

FOIA MARKER

**This is not a textual record. This is used as an
administrative marker by the William J. Clinton
Presidential Library Staff.**

Collection/Record Group: Clinton Presidential Records
Subgroup/Office of Origin: Council of Economic Advisers
Series/Staff Member: Joseph Stiglitz
Subseries:

OA/ID Number: 9569
FolderID:

Folder Title:
IPCC [Intergovernmental Panel on Climate Change] - Volume II [5]

Stack:	Row:	Section:	Shelf:	Position:
S	20	5	9	3

DRAFT

September 1994
(3rd Draft)

6

The Social Costs of Climate Change: Greenhouse Damage and The Benefits of Control

**D.W. PEARCE, W.R. CLINE, A.N. ACHANTA, S. FANKHAUSER,
R.K. PACHAURI, R.S.J. TOL AND P. VELLINGA**

Contents

6.1 Conceptual Framework

- 6.1.1 Purpose of the Chapter
- 6.1.2 The Nature of Damage Assessment
- 6.1.3 The Valuation of Market and Non-Market Impacts
- 6.1.4 Transient and Equilibrium Warming
- 6.1.5 Time Horizon and Discounting
- 6.1.6 Technological Change
- 6.1.7 Adaptation
- 6.1.8 Recent Scientific Evidence

6.2 Damage Estimates for Benchmark Warming (2xCO₂)

- 6.2.1 Agriculture
- 6.2.2 Sea Level Rise
- 6.2.3 Forests
- 6.2.4 Water Supply
- 6.2.5 Space Cooling and Heating
- 6.2.6 Insurance
- 6.2.7 Other Market Sectors
- 6.2.8 Health
- 6.2.9 Air Pollution
- 6.2.10 Water Pollution
- 6.2.11 Migration
- 6.2.12 Human Amenity
- 6.2.13 Ecosystem and Biodiversity Loss
- 6.2.14 Extreme Weather Events
- 6.2.15 Damage Estimates: Summary

6.3 Damage Estimates for Longer Term Warming

6.4 Catastrophic Risks

6.5 Regional Implications of Global Warming Damage

- 6.5.1 Regional Damage Estimates
- 6.5.2 Japan
- 6.5.3 Africa
- 6.5.4 Bangladesh
- 6.5.5 India
- 6.5.6 Indonesia
- 6.5.7 Malaysia
- 6.5.8 Thailand
- 6.5.9 Latin America
- 6.5.10 Small Island States
- 6.5.11 Conclusions on Regional Impacts

6.6 From Greenhouse Damages to Abatement Benefits

6.7 The Secondary Benefits of Abatement Strategies

6.8 Comparing Benefits and Costs of Response Strategies *[may be moved to another chapter]*

6.8.1 Social Efficiency of Abatement

6.8.2 Possible Implications

6.9 Summary and Conclusions

Boxes

- Box 6.1 Estimating the Value of a Statistical Life
- Box 6.2 Damage Aggregation Across Countries and Individuals
- Box 6.3 Relative Damage in Developing and Industrialised Countries
- Box 6.4 Valuation of Electricity Related Externalities in California

Figures

- Fig 6.1 2xCO₂ Damage vs. Abatement Benefits

Tables

- Tab 6.1 Overview on Climate Change Impacts
- Tab 6.2 Preference Valuation for Endangered Species and Prized Habitats
- Tab 6.3 Reported Fatalities due to Weather Events 1989-1992
- Tab 6.4 Economic Damages from Global Warming: US Economy at Present Scale
- Tab 6.5 Quantitative 2xCO₂ Damages in Different World Regions
- Tab 6.6 Monetary 2xCO₂ Damage in Different World Regions
- Tab 6.7 Expert Opinion on Climate Change Damage
- Tab 6.8 Illustrative Damages from Long Term Warming: US Economy at Present Scale
- Tab 6.9 Losses of Rice Output due to Sea Level Rise in Coastal Zones of Bangladesh
- Tab 6.10 Vulnerability Index for Different Categories of Countries
- Tab 6.11 The Social Costs of CO₂ Emissions in Different Decades
- Tab 6.12 Reduced Air Emissions due to CO₂ Abatement
- Tab 6.13 The Social Costs of Air Pollution

6.1 Conceptual Framework

6.1.1 Purpose of the Chapter

This chapter is concerned with the nature of the damage from climate change. Damages here refer to the consequences of these effects for individual and social welfare. The chapter assesses the possible aggregate scale, the geographical distribution, and the nature of those damages. It raises some issues relating to decision-making rules (Chapter 5) since alternative ethical approaches to harm done to future generations have implications for damage assessment.

6.1.2 The Nature of Damage Assessment

Two broad perspectives have emerged on ways to analyse decisions which have adverse effects on generations yet to be born: the benefit-cost framework and the sustainability framework. While they initially appear to be very divergent, they have features in common.

The *benefit-cost framework*. It requires that the future damages be weighed up, integrated into an overall assessment, and then compared to the costs of measures undertaken now by the current generation. In turn, there are two perspectives on the way in which benefits and costs should be compared:

- (i) the *judgemental benefit-cost* framework, in which gains and losses are compared but without reducing them to common units. On this approach, the monetary costs of control might be compared with some wide-ranging *environmental impact statement* representing the best state of knowledge about climate change impacts, together with assessments of the *distributional incidence* of those impacts both geographically and across time;
- (ii) the *monetised benefit-cost* framework. On this approach, the common unit of money is used to 'reduce' the benefits of climate control to the same units as costs to permit direct comparison, but only as far as 'monetisation' is credible. (Nordhaus 1991, 1993a, 1993b; Peck and Teisberg, 1992; Cline, 1992a; Hope *et al.* 1993; Manne *et al.* 1993; Tol 1994b)

Approach (i), which often reduces to multi-criteria analysis, is discussed in Chapter 5.

Approach (ii) is characterised by the following features:

- (a) benefits and costs are defined in terms of human preferences. A benefit is anything that improves an individual's wellbeing; a cost is anything that reduces that wellbeing;
- (b) those preferences are expressed in the market place by willingness to pay (WTP) for a benefit and willingness to accept compensation (WTAC) for a cost;
- (c) where markets do not exist - for example with respect to ecosystem change - WTP and/or WTAC are measured through 'surrogate markets' or 'created markets'. Surrogate markets are real markets in which environmental change has an influence:

a house price or land value may be higher because of an environmental amenity for example (the hedonic property price method). Created markets reflect people's responses to questions put to them about their willingness to pay (the contingent valuation method);

- (d) the 'intrinsic' values of other species and ecological systems may be captured at least in part by created markets since people may be expressing their understanding of intrinsic values when they express their willingness to pay for the continued existence of an environmental asset even though they may make no use of it, nor do they intend to use it ('passive use', or 'existence' value - see Carson *et al.* 1994);
- (e) future generations' preferences count at least in so far as they are assumed to want what current generations want. If there is evidence that they will want more environmental assets affected by climate change, then this 'rising relative preference' can be accommodated by benefit-cost approaches by allowing benefits or cost to rise through time;
- (f) future generations' preferences may count equally with current generation preferences if the *pure time preference* component of the *discount rate* is zero. If it is positive, their preferences count less in the benefit cost framework (see Chapter 3), but some judgement is implicitly being made about them. For example, if future damage costs from global warming are discounted at a positive rate, the implicit assumption is that the benefits of burning more fossil fuels now will partly accrue to future generations in the form of higher economic development. However, this approach overlooks the possibility that climate change itself may make future generations worse off by threatening their development potential: the discount rate becomes endogenous - it ceases to be an externally 'given' factor (Markandya and Pearce, 1988);
- (g) since WTP is constrained by income, it is likely to be less (but not necessarily so) for low income groups than for high income groups. This may appear to give rise to an unfairness since the preferences of low income groups (countries) will carry less weight than the preferences of high income groups. One way to address this issue is to express the valuations as a proportion of income. Another is to give different weights to different income groups in the aggregation process (see Box 6.2). A third way might be to adopt the valuations of the higher income groups and apply them to all countries (e.g. Hohmeyer and Gärtner, 1992. See also Box 6.1).
- (h) aggregation of damages is also a hallmark of benefit-cost studies. Care has to be taken in interpreting such aggregate figures since they clearly mask (a) substantial regional variations in impact within a country and between countries, and (b) dislocation costs in adapting to changed local impacts. The aggregation of sectoral impacts also tends to imply that losses in one sector are compensated for by gains in other sectors.

The second overall perspective - the *sustainability approach* (e.g. Howarth and Monahan, 1992; Spash, 1994) - gives the highest priority to the avoidance of 'unacceptable' damage to future generations. Rationales for avoiding this harm sequence:

- (a) there is reasonable evidence to suppose that actions now in emitting greenhouse gases

- will cause significant damage to future generations, including unborn generations;
- (b) future generations are defenceless against actions taken now in the knowledge that those actions may cause harm;
 - (c) current generations have obligations to future generations at the very least through a set of links from parents to children, from children to their children, and so on (Howarth, 1992), or, more generally, because future generations have rights even when those generations are not identifiable, and even when their existence is contingent on actions taken now;
 - (d) probable improvements in the wellbeing of future generations cannot be treated as 'compensation' for harm knowingly inflicted on future generations by current generations, any more than harming the poor now can be excused by paying them compensation after the event (Spash, 1994);
 - (e) hence doing harm is not reversible by doing good. Benefits and costs cannot be 'traded off' in the sense advocated by benefit-cost analysis *regardless of whether the benefit-cost analysis is monetised or not*. There is a *duty* to avoid future harm.

As with the benefit-cost approaches, all the propositions in the sustainability approach are open to dispute. Controversial assumptions include: (i) that harm can accrue to individuals whose existence is contingent on actions now and (ii) that trade-offs can be avoided, since any action now incurs a cost of abatement, and any abatement cost involves losses for others which in turn implies that other individuals' rights may be impaired.

Within the sustainability approach two views are:

- (i) that since the obligation to avoid harm is absolute, the cost of avoiding harm is irrelevant: the benefits of control are so large that inspection of costs is unhelpful. This is the *absolute standards* approach;
- (ii) that harm should be avoided subject to a constraint that avoiding harm does not itself impose 'unacceptable cost' - the *safe minimum standards* approach.

