in contrast to additional window cleaning). Hohmeyer (1988) estimated the flow of damages from corrosion to be in the range of 2.3 to 4.2 billion DM/yr.

Air pollution also causes vegetation damages by acidic deposition of photochemical oxidants (*acid rain*). Freeman estimated the benefits of a 20%

air pollution reduction in terms of reduced damage to vegetation to be in the range of US\$0.2-US\$2.4 billion/yr (Freeman, 1979). Total damages would, of course be five times greater. Crocker arrived at more narrowly bounded figures of US\$3.1 billion/yr, including forest losses of US\$1.75 billion, agricultural losses of US\$1 billion, and aquatic ecosystem damages of US\$0.3 billion (Crocker, 1979).

In Europe, the most visible and severe damages to vegetation are found in the forests. One study evaluated the forest decline as an annual loss of value of 5.5 to 8.8 billion DM (Ewers *et al.*, 1986). Hohmeyer estimated additional damages to agricultural crops of 1 billion DM/yr (Hohmeyer, 1988). No damages to wild flora and fauna were taken into account. Recent studies at IIASA have estimated air pollution-related losses to European forests (excluding the USSR) to be US\$23 billion annually (in 1987 US\$/yr) of which roughly 30 percent is attributable to reduced harvests and 70 percent to lost recreational and other benefits (Nilsson, 1990). To this must be added a further US\$7.4 billion in losses from the European USSR.

Tables 8 and *9* summarize the numbers chosen by Freeman and Hohmeyer (Freeman, 1979; Hohmeyer, 1988). Note that both authors assume large confidence intervals which should be interpreted as the possible range of values of minimum cost figures. The figures are underestimates, to the extent that some important components are still omitted, for example loss of quality of life. Using *Tables 8* and *9* we can relate damages to specific types of fuel consumption. Freeman's damage figures are based on the benefits of pollution control with a 20% reduction - over ten years ago. However, as shown in *Figure 9* the level and composition of emissions in the USA has not changed dramatically since the 1970s.

For the purposes of this study, the decline in emissions is assumed to be compensated roughly by the increase in prices. For the US transport sector, we impute benefits of 0.275 × US\$107 = US\$29.4 billion/yr associated with 1315 Mt-CO_2/yr emissions. This yields a net benefit of US\$22 per ton of CO_2 eliminated by consuming less petroleum based fuels. Similarly, for the electricity sector, we obtain 0.334 × US\$107 = US\$35.7 billion/yr. Dividing by related emissions of 1532.54 Mt-CO_2 implies a benefit of US\$23 per ton of CO_2 eliminated, mainly by consuming less coal. EPA is currently conducting a major review of air pollution damages. Unpublished and unofficial EPA estimates in 1988 set the damages at US\$750 per ton of SO_2 eliminated, US\$700 per ton of VOC eliminated, and US\$70 per ton of NO_x eliminated, with a fairly wide range of uncertainty. If we were to assume that a ton of CO_2 were to be eliminated by burning correspondingly less coal (2.5% S),

Table 8. Annual benefits of an air pollution reduction of 20% (billion 1978 US$/yr).

Damages to USA	Range	Best point	Percent
Health	3.1–39.3	16.8	80%
Soil	0.5–5.0	2.0	9%
Vegetation	0.2–2.4	0.7	3%
Materials	0.5–1.4	0.9	4%
Other	0.1–8.9	1.0	4%
Total	4.4–57.0	21.4	100%
	(US$21.4: -80%, +166%)		

Source: Freeman (1979).

Table 9. Estimated annual damages from air pollution by type of damage (billion DM/year).

Damages to FRG	Range	Center	Percent
Health	1.6–40.3	21.0	65%
Materials	2.3–4.2	3.2	10%
Vegetation	6.5–9.5	8.2	25%
Total	10.4–54.0	32.2	100%
	(DM 32.2 ±67%)		

Source: Hohemeyer (1988).

the reduction in SO_2 emissions alone would be about 0.017 tons, worth 0.017 × US$750 = US$12.75. Allowing for the benefits of eliminating other pollutants, our figure of US$23 per ton appears reasonable.

Based on similar calculations for the FRG, air pollution damage from mobile sources amounts to 103 DM (roughly US$57 at current exchange rates) per ton of CO_2 eliminated. For electricity generation, we obtain 51 DM (US$28) per ton of CO_2 eliminated. The fact that the German figures are higher than the US figures is understandable, in view of the fact that damages are a function of exposure, and the FRG is a more densely populated country. It should be emphasized, again, that these figures are not precise. In fact, the range of uncertainty on the upper side is of the same order as the number, while on the lower side it is half the number.

9. Conclusions for Policy

It is not our purpose to try to establish an optimal policy instrument to induce energy conservation, nor even an optimal tax policy (given the economists usual prejudice in favor of taxes over regulation). In this context, it seems to us that optimality is an inappropriate goal. Not only is it essentially impossible to achieve, but the time and effort expended on the debate is a distraction from the real issue. Current policies were not optimized from an economic perspective, nor is the political system conducive to optimization. But it is not difficult to assemble persuasive arguments that almost any tax on extractive resources – especially those whose intensive use results in large, unpaid social and environmental costs – is preferable to the present system of taxing labor (either directly or in the guise of value-added), assets (capital) and consumption.

Taxation is unquestionably an effective method of modifying social behavior, from consumption to investment, as economists have long recognized.[10] A general principle of tax policy should be to reduce or eliminate taxes on desirable behavior (such as personal savings or capital investment) and to increase taxes on undesirable consumption items such as cigarettes or alcoholic beverages. With respect to the consumption of energy (mostly from fossil fuels) and other environment-destroying toxic substances, however, tax policy in the USA is contradictory. Most countries set very high taxes on all forms of energy use, especially automotive gasoline. (Despite high taxes, the energy and automotive industries of Europe and Japan remain healthy.) The USA does not tax energy or toxic materials use, despite an obvious need for more government revenue, out of political concern for the jobs that might be lost.

With respect to revenues, the assumption made by many conservatives is that revenues siphoned out of the private sector by any tax will be used totally unproductively by the government. Liberals, on the other hand, seem to assume just the opposite. In the present context, the liberal assumption would be that revenues from a carbon tax (or a sulfur tax) would be automatically used to compensate for the environmental damages caused by

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[10] The major argument of the *supply-siders* in the early Reagan years was that excessive taxes on income would discourage productive effort, whence tax-cuts would actually generate new entrepreneurial activity. The long-standing argument for eliminating capital gains taxes is based on similar notions. Virtually all economists would agree that income or capital gains tax cuts are stimulative. The major argument is whether the revenue gains for the government would exceed the losses, which is a very different issue.

the buildup of CO_2 or SO_x. The truth is certainly not so simple, either way. But, disregarding the use of the tax revenues, it would still be socially beneficial to impose such a tax as long as its net cost to energy users (i.e., society) is less than the social benefits – reduced environmental damages – of lower fossil fuel combustion.

For each ton of CO_2 eliminated, we estimated these benefits as follows: US$30 for natural gas (based on *greenhouse effects* of CO_2 alone, ignoring likely methane leakage which would probably justify a much higher tax), US$52/ton for petroleum and US$53/ton for coal in the USA. Two fifths of the benefits in the case of petroleum and coal are attributable to associated reductions in other pollutants, notably NO_x, SO_x, particulates, and unburned hydrocarbons. For the FRG the petroleum and coal figures are, respectively, US$87 and US$58.[11] In the case of the FRG, health-related benefits of reduced NO_x and SO_x outweigh climate benefits.

To obtain this assumed benefit, consumption must be reduced by raising the effective price to consumers. The reduction in consumption resulting from a rise in price (or tax) depends on the price elasticity of demand. (The less elastic the demand, the greater the reduction in consumption per increment of added price). Nobody knows exactly what the price elasticity of demand for petroleum or coal is, but a number that "seems more or less right" to most economists is -0.3. That is, a fuel price increase of 1% would result in a drop of 0.3% in demand for that form of fuel. Roughly, a 100% increase in the price of fuel would result in a 30% cut in use.