The sustainability approach takes a long-term view and stresses the need to sustain a viable global ecological system. It therefore tends to be characterised by:

- (a) the avoidance of unacceptable risk where risks are known;
- (b) the 'precautionary principle' - whereby actions giving rise to *possible* but quantitatively unknown but potentially very large risks are avoided or corrected. The precautionary approach *logically implies* a benefit-cost comparison since it assumes that the (expected) value of damage exceeds the costs of abatement;
- (c) the view that what is unacceptable is only partly measured by reference to individuals' preferences since (i) individuals are not well informed about climatic risks, (ii) experts are similarly not well informed due to uncertainty about climate change and its effects,

- and (iii) human preferences may not capture other values, e.g. intrinsic values;
 - (d) very low discount rates of the order of a few percentage points, and maybe even zero.
- Whereas the benefit - cost approach seeks to measure the scale of damage, the sustainability approach assumes that damage will be 'significant', so much so that action is warranted regardless of quantification.
- The sustainability approach often tends to have as its objective a concern to avoid exceeding some target rate of temperature rise, usually quoted as 0.1°C per decade, and some absolute overall rise in temperature of 2-3°C. Examples include Krause *et al.* (1989) and Rijsberman and Swart (1990). The costs of achieving these constraints are assumed to be worth incurring in order to avoid the risks to future generations.
- With reference to the benefit-cost approach, it is well known that a time path in which the present value (i.e. the discounted value) of benefits minus costs is maximised need not be a sustainable path, and that a sustainable path could, in turn, be unacceptable in terms of its implied living standards for each generation (Page, 1977; Pearce *et al.*, 1994; Pezzey, 1994). The choice between benefit-cost approaches and sustainability approaches therefore depends crucially on (a) attitudes to uncertainty, (b) the degree of concern for the wellbeing of future generations, and (c) beliefs about the damage function, i.e. the way in which warming relates to damages.
- A consensus viewpoint stresses the following common features of both the sustainability and the benefit-cost approaches:
- (a) the existence of uncertainty cannot justify 'business as usual', i.e. doing nothing. Action on climate change is justified since the damage costs could be very high, the 'coefficient of concern' for the future is not zero, and there are costs of delayed action since greenhouse gas impacts may not be reversible;
 - (b) the right benefit-cost perspective is one which investigates the benefits and costs of taking actions. Such actions are likely to yield benefits of a similar order of magnitude as the costs of the actions for some time to come, since avoided climatic damages are not the only benefits of those actions. This underlines the difference between *damage estimation* and *abatement* benefits: the latter include the avoided damages estimated by the former concern, but also include other benefits from greenhouse gas abatement (see Section 6.7);
 - (c) neither sustainability nor 'maximising net benefits' is an obviously non-controversial objective. Sustainability cannot be an overriding objective independently of the quality of life that is sustained or the costs of achieving it. Maximising net benefits cannot be an overriding objective since it may be consistent with an approach which discriminates against future generations. This suggests an approach in which the best features of both approaches are taken: a concern for the wellbeing of future generations, the wellbeing of Earth itself, and acknowledgement of the limited resources that all societies have at their disposal to tackle global problems. Such approaches come closest to the 'safe minimum standards' approach: taking a

precautionary approach in favour of the environment unless the demonstrated costs of so doing are very high. Precaution would have its justification in very high damage costs: damage costs must therefore be investigated. The acceptability of control costs is dealt with in Chapters 8 and 9.

6.1.3 The Valuation of Market and Non-Market Impacts

The benefit-cost approach requires that the damages from climate change be expressed, as far as is possible, in terms of money units reflecting human preferences. Many of the impacts of climate change will not be revealed directly in the market place - the so called non-market impacts. The absence of markets does not mean that non-market impacts are any less important than market impacts. The point is to ensure that non-market impacts are adequately accounted for.

Non-market impacts may take a variety of forms. One important example is the impact of warming on human health. Human health is, generally, publicly provided without direct charge. In some cases, there are surrogate markets for risks to life. Occupations are subject to varying degrees of risk of accident and ill-health and that risk is sometimes compensated for by variations in wages. The 'risk premium' in the wage can then be interpreted as a valuation of the risk (see Box 6.1). Valuation of morbidity is more complex: contingent valuation approaches are best suited to such indicators but, as yet, few studies exist outside the USA. In their absence, second best measures such as the costs of treatment tend to be used.

The general approach in benefit-cost studies is to treat market and non-market impacts on the same footing. Non-market costs can be high, between 30% and 80% of the total. Tol (1994a) suggests that the way non-market impacts are treated matters, however. The reasons are: (a) they affect human wellbeing directly (through the utility function), rather than through production, (b) they are liable to be less substitutable and (c) their value will rise relative to other (production) damages.

Market price (in the case of market goods) and elicited WTP (for non-market goods) reflect people's appreciation for the *marginal* (last) unit of a good or service consumed. The utility gained from consuming the first unit of a good is usually much higher than that from consuming the last unit, however. Especially for food and other products with price inelastic demand - where the appreciation of additional units beyond an essential minimum decreases rapidly - the value lost from a cutback in availability will be understated if the quantity loss is evaluated at the original (ex ante) price. Price increases as a consequence of global warming then become important. The correct measure to assess the costs of global warming in such cases is the change in producer and consumer surplus. Consumer surplus is the excess of what consumers would be willing to pay if necessary above what they actually pay. Producer surplus is what producers receive in excess of their actual costs of production. This consideration also means that it can be misleading to gauge the potential impact of global warming by the present size of a sector in the economy. In industrial countries agriculture is typically on the order of 3 percent of GDP, but reduction of X percent in agricultural output could cause far more than 0.03X percent of GDP economic loss because of the induced price increase and loss of consumer surplus.

6.1.4 Transient and Equilibrium Warming

The time dimension of damage, and the difference between transient and equilibrium warming are also important. Ocean thermal lag causes realized equilibrium warming from a given steady-state increase in greenhouse gas concentrations and their consequential radiative forcing to be delayed by at least two, and perhaps several, decades¹. Among economic analyses, Cline (1992a) simply applies a 25 year lag, whereas other models (e.g. Nordhaus, 1993a, b) often explicitly model thermal capacities of, and transfer between the atmosphere, upper ocean and lower ocean. The lag of realized warming introduces an inherent asymmetry into the economics of global warming: advantages associated with emissions (e.g. the benefits of automobile driving or electricity generation) occur immediately, whereas economic damages occur only after a significant lag.

In addition, an even more fundamental asymmetry is that emissions in a given year typically generate a contemporary, one-year flow of advantages, but create a stock of warming that then produces a recurrent annual flow of damages into the indefinite future. There is thus an inherent temporal asymmetry between earlier satisfaction from emissions and later, more persistent damages, even if thermal lag is ignored.

For a specified radiative forcing, the transient warming may not follow a smooth path between present and future equilibrium climate. Transient climate change in a particular region cannot therefore be assumed to be a steadily rising fraction of equilibrium impact; instead, there could be discontinuities and reversals. Damages is likely to be sensitive to such variability. Adjustments of natural systems and social institutions are not instantaneous. A world with continual climate shocks would affect the ability of economic and natural systems to adjust and to recover. The economic implication is that the strategy of relying solely on adaptation rather than abatement could have higher costs than implied under a smooth transient path.

In addition, it is generally agreed that the faster warming occurs - either because of higher climate sensitivity (equilibrium warming for a given radiative forcing) or a shorter ocean thermal lag - the greater the economic damages will be. That is, damage is a function of absolute warming as well as the rate of warming. Species and forests will have less time for migration; agricultural and other climate-sensitive human activities will have less time for adaptation. In a survey of experts' opinions Nordhaus (1994a) finds that for a hypothesized warming of 6°C, the mean estimate of damage is 6.7% of world product if the arrival date is 2175, but 10.4% if the warming occurs by 2090 (with wide extremes around the mean in both cases, see Table 6.7 below).

6.1.5 Time Horizon and Discounting

Given the long time horizon of the global warming problem the question of discounting is

¹ Under business-as-usual conditions of steadily rising concentrations, realized warming at a point in time is roughly 60% of equilibrium or committed warming corresponding to radiative forcing already present, for atmospheric models with climate sensitivity parameters of 4°C; and 80%, for 1.5°C (IPCC, 1990a).

crucial for the valuation of climate change impacts. Unfortunately, there is no agreement on the "correct" discount rate and different rates have been used in applied studies so far (see Chapter 4 for details). In a benefit-cost analysis of greenhouse abatement, Cline (1992a) adopts a zero rate of pure time preference (ρ), and sets the social rate of time preference (S RTP) at 1.5% per annum, the result of an assumed consumption growth rate of 1% multiplied by an elasticity of marginal utility of 1.5. After taking account of the share of resources coming out of capital (20% economy-wide, versus 80% out of consumption) and shadow-pricing capital effects (at a price close to two units of consumption equivalent to one unit of capital), Cline's effective discount rate is in the range of 2% per annum. This is in keeping with recent work by Pearce and Ulph (1994). In contrast, most global warming optimization models (e.g. Nordhaus, 1993a, b; Peck and Teisberg, 1992; Manne *et al.*, 1993) apply a pure rate of time preference of 3%. They typically also use a logarithmic utility function, which, for a per capita growth rate of 1-2%, implicitly adds another 1-2% for utility-based discounting, to give a S RTP of 4-5%. The divergent discounting methods explain much of the difference in the policy findings of different studies.

6.1.6 Technological Change

Even over two or three decades, technological change can profoundly alter the options available for low cost adaptation, on the one hand, or for greenhouse abatement, on the other. Over a time horizon of two or three centuries the technological unknowns become overwhelming. Cline (1992a) suggests that this problem can be obviated if it is assumed that the proportional effects of technological change are the same for abatement costs as for the benefits of limiting warming. Thus, whereas technological breakthroughs on seed varieties might neutralize damage from increased droughts, thereby reducing the benefit of limiting warming, breakthroughs in non-fossil-fuel (e.g. solar) energy could correspondingly reduce the opportunity cost of reducing carbon emissions. The assumption that unanticipated technological changes are distributed evenly on both sides of the benefit-cost calculus provides a logical basis for proceeding with the benefit-cost analysis of abatement applying the best expectations of technologies on both sides. However, the powerful influence of technological change means that there is a wide band of uncertainty around the comparisons from this standpoint, added to that already present from climate uncertainty.

Policy also affects technological change. Especially over a time horizon of many decades, new technology will respond to price signals sent by policy. Thus, the future path of energy supply technologies is likely to hold a wider array of low-carbon alternatives, if there is a price signal discouraging carbon emissions.

6.1.7 Adaptation

The severity of global warming impacts will depend on people's ability to adapt to a warmer world. Measures will generally be taken to accommodate to global warming, both on an individual level and by society as a whole. The search for more resilient crops will be intensified, vulnerable coastlines will be defended by sea walls, new buildings will be located and designed in a way to better withstand the force of extreme weather events. On an individual level farmers will change crops or adjust planting dates. Households will increase their demand for air conditioning, people may migrate to less affected regions, and so on.

However, the degree of adaptation in developing countries is likely to be far less than in developed countries due to (a) lack of financial resources and (b) lack of institutional capacity. Where it is feasible, adaptation can potentially be a very powerful option. In a stylized cost-benefit model of global warming policies, Hope *et al.* (1993) found strongly positive cost-benefit ratios for an "aggressive adaptive policy" in Europe, mainly in the form of coastal protection. The benefits of adaptation exceed the costs by more than a factor 20. Fankhauser (1994c) calculates optimal coastal protection levels of 50 to 100% for the countries of the OECD. In a series of country studies IPCC (1994) found that through appropriate adaptation measures the number of people at risk from flooding could on average be reduced by about 65%.

Agricultural studies provide a similar picture. In a case study of the Missouri-Iowa-Nebraska-Kansas (MINK) region, Easterling *et al.* (1993) found that low-cost adaptation measures, like earlier planting or increased irrigation, could succeed in reducing agricultural damages to the region by 30% or more (see also section 6.2.1). A comparable range was found by Rosenzweig *et al.* (1993) and (using the same yield data) Reilly *et al.* (1994). In the Rosenzweig *et al.* study a change of -1.2 to -7.6% in worldwide cereal production without adaptation is reduced to 0% to -5% with moderate farm-level adaptation and +1% to -2.5% with a more comprehensive managerial adjustment. As a consequence, the global welfare loss reduces from \$ -0.1 to -61.2 billion without adaptation to \$ +7.0 to -37.6 billion in the case of a moderate response (Reilly *et al.*, 1994).

Adaptation will in general not be costless, and may require extensive planning. The need for an integrated and forward looking coastal zone management has been identified as an essential prerequisite for the future development of coastal zones (IPCC, 1994). The significance of adaptation will also depend on institutional factors. Limited availability of irrigation water or of sufficient capital to finance increased input requirements (e.g. more fertilizer) may limit the scope of agricultural adaptation poorer regions (Rosenzweig *et al.*, 1993).

Conceptually, the costs of global warming impacts in the presence of costly adaptation consist of two parts: The costs of adaptation (e.g. for coastal protection), plus the costs of the remaining, unmitigated damage (e.g. the loss of unprotected land). In the estimates reviewed in section 6.2, for many categories the damages of global warming also incorporate considerations of adaptation. A prime exception is loss of biodiversity, for which there are few adaptation options. Damage from sea level rise is partly comprised of the cost of building coastal protection structures. Similarly, the impacts on the electricity sector caused by global warming amount to costs required or induced by adaptation (space cooling). Implicitly or explicitly most of the estimates incorporate both effects: costs of plausible adaptation, plus the remaining damages from unmitigated impacts.

The question of the optimal level of adaptation is strongly linked to that of optimal mitigation. The most desirable level of adaptation will depend on the amount of greenhouse gas abatement undertaken, and *vice versa*. Abatement and adaptation policies should therefore be carefully coordinated. For example, if significant abatement can be achieved at reasonably low costs, less action may be needed with respect to adaptation. Conversely, if the consequences of global warming could easily and cheaply be accommodated by adaptation, there would be less need for preventive carbon abatement (Fankhauser and Hope, 1994).

However, as suggested by the hybrid nature of most of the estimates, as *damage-cum-adaptation* costs, assuming a strict dichotomy between abatement and adaptation would be misleading. Indeed, an underlying point is that the greenhouse problem is likely to require both sets of actions. Even with the most aggressive abatement policy, benchmark $2\times\text{CO}_2$ warming seems likely to occur eventually, although the date can be greatly delayed. Conversely, even the most extensive adaptation strategy is unlikely to fully mitigate the adverse impacts of global warming. Adaptation is primarily a complement, not an alternative to greenhouse gas abatement.

6.1.8 Recent Scientific Evidence

The literature reviewed below largely takes as its point of departure the scientific appraisal of IPCC (1990a). It is important to consider whether changes in the scientific assessment since then provide grounds for altering the economic evaluation of the greenhouse effect. In the 1995 review, IPCC Working Group I (scientific assessment) has identified the following changes in the underlying impact science that might affect the measurement of damage. [This section to be checked against IPCC 1995].

First, while the climate sensitivity parameter range remains at $1.5\text{--}4.5^\circ\text{C}$ for equilibrium $2\times\text{CO}_2$, transient realised global mean surface temperature is now expected to rise by a central estimate of roughly $0.25^\circ\text{C}/\text{decade}$, or by 2.5°C by 2090 over the 1990 base. The corresponding central estimate in the 1990 report was $0.3^\circ\text{C}/\text{decade}$, for a cumulative 4.2°C over the preindustrial base by the year 2100. This diminution is attributable to consideration of terrestrial uptake, incorporation of the effect of ozone stripping in the evaluation of radiative forcing from CFCs, and the influence of aerosol sulphates.

Second, there is increasing emphasis on regional differences. These stem importantly from the differential impact of ocean thermal lag. In the Northern Hemisphere, with greater land mass relative to oceans, realized warming may be $0.5^\circ\text{C}/\text{decade}$, twice the pace of the global mean. Centres of land masses may have warming two to three times the global mean. Of specific interest for social cost estimates is the effect of increasing land-ocean temperature differentials.

Third, a central estimate for sea level rise by the year 2100 is now placed at 45 cm, compared to 66 cm in IPCC (1990a).

The broad thrust of these changes is to moderate the expected pace of mean global warming, but to intensify the role of variability and surprises at the regional level. For mid-continental areas in the Northern Hemisphere, the new estimates would seem to leave even the mean pace of warming close to that in the earlier report of IPCC (1990a). Increasing ocean-land differentials suggest greater precipitation changes and higher storm damages. Importantly, the new incorporation of aerosol sulphates also carries the implication of potential acceleration from baseline warming if there is greater progress than expected in the reduction of urban pollution and thus reduction in these aerosols (Wigely and Raper, 1992).

In view of these considerations, it would seem that increased damage associated with variability and unpredictability, as well as greater attention to the high regional warming coefficients for the Northern Hemisphere and for mid-continental areas, would broadly

compensate reduced damages from the standpoint of the timetable of mean warming. This would mean that the time path for mean global warming over the next century would only be reduced by 17% (from $0.3^\circ\text{C}/\text{decade}$ to $0.25^\circ\text{C}/\text{decade}$). On this basis, there would appear to be little reason for altering the broad orders of magnitude of the damage estimates in the economic effects literature reviewed below. At the most, the revised assessment might imply somewhat later damages for the Southern Hemisphere (and thus, broadly, for developing countries).

6.2 Damage Estimates for Benchmark Warming ($2\times\text{CO}_2$)

Monetary values for climate change damages have been estimated for a number of sectors in the market economy. In addition, there are non-market damages, which are typically more difficult to quantify (e.g. species loss), and a mixture of both market and non-market effects in some sectors (e.g. forest loss in lumber and public use value). Table 6.1 provides an overview of the categories of damages that might be caused by climate change and associated sea level rise. The estimated damages are not complete. For some categories, monetary estimates of damages have not been attempted. For other categories, the estimated damages only partially reflect the potential welfare loss. In many cases, the preferred measure of welfare impacts - willingness to pay - is approximated by other indicators. Estimates are predominantly for the United States and other OECD countries. Material relating to other countries is sparse although increasing. The incomplete nature of the damage estimates presented here must be borne in mind when evaluating the full welfare implications of global warming. Finally, all the estimates are subject to uncertainty. Where possible, ranges of values are indicated.

[Table 6.1]

Most estimates are for equilibrium global warming associated with a doubling of pre-industrial carbon dioxide equivalent of all greenhouse gases (referred to here as benchmark warming). Absolute estimates are usually based on the present-day economy, and then expressed as a percentage of GDP. Projections then apply these percentage impacts to future world product (e.g. to 2060 for realized benchmark warming), although some of the effects are likely to grow more than proportionately with GDP and others less than proportionately.

6.2.1 Agriculture

Global warming is likely to damage agriculture in many areas but aid it in others. The principal damage will arise from heat stress and decreased soil moisture. Warmer temperatures cause the growing cycle of many plants to accelerate, allowing less time for plant development before maturity. Continental interiors are expected to become drier with global warming. The principal offsets would be longer growing seasons in cold Northern climates, and the fertilization effect of greater atmospheric carbon dioxide.

Rind *et al.* (1990) use GCM results to calculate that for many mid-latitude locations (e.g. the United States), the incidence of severe droughts that currently occur only 5% of the time would rise to a 50% frequency by the 2050s, based on the difference between precipitation and potential evapotranspiration (E_p). They find that:

E_p increases most where the temperature is highest, at low- to mid-latitudes, while precipitation increases most where the air is coolest and easiest to saturate by the additional moisture, at higher latitudes (p. 9983).

On the favourable side, higher atmospheric carbon concentrations are expected to increase photosynthesis, which combines carbon dioxide and water to produce carbohydrates. Laboratory experiments suggest that doubling of CO_2 from 330 to 660 ppm could raise yields by 34% for C_3 crops (wheat, rice, soybeans, fine grains, legumes, root crops, most trees) and 14% for C_4 crops (maize, sorghum; see Schneider and Rosenberg, 1989b). However, open-field conditions may not necessarily achieve the same yield increases (Parry, 1990; Evans *et al.*, 1991; Körner and Arnone, 1992; Erickson, 1993). Bazzaz and Fajer (1992) note that the laboratory experiments are dependent on availability of fertilizer and water, and conclude that because of "competitive interference and limited nutrients ... we do not expect that agricultural yields will necessarily improve in a CO_2 -rich future." Moreover, the doubling of atmospheric carbon is conceptually the wrong experiment for calculating the effects of benchmark (equilibrium) warming. After taking account of other greenhouse gases, the CO_2 concentration in the $2\times\text{CO}_2$ -equivalent equilibrium would be only 440 ppm (Cline, 1992a, calculated from IPCC, 1990a).

In assessing agricultural damage on a global level, changes in trade flows are of crucial importance. Kane *et al.* (1992) apply the US Department of Agriculture's Static World Policy Simulation (SWOPSIM) model of agricultural trade to emphasize the importance of trade effects. Even in a "very adverse" scenario in which yields fall by 5% - 40% in most developed countries, the former Soviet Union and China, and remain unchanged in most other developing countries, net global welfare declines by only 0.47% of GDP. World food prices are expected to increase in the order of 40% or more, with repercussions on both producer and consumer welfare. In a food exporting country like the United States, for example, consumers are expected to lose \$40 billion annually in consumer surplus (at 1986 prices), while US farmers gain \$19 billion annually in producer surplus because price increases more than offset yield reductions. Of course, the implication is that a corresponding loss of consumer surplus occurs for importing nations, associated with terms of trade gains on US farm exports. The main loser identified in this particular model run is China, with economic losses of more than 5% of GDP. Increased world food prices also heavily affect consumers in the former Soviet Union. In a second, more optimistic scenario, worldwide impacts are practically zero, with negative results in Canada, Japan and Europe being offset by gains in Australia, and now also the former USSR and China. The Kane *et al.* figures, averaged over all scenarios, are reproduced as the agricultural damage in Table 6.5.

In another global study Rosenzweig *et al.* (1993) coordinated research applying crop simulation models in 18 countries to examine the impact of benchmark $2\times\text{CO}_2$ -equivalent warming on yields for wheat, rice, maize, and soybeans by 2060. Linking the results in a world trade model (Basic Linked System), they calculated the impact on production levels, prices, and the number of people at risk from hunger. The study finds that crop yields would decline in the low latitudes, where they are currently grown near their limits of temperature tolerance. However, yields could increase at middle and high latitudes when carbon fertilization is included. In the case of moderate adaptation, output rises in developed countries by 4% - 14% but falls by 9% - 12% in developing countries (which must import).

Depending on the GCM used, global output falls by 0% - 5%, prices rise by 10 - 100%, and the number of people at risk from hunger rises from a baseline of 640 million to a range of 680-940 million. Although the results are open to the critique that the climate models used (GISS, GFDL, UKMO) have sensitivity parameters higher than the IPCC's 2.5°C (Reilly and Hohmann, 1993), from another standpoint the results are optimistic. They employ a carbon concentration of 555 ppm, which is essentially a transient concept for the year 2060, rather than an equilibrium concept for $2\times\text{CO}_2$ -equivalent (440 ppm)².

The number of additional people suffering from hunger has also been estimated by Hohmeyer and Gärtner (1992). Their estimate of 900 million deaths over a 20 year period up to 2030 is based on a rather *ad hoc* line of reasoning, though. Their figure, which measures actual casualties, also appears rather high, compared to the more sophisticated Rosenzweig *et al.* (1992) estimates of people *at risk*.