Coal costs about US$50/ton. It is about 80% carbon. To obtain a reduction of one ton of CO_2 (worth more than US$30 in terms of climatic benefits and more than US$20 in terms of air-quality benefits) consumption of 0.273 tons of coal-carbon must be eliminated. This corresponds to 0.34 tons of coal not burned. Assuming a price elasticity of -0.3, this is the reduction that would be achievable by increasing the price to consumers by 100%. In short, any tax that doubles the price of coal (i.e., US$50/ton) would save over US$50 in environmental costs to the society as a whole, while also producing about US$33 in net revenues for the government – to use productively, or not. In the US, based on a pre-tax consumption of 500 million tons per annum, such a tax would cut consumption by 170 million tons and generate US$16.5 billion in revenues.

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[11] To convert these benefit numbers to dollars per ton of actual fuel, remember that each ton of carbon dioxide emitted corresponds to 0.273 tons of carbon in the fuel, so the benefit is in proportion.

Of course, there would also be both short term adjustment costs (e.g., shifts to natural gas or untaxed fuels) and long-term "drag" costs on the economy. The effect of the higher coal price would be passed through, for instance, to the steel industry and to the consumers of steel products; similarly it would affect the cost of electricity and all users of electricity. The end result would be a structural shift further away from energy-intensive industries and towards energy conservation services and non-fossil sources of energy (such as solar electricity).

Yohe and his colleagues investigated the potential drag effects of a 100% carbon tax (phased in over the 20 years from 2000-2020) or an equivalent consumption restriction (Yohe *et al.*, 1989). Their assumptions are based on work suggesting that the sudden increases in petroleum prices that occurred in 1973 and 1979 caused drops in productivity growth (Olson, 1988). It is assumed that any tax on fossil fuels would have the same depressing effect. Assuming productivity drops ranging from 0.05% p.a. to 0.7% p.a. for a carbon tax amounting to 100% of current prices, cumulative lost productivity of US$75 to US$550 billion would be experienced up to the year 2010.

This approach is not very convincing, for two reasons. First, the essence of the "oil shock" was that money was taken from western producers and consumers and deposited in bank accounts belonging to (predominantly) OPEC members. They, in turn, increased their spending for consumer goods, military goods, and long-term infrastructure projects, none of which contributed to increased productivity in the west. On the other hand, the impact of a tax collected within the western economies would, of course, depend on how the money was spent. However, if the new tax were offset dollar for dollar by a reduction in other taxes, there is no reason to expect an automatic depressing effect on the economy. Second, we note that the observed productivity drop since 1973–1974 has many other possible explanations, of which the most widely accepted seems to be that it reflects the inevitable "catchup" of the US by Europe and Japan.[12]

In summary, we think a carbon tax (proportional to the carbon content in different fuel types) and/or a sulfur tax (proportional to the sulfur content in the airborne or water-borne emissions) would be consistent with the so-called

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[12] In fact, an OECD Seminar on the "Apparent Productivity Paradox" held in June 1989 and attended by a number of the world's top economists, considered in detail a number of the extant theories of the decline in productivity growth since 1972–1973. The rise in energy prices as a causal factor was not even discussed. This does not mean that energy prices played no role, but it appears that most economists who attended no longer believe that role to have been crucial.

"polluter-pays" principle and would avoid some of the administrative burden associated with regulation. In order to avoid severe market disturbances, such a tax should be slowly phased in (over one or two decades), in the context of international cooperation. We strongly suggest that the (rather high) tax revenues could (and should) be used to reduce other forms of taxes. As we have noted, such taxes now fall mainly on labor, capital, and trade, economic activities that should be encouraged – insofar as they do not involve the use of fossil fuels or toxic materials – rather than discouraged.

It is interesting to compare our final results with those of Nordhaus (1989), in terms of marginal shadow costs of abatement. The Nordhaus analysis assumed that the cost of abatement rises monotonically with the degree of abatement, i.e., percentage of CO_2-equivalent reduction. The major policy conclusions of his analysis were as follows:

- CFC phase-out is the lowest cost option. Total elimination would cut the CO_2-equivalent emissions by 14%. A high gasoline tax would be the next most effective policy option.
- Reforestation is not a cost-effective option (at marginal costs assumed to be US$100/ton of CO_2 removed).
- The shadow costs of CO_2 reduction by a global carbon tax would exceed the benefits except at low levels of abatement. It is not an efficient policy.