On a regional level, a study for the European Union predicts that overall agricultural yields in Europe are likely to increase as result of increased temperature and precipitation. Welfare gains of ECU 3.2 billion are predicted for 1°C warming and 12.2 billion for 4°C (CRU/ERL, 1992). Gains would mainly occur in the north, while the outcome for southern Europe would be more mixed.

For the United States, Adams *et al.* (1993) estimate the combined economic effects of global warming on agricultural producers and consumers under different scenarios. Impacts are generally negative if based on the $2\times\text{CO}_2$ predictions of the UK Meteorological Office. Using the more benign GISS and GFDL forecasts yields mostly positive impacts, except for the cases without CO_2 fertilization: producer gains, particularly in the north, are generally large enough to offset the losses faced by consumers and producers in the south. In their "standard" scenario with a CO_2 concentration of 550 ppm and no trade and adaptation effects, the estimated agricultural impacts range from -\$18 billion (UKMO) to +\$10 billion (GISS). Substantial economic losses are predicted in all scenarios once temperatures rise by 4°C . Based on earlier estimates by US EPA (1989), Nordhaus (1991) and Cline (1992a) have estimated US damages of roughly zero and \$17.5 billion, respectively. The former estimate is based on a 660 ppm scenario, while Cline assumes 440 ppm, consistent with CO_2 -equivalent doubling.

A study of the Missouri-Iowa-Nebraska-Kansas (MINK) area introduces the further influence of farmer adaptation (earlier planting, use of longer season varieties, changes in tillage to conserve water; see Easterling *et al.*, 1993; Rosenberg and Crosson, 1991a, b). Using actual climate conditions of the 1930s as an analogue for a 2030s climate, the study finds that without carbon fertilization climate change cuts agricultural production in the area by 17.1%, but only 12.1% with on-farm adaptations. Adaptation thus reduces losses by about one third. If 100 ppm carbon fertilization is added as an offsetting factor, output is reduced by only 8.4%. This loss is cut further to 3.3% by adding the influence of adaptation. Considering that regional temperatures were only about 1°C higher than today in the 1930s, and adjusting

² The eventual equilibrium warming consistent with the 2060 greenhouse gas concentrations would be higher than benchmark warming (because of the lag of two decades or more between committed and realized warming, associated with ocean thermal lag).

for commensurate carbon fertilization, the MINK results suggest losses on the order of 10% for benchmark 2xCO₂ warming, even with farmer adaptation.

In another US study Mendelsohn *et al.* (1992) argue that the production function method commonly used in crop models inadequately captures induced producer responses. They suggest that existing cross-section data across different climatic regions can provide a better guide to total effects incorporating these responses. They use county-level US data to regress farmland values on climate and a number of other relevant variables. They simulate the impact on aggregate US agriculture of global warming causing a rise of 2.8°C (5°F) in mean temperature and 8% in rainfall. Under these assumptions, US agriculture experiences losses of \$6 billion to \$8 billion annually if county results are weighted by shares in cropland area, but -\$0.7 billion to +\$2 billion if the weights are shares in crop revenue (which gives much more weight to irrigated lands of the West and South). The study shows that agricultural land value is strongly influenced by climate, even after taking into account adaptation. The cross sectional data used in the study reflect agricultural practices that are highly adapted to the local climate, and yet the authors still find large productivity differences related to climate. The evidence indicates that warmer summers have a negative impact on land values, and by implication productivity. This is persuasive empirical evidence that adaptation is unlikely to completely offset the effects of climate change on agriculture.

6.2.2 Sea Level Rise

IPCC (1990a) estimates that under business as usual, realized global warming above preindustrial levels would amount to 4.2°C by the year 2100 and that the corresponding sea level rise would reach 66 cm. In a model incorporating biosphere feedback (carbon fertilization), stratospheric ozone depletion, and sulphate aerosol screening, Wigley and Raper (1992) used the subsequent 1992 updated emissions projections of the IPCC to calculate that as a best guess, realized warming from a 1990 (not preindustrial) base would amount to 2.5°C (rather than 3.3°C) and sea level rise by 2100 would reach 48 cm (rather than 66 cm).

Both the original and updated IPCC-based estimates refer to the transient, rather than the equilibrium impact of sea level rise. Unlike other damage categories, for sea level the equilibrium effects are far greater and take much longer to occur than the point estimates corresponding to the first year the equilibrium warming is realized. For a discrete warming shock, the sea level continues to rise for up to 500 years (Titus, 1992; Manabe and Stouffer, 1993). A crude way of converting this growing long-term effect into a point estimate is to use a benchmark of 1 metre sea level rise, even though realized increases by 2100 are estimated to be lower.

The costs of sea level rise divide into three types: capital costs of protective constructions, the recurrent annual cost of foregone land services, and the costs associated with increased flood frequencies.

Protection Costs: US EPA estimated that for the United States, a 1 metre rise in sea level by the year 2100 would require \$73 billion to \$111 billion cumulative capital costs to protect developed areas through the building of bulkheads and levees, pumping sand, and raising barrier islands (US EPA, 1989). Assuming that capital costs would be spread over a 100-year

period, Cline (1992a) estimated costs in the order of \$1.2 billion for capital construction. Gleick and Maurer (1990) estimate capital construction and maintenance costs for protecting the San Francisco bay from 1 metre rise at \$200 million annually, or a sixth of the US total estimated in Cline (1992a), suggesting the latter may be an underestimate. Fankhauser (1994a) estimated annuitised costs of coastal protection against a 50 cm rise in the order of \$1 billion worldwide, with about half of it occurring in non-OECD countries.

Land Loss: The US EPA (1989) report estimates that under a 1 metre rise scenario unprotected dry land amounting to 6,650 square miles would be lost in the US, and 49% of today's 13,000 square miles of wetlands would be lost (Titus *et al.*, 1992). Titus *et al.* indicate that wetlands preservation programs typically cost up to \$30,000 per acre. Using a more conservative \$10,000 capital cost per acre of wetlands, placing coastal dryland value at \$4,000 per acre, and applying a rental opportunity cost of 10%, Cline (1992a) estimates the annual US losses from a 1 metre rise at \$4.1 billion for wetlands and \$1.7 billion for dryland. Assuming only a 50 cm rise in sea levels, but doubling wetland costs to \$20,000 per acre, at least in developed countries, Fankhauser (1994a) obtains a cost estimate of \$45.6 billion annually for foregone land services worldwide. With over 85% of coastal wetland loss occurring in developing countries, low income regions are by far the most heavily affected areas. For the OECD (excluding Canada, Australia and New Zealand) Rijsberman (1991) estimates a loss of coastal wetlands in the order of 48,000 - 64,000 km² for a 1 metre rise, more than 50% of the remaining habitats. In comparison, Fankhauser (1994a) assumes a 33% loss under a 50cm rise.

Sea Surges: A 1 metre rise in sea levels could increase the number of people subject to annual flooding by about 20%, according to estimates by IPCC (1994). Particularly at risk would be coastlines along the Indian Ocean, in the South Mediterranean and in Africa, as well as small island states. A number of case studies exist which identify the impact of sea level rise on sea surges in the USA (see Titus, 1987). The annual average damages in Charleston, South Carolina, could double due to an 88 cm sea level rise; the damages of a 100 year storm in Galveston, Texas, could triple (Note that cost-effective protection measures can mitigate this loss). US FEMA-FIA (1991) estimates that the area inundated by a 100-year flood will increase from 19,500 square miles to 23,000 and 27,000 square miles for a 1-foot and 3-foot sea level rise, respectively, by the year 2100. The region most significantly affected would be the Louisiana coast. The expected annual flood damage in the year 2100 increases by 36-58% (\$150 million) for a 1-foot rise and by 102-200% (\$600 million) for a 3-foot rise in sea level. For the European Union, CRU/ERL (1992) calculate that the consideration of periodic flooding would increase the costs of sea level rise by as much as a factor 2.7.

6.2.3 Forests

Global warming is expected to cause a poleward migration of forests, and change in their composition. Sedjo and Solomon (1989) use the Holdridge Life Zone classification system together with GCM projections of changed climate by grid area to calculate that the steady-state effect of 2xCO₂ warming would be to reduce boreal forests by 40% and temperate forests by 1.3% in biomass, but increase tropical forests by 12%. The net change would amount to a decline of 3.7% globally in biomass, and 5.8% in area. Based on these figures, Fankhauser (1994a) has estimated annual forestry damages of \$1.8 billion in OECD countries

and \$2 billion worldwide, using forest values of 2,000, 400 and 200 \$/km², respectively, for high, middle and low income countries. Because of the positive impact on tropical forests and the use of higher forest values in developed nations, most forestry damage occurs in OECD countries.

Compared to the equilibrium estimates of Sedjo and Solomon, transient effects over as much as three centuries would be much more severe. Whereas the latitudinal borders of potential location for given species would migrate poleward by 600 to 1,000 km over the next century, the actual migration pace could be as low as 100 km (US EPA, 1989). Dieback along low-latitude boundaries would thus exceed additional growth on the poleward boundaries. Over the next 100 years US forests could lose 23% - 54% of standing biomass in the Great Lakes region and 40% in the West.

On this basis, Cline (1992a) estimates a loss of 40% for US forests. Estimating the value of annual wood extraction at \$10 billion, and allowing for some limitation of losses through reforestation, he estimates net US forest loss from benchmark 2xCO₂ warming at \$3.3 billion annually over the relevant horizon, solely for commercial wood products.

Titus (1992) places US forest damages an order of magnitude higher, at \$44 billion annually (central estimate). He estimates a median percentage biomass loss of 34% in the 30 states he examines. His much higher damage estimates thus stem not from greater biomass loss but from a higher valuation of unit forest area. Using a comprehensive measure that includes recreation and other value, Titus values forested area at \$45 to \$150 per acre per year of forest (above raw land value). The Titus estimates would make US forest loss the largest damage category. At the other extreme, Nordhaus (1991) judges that forest losses would be "small". This range suggests especially large uncertainty for estimates in this category.

6.2.4 Water Supply

Warming is expected to put stress on water supply. A smaller share of precipitation in the form of snow, combined with earlier snow-melt, would mean higher run-off in the winter. Run-off in the spring and summer would correspondingly be reduced. In those areas and/or periods where precipitation declines, the combination of higher evaporation (from warmer temperatures) and lower precipitation would reduce soil moisture and water levels and flows. At the same time, the demand for water would tend to rise with warming, because of increased needs for irrigation and for cooling in electric power production (US EPA, 1989).

The IPCC stresses that river basin run-off is very sensitive to small variations in climatic conditions, because run-off is a residual between precipitation and soil absorption or evaporation; and small changes on any of the underlying variables can cause a much larger proportionate impact on this residual. For the United States, water basin simulation models show that in a warmer, drier climate (+2°C, -10% precipitation), water supply in 18 major water regions covering the bulk of national supply would decline by approximately one-third (calculated from IPCC, 1990b).

For the US, the EPA (1989) predicts that 2xCO₂ warming would reduce annual water deliveries in California's central valley basin by 7% - 16%, even as demand for water rises by about 50% as early as 2010. For the Sacramento basin, Gleick (1987) estimates that a 4°C

increase in temperature would decrease summer run-off by 55% even if there were a 10% rise in precipitation. For the Boston area, Kirshen and Fennessey (1992) apply water balance models to GCM projections for benchmark warming and find that reliable water yields of existing water systems could fall by as much as one-third (GISS, GFDL), but could also rise (UKMO, OSU), because some models predict falling precipitation and others rising. If zero change in precipitation is imposed, the mean model estimate is a decline of 18% in reliable water yield.

Cline (1992a) sets 10% as a central estimate for water supply reduction in the United States from benchmark warming. He estimates national annual withdrawals at 0.4 billion acre-feet, and unit price at \$250 per acre foot. The resulting estimate of annual damage is \$7 billion. Titus (1992) uses a larger volume impact, but lower unit prices to reach a central estimate of \$11.4 billion annual losses. For the European Union CRU/ERL (1992) estimate that the costs of reduced water run-off would amount to ECU 5.8 billion for 1°C warming and 18.8 billion for 4°C.

Fankhauser (1994a) uses a somewhat lower percentage volume loss than the US studies, but, at least for OECD countries, a unit price more than twice as high as Cline's. He estimates annual losses at \$34.8 billion for the OECD, and \$46.7 billion worldwide. Again, the high share of OECD damages is due to differences in valuation between regions. In physical units about three quarters of water losses occur in non-OECD countries (see Table 6.5).

In all cases, more efficient water allocation with less low-priced water allocated to agriculture and more to urban use could attenuate losses in water supply, but would aggravate prospective agricultural output losses. Gleick (1992) and Homer-Dixon *et al.* (1993) have emphasized another dimension of water supply effects: the potential for political conflict, such as the dispute over the Jordan river basin that contributed to the 1967 war in the Middle East. From this standpoint associated damages might appropriately include higher defense costs, in terms of economic reckoning, or perhaps more appropriately some unquantified social cost of increased probability of regional wars.

6.2.5 Space Cooling and Heating

Global warming would impose higher air conditioning (space cooling) costs, but reduce heating costs. For space cooling costs in Japan, Nishioka *et al.* (1993) report estimates of a 2% increase in electricity demand per °C warming for temperatures between 24-30°C, and 1% increase for temperatures between 17-24°C. No significant change in demand was found for temperatures above 30°C.

On the basis of detailed energy projections, the US EPA (1989) has estimated that with warming of 3.7°C by 2055, there would be a net increase in US electricity demand by about one-fifth above baseline, requiring additional annual operating costs of \$53 billion and cumulative capital cost increases of \$224 billion. Scaling back these estimates for consistency with present-day economic size and for warming of only 2.5°C, Cline (1992a) estimates annualized damages of \$11.2 billion from higher net electricity requirements under benchmark warming. Arguably, this estimate is understated, because with global mean warming of 2.5°C, US warming would amount to 3.9°C. Titus (1992) uses the same underlying study to reach a central estimate of \$5.6 billion.

More informally-based estimates of the corresponding savings on space heating are considerably lower, in the range of \$1 billion annually (Nordhaus, 1991; Cline, 1992a). Work by Loveland and Brown (1992) confirms that prospective global warming is likely to increase energy requirements for air conditioning by more than it reduces energy needed for heating. A major reason is that cooling is by electricity, which is much more expensive per BTU than oil or gas (the dominant heating fuels; Titus, 1992). Taking into account anticipated baseline building standards by 2040, Loveland and Brown (1992) estimate that 2xCO₂ warming would raise cooling demands by 35 to 75% for most US areas, and increase peak loads by 6% - 12%. Cline (1993e) applies the Loveland-Brown data to estimate that the weighted average of energy requirements amount to 16 BTU per square foot per degree day for cooling and only 2.6 BTU for heating. As a result, net damages would result from global warming even though in an initial phase warming would actually move average US temperatures closer to 65°F and thus could reduce unweighted degree-days of climatisation. This is not an undisputed result, though. A study by Rosenthal *et al.* (1994), for example, reaches exactly the opposite conclusion, predicting net *benefits* for the US in the order of \$12 billion for 2.5°C warming.

Extrapolating the US EPA (1989) data to other geopolitical regions, Fankhauser (1994a) assumed an increase in electricity demand of 3.2% in all regions considered, except for the former Soviet Union, where electricity demand is assumed to decrease by 1%. This results in increased space cooling costs of about \$20 billion in the countries of the OECD and \$23 billion worldwide.

Based on estimated changes in heating and cooling degree days, CRU/ERL (1992) calculated significant benefits from reduced heating expenses in the European Union. Gains in Northern Europe are only partly offset by increased costs in Portugal, Spain and Greece. A 1°C rise in temperature would yield net benefits in the order of ECU 13 billion. For 3°C warming the figure would rise to about ECU 32 billion. These rather optimistic results appear to be mainly due to the dominance of heating over cooling degree days in the baseline case without warming.

6.2.6 Insurance

The insurance industry protects other economic sectors from the financial consequences of unexpected or uncertain events, including weather extremes. As such, it is highly exposed to changes in these extremes and thus to climate change. The basic function of insurance is to transfer financial risk from an individual to a group, i.e. to spread a specific individual loss over everybody potentially affected. The present capacity of natural hazard insurance is about \$100 billion. For comparison, in 1992 hurricane Andrew alone caused an economic damage of \$30 billion, about half of which was insured (Dlugolecki *et al.*, 1994, 1995). Since 1987, after a relatively quiet period of about 20 years, the insurance industry has been confronted with a large number of major weather related catastrophes, i.e. events which involved insured losses of over \$1 billion. This increase was caused by a variety of factors, including population growth, increased standards of living, concentration of people and capital in large conurbations, the development of extremely exposed areas, and environmental changes. Although there is no clear connection to the enhanced greenhouse effect, the reaction of the sector is illustrative of what would happen if climate change were to lead to an increase in the number and intensity of extreme weather events (Berz and Conrad, 1993;

Dlugolecki *et al.*, 1994, 1995; Leggett, 1993; Tol *et al.*, 1994). Initially premiums were increased and cover was restricted. In some areas, such as the Caribbean and the Pacific, insurance and reinsurance supply was temporarily withdrawn after a sequence of hurricanes in the late 1980s and early 1990s. As a further reaction, the insurance sector is currently also considering (Dlugolecki *et al.*, 1994, 1995; Tol *et al.*, 1994):

- (a) alterations in premia determination, incorporating more knowledge on the actual risk (so far, premia have primarily been determined by competition and recent claims);
- (b) changing the product, limiting the insurer's exposure;
- (c) extending the available funds through further pooling and accumulation. This may require alterations of existing fiscal and institutional regulations;
- (d) risk management, i.e. getting involved in restricting the damage caused by weather events;
- (e) lobbying for, and investing in environmentally sound policies and projects.

While a number of these points help in reducing the overall exposure to weather hazards, many merely affect the exposure of the insurance sector itself. Only limiting the insurers' exposure obviously leads to an expansion of the exposure to others. Little research has been done to assess the consequences of such a policy on households, industry and government.

6.2.7 Other Market Sectors

Construction: Nordhaus (1991) suggests that the construction sector in temperate climates would be favourably affected by global warming because of a longer period of warm weather. However, although construction is adversely affected by frost, it is also inhibited by rainfall, and GCMs typically predict an increase in global mean precipitation by about 8% as the consequence of benchmark 2xCO₂ warming (IPCC, 1990a). Solomou (1990) has examined data on construction and rainfall in the period 1856-1913 and found a close negative correlation between the two. The IPCC similarly notes adverse effect of rainfall on industry more generally, and cites Parry and Read to the effect that "rainfall is responsible for more delays than any other climatic variable" for UK industry (IPCC, 1990b, p. 5-23). However, estimates are not available on the net effects of warming and increased precipitation on construction or industry more generally.

Tourism and Leisure Activities: Studies by the Canadian Climate Program Board suggest that as a consequence of a shortened period of snow cover Quebec could lose 40 to 70% of skiable days. In Ontario, the shorter skiing season may cause a loss of up to \$50 million in revenue (Canadian Climate Program Board, 1988a, b). Losses would presumably be larger in relative terms in US ski areas, where the temperature base is already higher. Annual US ski activity amounts to an estimated \$5.6 billion and 53 million skier visits (Waters, 1990). Assuming a 60% reduction from benchmark warming, and allowing for released productive labour and capital, Cline (1992a) estimates ski industry losses at \$1.7 billion annually.

The tourist industry will also be affected by beach washing and the inundation of beaches

(Baan *et al.* 1993), as well as likely coral reef death and other ecosystems loss (US EPA, 1989)³. These impacts could be particularly significant for small island states, where tourism frequently accounts for over a third of GDP (see Turner *et al.*, 1994). On the other hand, there could be gains from global warming in other leisure sectors such as camping, boating and sunbathing. The Ontario case study, for example, predicts an increase in the camping season of up to 40 days in some areas (Canadian Climate Program Board, 1988b). In many regions, however, an increase in summer activities could be hampered by increased rainfall. CRU/ERL (1992) have developed a "comfort index", using temperature, sunshine and rainfall as indicators of the suitability of climates for leisure activities. Using this index and figures on current European tourist revenues they estimate that 1°C warming could benefit tourism in the EU by about ECU 4.7 billion. As temperature rises, the impact value at least in Southern Europe soon becomes negative, though.

Urban Infrastructure: The US EPA (1989) has examined the impact of global warming on urban infrastructure costs. For coastal cities, sea level rise or more frequent droughts would increase the salinity of coastal aquifers and tidal surface waters, requiring a response where these are the sources of metropolitan water supply. In addition, more frequent and intense storms would likely overload existing storm sewer systems. Using US EPA studies for New Orleans, New York, Philadelphia, and Miami, Cline (1992a) suggests that annualized damages of benchmark warming for US urban infrastructure could amount to \$100 million yearly.

6.2.8 Health

There is a U-shaped relationship between mortality and outdoor air temperature. Death rates increase as a consequence of both heat waves and very cold weather. The lowest mortality rates are found at temperature levels of about 16-25°C (Kunst *et al.*, 1993; Haines and Parry, 1993). Global warming could lead to an increase of heat related deaths from coronary disease and stroke which is likely to more than offset the reduction in winter mortality. Air pollution increases the occurrence of respiratory diseases (emphysema and asthma), and longer, warmer summers are expected to increase the severity of air pollution.

In addition to directly heat related health effects, there could be indirect losses from increased vector-borne diseases (e.g. carried by ticks and mosquitoes). The risk areas of diseases like malaria or yellow fever may shift as their vectors adjust to new climate conditions (Haines and Parry, 1993). WHO (1990), for example, suggests that the so far disease-free highlands of Ethiopia, Indonesia and Kenya might be invaded by vectors. A study for Indonesia predicts a fourfold increase the incidence of dengue fever and a 20% increase in malaria cases (Asian Development Bank, 1994). Vector-borne diseases may also spread into developed countries. Hohmeyer and Gärtner (1992) estimate that under 2xCO₂, an extra 200 million people could be exposed to malaria worldwide. Simulations for the United States on a possible increase of malaria are however inconclusive (US EPA, 1989).

The increased occurrence of flooding could lead to a higher incidence of diseases associated

³ Some of these impacts may, as forgone use value, be included in estimates for ecosystems loss (see Section 6.2.13).

with poor sanitation standards, particularly in developing countries. For Indonesia it has been estimated that by the year 2070 cases of diarrhoea could raise to over 900 per 10,000 inhabitants, compared to 300 cases/10,000 people in 1989 (Asian Development Bank, 1994).