For the case of high costs associated with greenhouse warming (US$37/ton of carbon dioxide or equivalent RIG) the optimal policy would yield a 28% reduction in CO_2-equivalent emissions and 94% reduction of CFC use.

We have arrived at significantly different conclusions, partly because we disagree with the underlying cost assumptions, and partly because we have tried to take into account ancillary benefits of policies that would reduce other pollution-related damages.

In our view, as stated above, the most cost-effective policy is likely to be energy conservation combined with substitution of natural gas for other fuels to the extent dictated by direct cost savings. This would reduce energy consumption by 20% or so and carbon dioxide emissions by about 25% compared to present levels, though the overall impact on RIG emissions would be more like 12%. The most effective policy to bring about this degree of conservation would be a carbon tax on all fossil fuels supplemented by a sulfur emissions tax on sulfur-containing fuels.

The virtual elimination of CFCs, as suggested by Nordhaus, would probably be the next most cost-effective policy, with a further 14% reduction in RIGs. Further abatement beyond that would be achievable by some combination of further energy conservation, fuel substitution, and the introduction of non-polluting solar (or other) energy sources, combined with extensive reforestation. We are unable to evaluate the relative costs and benefits of these policies in more detail at this time, however.

Appendix A: Forests

A popular proposal is to sequester excess atmospheric carbon dioxide by means of photosynthesis, using large plantations of fast-growing trees as a sink. To halt the present annual atmospheric increase of carbon (2.9 Gt of C per year) by massive afforestation, the required land area in temperate climate regions would be about 465 million hectares (Mha) (Sedjo and Solomon, 1990). This is equal to 1.5 times the present forest area of the USA or 15% of the global forest area. The land requirement is large but not totally out of the question. For instance, it is biologically feasible to double the biomass density (see, for example, Sedjo and Solomon, 1990; Ranney *et al.*, 1987).

Planting costs are estimated to be between US$230-US$1000/ha (averaging US$400/ha). In the USA suitable land costs roughly US$400-US$1000/ha, although in some regions it would be lower. Land costs represent real opportunity costs, since land used as carbon sink cannot be used for crops of pasture. The prospects of finding a large area of suitable land in the western countries appears slim. However, it is estimated that there is at least 500 Mha of degraded or deforested tropical land (Houghton and Woodwell, 1989). Degraded land costs much less; in Indonesia total costs of US$400/ha are indicated (Sedjo and Solomon, 1990); in India, costs are even lower (Myers, 1989).

Total costs of US$372 billion for new plantations in temperate zones and US$186 billion in the tropics, would result in marginal costs of reducing CO_2 of US$35/ton and US$17/ton respectively (Sedjo and Solomon, 1990). These figures are in sharp contrast to the pessimistic US$200/ton estimated by Nordhaus (Nordhaus, 1989).

Appendix B: Reducing CFCs

Chlorofluorocarbons (CFCs) are chemically inert compounds, used as solvents, propellants, and refrigerants. They are not readily degraded by chemical reactions in the lower atmosphere. As a consequence, CFCs gradually diffuse into the stratosphere where they are effective absorbers of long-wave (IR) thermal radiation. Because CFCs are about 20,000 times more efficient than CO_2 as IR absorbers, the two most common CFCs, CFC-11 and CFC-12, alone contribute about 14% of all RIG emissions.

The replacement of CFCs is relatively cost efficient because of the small quantities involved. It is fairly easy to find substitutes for the propellant and solvent uses. The most difficult use to dispense with is refrigeration and air-conditioning. However, there are a variety of technically feasible substitutes for CFCs with shorter atmospheric lifetimes and/or less absorption strength in the critical frequency band. Despite some disadvantages such as greater flammability and reduced efficiency as refrigerants it is reasonable to assume substitution costs of the order of US$5/kg, or about US$ 0.25/ton of CO_2 equivalent eliminated (Pool, 1988).

Problems will arise in developing countries. China, for instance, is planning to raise refrigerator production by the year 2000, and to boost CFC production to levels tenfold higher than those in the USA today; China did not sign the Montreal Protocol (Miller, 1989).

A non-trivial incidental benefit of CFC reduction would be a slower rate of depletion of the stratospheric ozone layer. We have no quantitative estimate of monetary worth of this, however.

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