Kunst *et al.* (1993) have analysed the statistical relationship between mortality and air temperature in the Netherlands. They found that a 30 days increase in air temperature of 1°C above its ideal level would lead to a rise in mortality of 1.1 - 1.9%. A 1°C drop from the optimum would cause a slightly lower rise of about 0.8 - 1.3%. For the UK Langford and Bentham (1993) estimate that the higher temperatures predicted for 2050 (about 2.5°C) could result in some 9000 fewer winter deaths per year. Kalkstein has used statistical methods to analyse the mortality impact of changed weather conditions under 2xCO₂ for 15 major US cities (US EPA, 1989; Kalkstein, 1989). Even after accounting for induced acclimatization (based on mortality statistics for control cities with comparable present climate conditions), he finds that increased summer deaths substantially exceed decreased winter deaths. Cline (1992a) and Fankhauser (1994a) weight these results by population and extrapolate that benchmark warming would increase mortality by about 27-40 persons per million population, depending on the warming scenario. Without acclimatization this figure would be about six times higher. For the United States the more conservative figure including acclimatization translates into 6,600 to 9,800 additional deaths annually at present US population scale.

Mortality effects could be particularly damaging in the more vulnerable countries of the developing world. In Shanghai, for example, death rates from heat stress are currently over twice those in New York City (Haines and Parry, 1993). Health problems associated with hot spells are also significant in Bangladesh (Asaduzzaman, personal communication, 1994) and Pakistan (Asian Development Bank, 1994). Using uniform mortality rates, Fankhauser estimates that about 115,000 casualties will occur in non-OECD countries, compared to some 23,000 in the OECD (for 2.5°C warming, see Table 6.5). Tol (1994b), using the same estimates but without scaling to 2.5°C warming, arrives at a figure of 215,000 casualties worldwide.

Expressing the value of this loss in monetary terms is controversial (see Box 6.1). Cline (1992a) uses lifetime earnings to place statistical life valuation at a conservative \$595,000 and reaches a corresponding estimate of \$5.8 billion in annual US losses from benchmark warming. Using higher values Titus (1992) obtains annual damages of \$9.4 billion for the US. Fankhauser use value-of-statistical-life estimates of \$0.1 to 1.5 million, depending on regional income levels, and obtains mortality damages of \$10 billion in the US, \$34 billion for the OECD and \$49 billion worldwide. If an identical value of \$1 million for all lives were used worldwide this latter figure would rise to almost \$140 billion. The rationale for uniform statistical life values is however unclear (Box 6.1). Tol (1994b) assesses a statistical life at \$250,000 + 175*(income per capita). With worldwide mortality costs of \$188 billion health damages account for more than half of his aggregate estimate of warming damages.

[Box 6.1]

6.2.9 Air Pollution

A warmer climate would aggravate urban pollution. In the United States, tropospheric ozone is the most severe problem in terms of the number of persons living in areas with air quality

indexes that violate national standards (75 million persons in 1986). Total suspended particulates (TSP) and carbon monoxide are also important (41 million each). TSP is also implicated in widespread health damage in the developing world and the economies in transition.

Numerous studies confirm that ozone concentrations rise with temperature (see e.g. IPCC, 1990b). The US EPA has summarized various US estimates with the conclusion that a 4°C rise in temperature (about what could be expected for the United States under 2.5°C global mean warming) could cause an increase in peak ozone concentrations by 10%. The result would be to double the number of cities in violation of the air quality standards from 68 to 136, causing most midsize and some small cities in the Midwest, South, and East to be added to the list of those presently in violation.

The US EPA has applied its past models relating ozone concentrations to emissions of volatile organic compounds (VOC) to estimate that, to offset benchmark 2xCO₂ warming, it would be necessary to reduce VOC in the United States by 700,000 tons from a year-2000 expected base of 6 million tons. At an estimated cost of \$5,000 per ton, the agency calculates that the resulting costs would amount to \$3.5 billion annually (US EPA, 1989). Cline (1992a) uses this figure as an estimate of US air pollution damage to be expected from benchmark warming. As an indicator air pollution control expenditure in 1987 was \$27 billion (US EPA, 1990b).

Titus (1992) estimates US tropospheric ozone damage from benchmark warming at \$27.2 billion annually. This is almost an order of magnitude higher than Cline, although both figures are based on the US EPA (1989) estimate. The difference appears to be that Titus projects a high baseline of VOC (volatile organic compound) emissions, at 3% growth and reaching an implied 70 million tons by 2060, whereas the US EPA estimate is based on the present scale of emissions. Although some allowance for growth in the base is appropriate, it seems unlikely that the pollution baseline would grow faster than GDP and energy output.

Instead of calculating the additional expenditures needed to maintain present air quality standards, Fankhauser (1994a) estimates the extra damage occurring if air quality standards were allowed to deteriorate. Assuming increases in NO_x and SO₂ emissions of 5.5% and 2%, respectively, he estimates additional air pollution damages of \$12 billion in the OECD, and \$15 billion worldwide (see also the cost of air pollution estimates provided in Table 6.13).

6.2.10 Water Pollution

Titus (1992) and Nishioka *et al.* (1993) have identified water pollution as a category with potentially large damages from global warming. They predict a likely decline in river flow under global warming because of lesser water run-off. Because rivers serve to carry away waste, lesser river flow leaves more waste to be removed by emissions controls. Nishioka *et al.* also discuss a possible decrease in the water quality of lakes through increased algae growth.

In assessing the impact of water pollution on the US Titus assumes that the discharge of pollutants would change by the same proportion as river flow. He cites US EPA estimates to establish a base of \$64 billion for US water pollution control costs in the year 2000 (at

constant 1990 prices). Based on estimates by Waggoner and Revelle, he calculates that run-off declines by 2% - 4% if either precipitation decreases 1% or temperature increases by 0.4°C. Setting the elasticity of control costs (percent change for a one percent change in river flow) at 1 to 1.7, Titus calculates that water pollution control costs imposed on the United States by benchmark global warming would be in a range of \$15 billion to \$67 billion annually, with a central estimate of \$34 billion. Like Titus' estimate for forest damage, this estimate dwarfs typical damage calculations for most other individual categories. Yet water pollution is one of the most under-researched aspects of economic damage.

6.2.11 Migration

Global warming could increase the displacement of people because of coastal inundation from sea level rise, increased droughts (e.g. from Mexico to the United States), and possibly increased tropical cyclones (e.g. from the Caribbean to the United States). Schelling (1983) views migration as an efficient adaptive response to global warming. However, presumably a cost should be imputed to the utility loss by families compelled to migrate (Jansen, 1993). Indeed, historically peoples have often fought wars to avoid being forced to leave their homelands. Tol (1994b) arbitrarily puts this loss at three times the average income per capita in the region of departure. This is reflected in Table 6.6. There is also a cost to the recipient host country. In many countries, e.g. in Europe and the United States, the costs of incorporating immigrants into the social welfare infrastructure are already a politically sensitive source of social and budgetary pressure.

Cline (1992a) reports estimates of 640,000 legal immigrants into the United States annually in recent years, in addition to perhaps 130,000 illegal immigrants (Goering, 1990). He hypothesizes an increase of 25% in illegal immigration and 10% in legal immigration as a consequence of benchmark warming. Based on total per capita spending by state and local governments, and assuming 18 months before an immigrant's tax payments cover the family's social infrastructure costs, Cline estimates costs at \$4,500 per immigrant; Ayres and Walter (1991) similarly cite a figure of \$4,000 per refugee accepted by the United States. Cline (1992a) estimates annual immigration costs to the United States from 2xCO₂ warming at \$450 million. The hardship and stress suffered by refugees remains uncounted, though. Fankhauser (1994a) has extended the Cline estimates to the world as a whole, assuming that current migration patterns will hold (see Table 6.5).

6.2.12 Human Amenities

Mearns *et al.* (1984) use statistical distributions of current temperatures to explore the impact of global warming on extreme temperature events for the United States. In their base case, they increase mean temperature by 3°F (1.7°C) and hold the variance and autocorrelation of daily temperatures constant. Under these assumptions, they calculate that the frequency of heat waves (defined as 5 consecutive days with a maximum temperature of at least 35°C) would multiply three-fold (estimated for Des Moines, Iowa). There is reason to believe that people would be willing to pay something to avoid a threefold increase in the incidence of heat waves. At the same time, global warming would reduce disamenity of severe winters in colder areas. The net balance under benchmark warming is unclear. As suggested below, however, for much higher warming over the very-long term, the amenity damages would be more likely to dominate.

Cline (1992a) provides an order of magnitude estimate of the value of the disamenity caused by a sharp increase in the number of hot spells in the USA; assuming that people are willing to pay 0.25% of their income to avoid this and other disamenities, a \$10 billion loss per year results⁴.

Leary (1994) has surveyed the available empirical evidence on the implicit valuation of amenity due to local climatic variation in the USA. The results of this study are:

- (a) that individuals value changes in climate and are willing to accept lower wages, or pay more for property, in return for an improved local climate. Some migratory patterns are explained by climate differences.
- (b) in the USA these values appear to be substantial, ranging from hundreds to thousands of US dollars.
- (c) households prefer sunny, mild climates. Increases in winter temperature and the number of sunny days are favoured, while higher summer temperatures deter migrants, so that hot summers appear to be a disamenity.

While these findings are intuitively appealing, characterisation of "climate preferences" is not, however, robust across the studies evaluated and it is not possible therefore to say whether climate change will, on balance, increase or decrease climate amenity. As with other aspects of the economics of climate change, these results are relevant only to the USA and, perhaps, other industrialised temperate zones where housing and labour markets respond to differentials in housing and work characteristics.

Amenity effects would vary by region, tending toward damages in presently warm areas and gains in presently cold areas. Potentially amenity valuations could be large in absolute terms, because they apply to the entire income base of the population. However, the tendency toward neutralization by the differential effects among geographic regions and between seasons would tend to reduce the overall magnitude of amenity effects.

6.2.13 Ecosystems and Biodiversity Loss

Perhaps the category in which losses from global warming could be among the largest, yet where past research has been the most limited, is that of species loss. There is a serious need for conceptual and quantitative work in this area.

The US EPA (1989) has noted in general terms the risk of increased species extinction from global warming, because of changes in habitat, predator/prey relationships, and physiological changes. It cites the poleward migration of forests as a major reason to expect stress on species, especially in view of natural and manmade barriers to animal migration. Another category of likely species loss is that of coral reefs, as suggested by recent instances of coral death from El Niño warming (Glynn and de Weerd, 1991).

⁴ As the estimate is purely speculative, it is excluded in the central estimates of that study, and from Table 6.4 below.

Economists identify three types of species value: direct and indirect use value (e.g. plant inputs into medicine and the role of forests in protecting watersheds, respectively); option value (preserving a species to retain the possibility that it may be of economic use in the future); and existence value (like the value society places on a rare work of art). Table 6.2 (based on Pearce, 1993) summarises the results of "contingent valuation" sample survey estimates of what the public would be willing to pay to preserve an endangered *animal species*. Average values range from \$1 - \$18 per person per year for preservation of an individual species, with a maximum of \$40 to \$64 obtained for humpback whales. The willingness to pay figure for the preservation of entire *habitats* is somewhat higher, with a range of \$9 - \$107 per person and year.

[Table 6.2]

The economic value of *plants* is dominated by their potential significance for medicinal purposes. Pearce (1993) notes that in the United States about 40 plant species accounted for plant-based prescription sales of some \$15 - 20 billion/year during the 1980s (at 1990 prices). This would imply an economic value of at least \$300 million per successful species and year. The figure could rise up to several billion dollars if values were calculated on the basis of deaths avoided using statistical life valuation. These are averages and some species are clearly more valuable than others. Nevertheless, the figures can provide some indication of the lost pharmaceutical value from disappearing species. Some 60,000 plant species are expected to become extinct over the next 50 years. Given that the probability of a plant species yielding a successful drug is between 1:10,000 and 1:1,000, between 6 and 60 plant species with potential drug value could thereby be lost. With a mean loss of 30 such species, and applying the price range just noted, Pearce (1993) calculates that the annual losses for the United States could amount to between \$8.8 billion and \$180 billion (assuming there are no synthetic substitutes). By implication, if global warming were to increase these expected losses by just 10%, loss of plant species alone could cause annual US losses from global warming on the order of \$1 billion to \$18 billion in gross value terms (less, once costs are allowed for).

Fankhauser (1994a) cites the Pearce (1993) survey (see Table 6.2) to arrive at a willingness to pay estimate of \$30 per person per year to avoid species and habitat loss from global warming. Total costs amount to about \$40 billion annually for the world as a whole, with about one third occurring in developing countries. Cline (1992a) arrives at an estimate of about \$4 billion annually as a notional value of species loss from benchmark global warming for the US, but suggests that the figure could as easily be an order of magnitude higher (\$40 billion). The estimate is based on an extrapolation of observed US public expenditures for the preservation of one particular species (the spotted owl).

6.2.14 Extreme Weather Events

Along with changes in the mean climate, changes in the extremes can be expected. Changes in the extreme values of meteorological variables are not necessarily proportional to changes in the mean; if, for instance, mean precipitation shifts upwards while at the same time the variability increases, the number of droughts might remain roughly the same whereas the number of floods rises drastically (Graßl *et al.*, 1995). Also, extremes are of more importance in studying the socio-economic impacts of climate change. Most societies, in

accommodating to the environment they live in, have developed strategies to cope with only a limited range of climatic events. Within this range, the 'normal' variability is regarded as a resource while the extremes constitute hazards (Heathcote, 1985). All kinds of adaptation mechanisms, such as insurance, exist to deal with these extremes. However, adaptation is costly, and therefore limited. Prevention is only to a certain extent better than cure.

Measures to adapt to natural hazards comprise a mix of physical, economic and societal features. At the physical level, there is the design of buildings and protection constructs, such as dikes. At the economic level, there are personal savings and insurance to cover the damage. At the societal level, there are social safety nets, charity, and the government. Different adaptation mechanisms exhibit different degrees of flexibility; an insurance policy is valid for one year, an average Dutch dike has a lifetime of about two centuries. Flexibility is enhanced as adaptation measures are under constant pressure of changes in population and industrialisation, and their densities, and the legal, economic, financial and social systems (Berz and Conrad, 1993). Additionally, climate constantly changes. The main difference between 'natural' changes and the enhanced greenhouse effect, however, is that the latter involves a prolonged tendency in one direction, uncertain in its magnitude and pace (Tol *et al.*, 1994).

It is clear from the above that the qualification 'extreme event' or 'disaster' is a social construct, which is hard to measure. The continuously changing mechanisms to cope with natural disasters complicate this matter further. Also, while the direct impacts of natural disasters may be harmful, the event might set in motion a chain of beneficial changes, compensating for the initial losses. Finally, a disaster is not only local in a social and temporal sense but also in a spatial sense. The current generation of GCMs is not capable of reproducing present extremes very well, certainly not without spatial filtering, let alone capable of deriving changes in extremes due to the enhanced greenhouse effect (Graßl *et al.*, 1995).

Little systematic research into the impact of changes in extreme weather events has been carried out. Most attention has been paid to tropical cyclones, the consequences on which appear to be one of the most controversial questions of climate change impact research.

Tropical Cyclones: On the basis of $2\times\text{CO}_2$ simulations with the GISS GCM, Hansen *et al.* (1989) conclude that global warming would bring "increased intensity" of "both ordinary thunderstorms and mesoscale tropical storms". Wendland (1977) has provided empirical support for the relationship of hurricanes to ocean surface temperatures. From monthly data for 1971-81, the frequency of hurricanes is closely related to the size of ocean area with temperature over 26.8°C , and the relationship is exponential. Similarly, Emanuel (1987) argues that tropical cyclones are "particularly sensitive to sea surface temperature".

Higher sea surface temperature causes a larger drop in barometric pressure. Applying a 2.3°C to 4.8°C range of GCM estimates for increased August temperatures in the tropics under $2\times\text{CO}_2$, Emanuel estimates that the destructive potential of hurricanes could rise by 40% - 50%. Houghton (1994) expects an increase in both the frequency and severity of tropical and other storms. Haarsma *et al.* (1993) report a 50% increase in the number of tropical disturbances under $2\times\text{CO}_2$. The maximum windspeed would increase by 20%. The Australian CSIRO 9 GCM also points at an increased cyclone activity, and shows that a

threefold increase is not impossible (Ryan *et al.*, 1992). Other results, on the other hand, give a less clear cut picture (see e.g. Broccoli and Manabe, 1990; Maunder, 1994; Raper, 1993). Idso *et al.* (1990), for example, argue that tropical sea surface temperatures would increase very little with global warming while the tropical tropopause could become more stable, leading to less intense cyclones. IPCC (1990a) judges that the impact of global warming on storm intensity is "ambiguous".

The existing economic estimates tend to include increased hurricane damage as part of the damage to be expected from global warming (see Tables 6.4 to 6.6). Thus, Cline (1992a) reviews past hurricane damage for the United States, and applies the 50% increase implied by Emanuel to estimate that benchmark warming would impose average annual damages of \$750 million. Considering that the IPCC did not indicate any likelihood that tropical cyclones might decrease, the expected direction is an increase. Because the most recent hurricanes have imposed even larger damages than most of those surveyed below, a lower implicit probability to account for uncertainty, applied to a higher damage base, could still yield central damage estimates comparable to those reported here.

In an average year about 70 to 80 tropical cyclones are recorded worldwide, causing damages of about \$ 1.5 billion, with a death toll of 15,000 to 23,000 lives (Smith, 1992; Bryant, 1991). The occurrence of cyclones is distributed unevenly over the globe. Northern regions like the former Soviet Union and Europe, for example, are only marginally affected. Based on the natural hazard map of Berz (1990), Fankhauser (1994a) has estimated that the United States is affected by 7% of all cyclones, while another 7% occur in China and 29% in OECD nations (Australia, Japan, New Zealand and the US). Combining this distributional pattern with the Smith/Bryant figures and the Emanuel estimate, Fankhauser (1994a) arrives at an additional 8,000 cyclone casualties, practically all in developing countries. Using the same value-of-life estimates as for health damages and adding in \$630 million additional property damages total worldwide hurricane damage amounts to about \$2.7 billion.

These average figures are overshadowed, however, by the disastrous consequences of individual events, with poorer countries, especially small islands, being particularly vulnerable (see Box 6.3). In 1970 a cyclone caused more than 500,000 deaths in what is now Bangladesh. In 1985 a similar disaster in the same region killed another 100,000 people (Bryant, 1991). The \$2.7 billion figure may therefore underestimate the true costs.

Extra-Tropical Storms: Dlugolecki *et al.* (1994, see also Munich Re, 1993) report worldwide losses due to major windstorm events to have averaged \$2.0, \$2.9, and \$3.4 billion (1990 prices) for the decades of the 1960s, 1970s, and 1980s, respectively. For 1990-1992 this figure has risen to \$20.2 billion. The larger part of these damages is due to tropical cyclones, however. The 1990 storms in Europe (Daria, Herta, Vivian and Wiebke) resulted in a total loss of DM 25.3 billion (Munich Re, 1993). However, while storm damages have clearly increased over the last decades, it is not clear how much of this rise is attributable to global warming. The results of Changnon and Changnon (1992) and CATMAP (Clark, 1988; 1991) indicate that most of it is probably due to increasing socio-economic vulnerability.

River Floods: Little information is currently available regarding the socio-economic impact of changes in the frequency and intensity of river floods (see Arnell and Dubourg, 1994).

Droughts: The impact of drought on agriculture has already been treated in Section 6.2.1. As an alternative way to estimate agricultural damage, Cline (1992a) reports an annual loss imposed on US agriculture by increased drought of \$18 billion/year. Water supply in general is dealt with in Section 6.2.4. The effect of decreased water run-off is partly dealt with in the section on water pollution (6.2.10). A further impact of drought is land subsidence. The 1975-1976 drought in England and Wales, for example, led to a cost of £100 million to the insurance industry (Doomkamp, 1993). By 1979 the costs had amounted to £220 million.

Hot and cold spells: The impacts of hot and cold weather spells on human amenity and health were treated in the respective sections above.

Total Losses: Table 6.3 (after Limbert, 1993) provides total fatalities attributed to weather events between 1989-1992 as reported for the six WMO regions. The average number of lives lost to natural hazards is more than 4,000 per year, with the highest proportion occurring in Asia. This is likely to be an underestimate, because some major events are not included. It is unclear which fraction of casualties has to be attributed to global warming, however.

[Table 6.3]

6.2.15 Damage Estimates: Summary

Tables 6.4 to 6.6 summarize the principal existing estimates of global warming damage for major regions of the world. In the United States, losses from benchmark $2\times\text{CO}_2$ equivalent warming reach over 1% of GDP in the Cline, Fankhauser and Tol compilations, and some 2.5% of GDP in the central Titus estimates. Titus specifies a lower and upper end of his range of estimates, at 0.8% and 5.4% of GDP, respectively. It should also be noted that the Titus estimates are based on GCMs with average warming parameters of about 4°C , higher than the IPCC's best guess of 2.5°C . Estimates for other OECD countries are mostly within the same order of magnitude of 1-2% of GDP (see Table 6.6).

Less comprehensive estimates by Nordhaus (1991), again for the US, arrive at a direct calculation of only 0.26% of GDP, primarily from sea level rise; but Nordhaus also sets 1% of GDP as a reasonable central estimate. The CRU/ERL (1992) estimates for the European Union, on the other hand, are significantly higher, with costs in the order of 1.6% of national income *per degree of warming*. The principal reason for this is a very high assessment of sea level rise damages. By augmenting sea level rise costs by a factor 2.7 to account for storm surges, the study may overestimate damages. On the other hand, their assessment of non-sea level rise impacts appears to understate true damages, with an overall beneficial outcome in these categories.

[Table 6.4]

[Table 6.5]

With the possible exception of the Titus calculations and, for some categories, the CRU/ERL estimate, these damage figures seem likely to understate the true impacts, for two reasons. First, several effects are not fully quantified (e.g. non-tropical storms, droughts, morbidity, transport). These are probably predominantly harmful, with the possible exception of climate

amenity values for some regions. Second, the figures are far from exact and one should allow for a considerable range of error. Many are deliberately kept conservative. Species loss valuation in particular could be far higher. It should also be emphasized that the estimates in Tables 6.4 to 6.6 refer to central warming expectations. The corresponding damages for upper-bound warming would be higher, and more than linearly so. Finally, when moving from the question of damage estimation to that of abatement benefits, a number of non-climate change related benefits need to be taken into account (see Section 6.7).

Regional differences can be substantial, as is exemplified by the estimates for developing regions and the former USSR (see also Section 6.5). For the former Soviet Union damage could be as low as 0.7% of GNP or even negative (ie climate change is beneficial). The negative figure by Tol (1994b) mainly stems from large beneficial impacts in the agricultural sector. In the Fankhauser study, on the other hand, possible beneficial yield impacts are more than offset by the adverse impact of increased world prices on food imports. The region will also suffer from particularly high health and air pollution costs. The extremely high estimate for the Asian regions and Africa, on the other hand, are predominantly due to the severe life/morbidity impacts. As explained above, both the quantitative assessment and the underlying value-of-life estimates are very volatile, and the probability range of total damage is particularly wide for these regions.

Damage is likely to be more severe in developing countries, compared to developed countries as is shown in Table 6.6, and discussed in Box 6.3. Table 6.6 reports damages in non-OECD countries of about 1.6-2.7% of GDP, some 50% higher than the OECD average. The main causes for this high estimate are health impacts and the high portion of natural habitats and wetlands found in developing countries. Although the data for the non-OECD estimates are significantly weaker, they provide a clear indication that global warming will have its worst impacts in the developing world, with a damage of probably at least 2% of GNP for $2\times\text{CO}_2$.

[Table 6.6]

In general, the estimates in Tables 6.4 to 6.6 show a relatively narrow band for central damage calculations for the United States, and for developed countries in general. It is important to recognize, however, that this field of estimates is probably biased toward convergence. The reason is that, with the exception of CRU/ERL (1992), the underlying sources of many of the estimates are the same, particularly US EPA (1989). The convergence tends to become extrapolated to other regions, too, considering that several of the international estimates in Fankhauser (1994a) and Tol (1994b) are obtained by extrapolation of the US estimates. The similarity of the estimates should therefore not necessarily be interpreted as evidence of their robustness. There remains a substantial degree of uncertainty in the estimates. Nevertheless the relative ranking of regions appears to be reasonably robust, with the most severe impacts to be expected in Asia and Africa, and northern and developed regions suffering less.

The worldwide estimates of Table 6.6 are expressed as the total sum of regional damages relative to the global sum of GDP. As discussed in Box 6.2, it can be argued on equity grounds that there should be greater weights placed on impacts for low-income countries than would result from simply applying their shares in the global income base. As shown in the box, under one commonly used utility function (logarithmic), equity weighting would tend

to raise the global aggregate damage measure. This would especially be the case for the Tol estimates, where damages are particularly high in developing countries.

[Box 6.2]

[Box 6.3]

It is useful to consider the results of an opinion survey of 19 global warming experts from both physical sciences and economics (Nordhaus, 1994a, see Table 6.7). For a 3°C actual warming by 2090, estimated global damages ranged from zero to 21% of gross world product, with a mean value of 3.6%. For a more rapid and severe warming (scenario B) the mean increases to 10.4% of GDP. Diverging from the estimates of Table 6.4, virtually all of the respondents judged that more than half of the damages would occur in the market sectors (such as agriculture), rather than in sectors outside the standard system of national accounts (biodiversity, amenity)³. The three natural scientists included in the survey gave the highest damage estimates, whereas the lowest estimates were from eight economists who had not done research on global warming. One implication of the survey is that the perceived scope of global warming damage tends to be considerably higher among natural scientists than among most economists. Natural scientists also attach a higher probability to the possibility of a calamitous outcome. This pattern suggests another reason why the estimates reported above may be under- rather than over-statements.

[Table 6.7]

6.3 Damage Estimates for Longer Term Warming

Most analyses of global warming focus on the doubling of atmospheric concentrations of carbon equivalent of all greenhouse gases above preindustrial levels. IPCC (1990a) indicates that concentrations could reach this benchmark as early as 2025 under business as usual policies. Yet there is no reason to believe that greenhouse gas emissions and atmospheric build up would stop at that point.

Sundquist (1990) has estimated that there are sufficient fossil fuel reserves to permit emissions of carbon dioxide to rise such that its atmospheric concentration might reach 1600 ppm by the year 2200, before the exhaustion of reserves would reduce emissions and allow concentrations to plateau through 2300 and then moderate back to about 1200 ppm over a 400 year period as the consequence of deep-ocean mixing. With pre-industrial concentrations of 280 ppm, this scenario amounts to a potential rise of nearly six-fold in carbon concentrations alone. Cline (1992a) uses a 300 years time horizon to investigate the very-long-term impacts of global warming. On the basis of fossil fuel (primarily coal) reserves estimated by Edmonds and Reilly (1985), he concludes that as much as 14,000 GtC in carbon could be available for use at reasonable economic cost. He applies three leading energy-carbon models (Reilly *et al.*, 1987; Nordhaus and Yohe, 1983; Manne and Richels, 1992) to project carbon emissions through the year 2100, and extrapolates their rates late in the 21st century through 2275. Average emissions rise from 7 GtC today to 20 GtC by 2100 and 56

GtC by 2275.

Under the assumption that atmospheric retention remains at its recent 50% level, Cline estimates carbon concentrations on the order of 2,200 ppm by 2275, or about eight times pre-industrial levels. The corresponding increase in radiative forcing would reach about 13 Wm⁻², from carbon alone, or some 19 Wm⁻² from all greenhouse gases. With the central IPCC climate sensitivity parameter (Λ) of 2.5°C for 4 Wm⁻², the resulting mean warming would be almost 12°C. On this basis, Cline (1992a) sets 10°C (the lowest range from the three emissions models) as a tentative benchmark for ultimate warming over a 300 year period. This would take the earth back to the climate of the mid-Cretaceous period 100 million years ago, when mean temperatures were an estimated 6°C to 12°C higher than today (Hoffert and Covey, 1992). If instead the upper-bound climate sensitivity parameter is applied (Λ = 4.5°C), very-long-term warming could reach approximately 18°C.

Recent simulations of the GFDL (Geophysical Fluid Dynamics Laboratory) general circulation model at Princeton University tend to confirm this range of 10-18°C for baseline warming. Manabe and Stouffer (1993) examine the effects of a quadrupling of pre-industrial carbon dioxide equivalent by 140 years from now. They note that this level amounts to a 1% annual increase in CO₂-equivalent concentration, consistent with the IPCC "business-as-usual" scenario. The equilibrium mean surface air temperature increase reaches 7°C, while the actual transient warming is 5°C. Manabe and Stouffer do not argue that atmospheric concentrations will in fact stop rising after 140 years. Instead, their interest is in examining the consequences of this specified century-scale scenario. They find that sea-level rise from thermal expansion alone reaches 1.8 meters by the 500th year, and would presumably be much greater if the effect of melting of ice-sheets were taken into account.

After first conducting an economic analysis of global warming using comparative static techniques with carbon doubling as the benchmark (Nordhaus, 1991), Nordhaus (1993a, b) has also adopted a centuries-scale horizon for his dynamic model DICE. However, Nordhaus' baseline involves warming of only 5.5°C by 2275, because of lower emissions (31 GtC by 2275) and lower atmospheric retention. Lower emissions stem from lower growth expectations, as Nordhaus' model assumes progressive slow-down in technological change that has the effect of limiting growth. Global product by the year 2275 is a multiple of only 7 times today's output in the DICE baseline, but 26 times in Cline (1992b), suggesting that diverging economic assumptions may be even more important than different assumptions about the scientific parameters for such long-term analysis.

If 10°C is used as a guideline to potential warming over a 300 year horizon (or much sooner if the upper end of the climate sensitivity parameter range proves valid), the corresponding economic damages could be very large. The central reason is that in many categories, damage is likely to rise non-linearly with warming. As one example, water run-off is a residual between precipitation, which rises linearly with global warming (and primarily in the higher latitudes), and evapotranspiration, which rises non-linearly (see e.g. Rind *et al.*, 1990). Similarly, Yohe (1993) finds that at intermediate sea level rise, a doubling of the rise causes damages to rise about 2-1/2 fold; and above 60 cm, a doubling of the rise causes a tripling of damage.

It seems likely that the damages of high, very-long-term warming would be especially

³ Nordhaus (1994a) includes human health in the non-market sectors.

pronounced in the non-market sectors. Human amenity could face major losses, even after accounting for adaptation. For example, Cline (1992a) estimates that with 10°C global mean warming, among 66 major US cities the number with average daily temperatures in July exceeding 90°F would rise from 18 presently to 62.

Attempts to quantify long-term damage are rare and highly speculative in nature. Most often, long term damage estimates are simple extrapolations of the 2xCO₂ equilibrium case, using different assumptions about the degree of non-linearity in the damage temperature relationship. Cline (1992a) uses a relatively modest degree of non-linearity for most effects, with an overall damage function exponent of 1.3. Nordhaus (1993a, b) applies a quadratic damage function in his main scenario, while Peck and Teisberg (1992) consider several specifications, including quadratic and cubic functions. Table 6.8 reports the central estimates in Cline (1992a) for US damage from 10°C warming. Against present economic scale, they amount to \$335 billion annually, or 6% of GDP. However, the figure is only illustrative. Assuming a quadratic temperature-damage relationship, US damage from 10°C warming would amount to over 17% of GDP. If more allowance is made for such categories as species loss the central range could rise to 2% of GDP for 2xCO₂ at 2.5°C and 12% of GDP at 10°C. With upper-bound warming, the very-long-term damage reaches 20% of GDP. In the long term scenario in the Nordhaus (1994a) poll of experts, respondents predicted a mean damage of 6.7% of GDP for 6°C warming by 2175. Answers ranged from negligible damages to 35% of GDP (see Table 6.7).

[Table 6.8]

In addition, warming on this scale could trigger some of the catastrophic results sometimes mentioned. Thus, Manabe and Stouffer (1993) find that the 7°C warming scenario is sufficient to cause the shutdown of the ocean conveyor belt (thermohaline circulation) that causes the present Gulf Stream. Similarly, although disintegration of the West Antarctic ice sheet is not considered likely under 2xCO₂ (IPCC, 1990a), it could be much more likely under 10°C. If this disintegration occurred, it would raise sea levels by 5 to 6 metres (Revelle, 1983), causing large land losses along coastlines and inundating many low lying islands (Schneider and Chen, 1980). Another catastrophe scenario is one of large and "sudden" temperature change. Thus, Dansgaard *et al.* (1989) indicate that Greenland ice cores show a rise of temperature by some 7°C in as short a period as 50 years some 12,000 years ago (Younger Dryas period). Climate catastrophes and surprises are further treated in the following section.

6.4 Climate Catastrophes and Surprises

The discussion so far has focused on the impact of the best-guess climate change and some reasonable upper and lower bounds in the next century (Section 6.2) and on the longer term (Section 6.3). This section makes some statements on the impact if all climatic dices roll the wrong way, i.e., if the enhanced greenhouse effect leads to rather unlikely but possible changes. Where some information on the physical mechanisms is available these changes are referred to here as climate catastrophes, and surprises otherwise. Most attention will be paid to the catastrophes as surprises are by definition unknown. Collard (1988) distinguishes between weakly and strongly catastrophic risks. The former category refers to the case in

which the product of the likelihood of an event multiplied by its consequences tends to zero as events become more and more disastrous, i.e. the probability of the event declines more rapidly than its impact grows. A strongly catastrophic risk describes the converse situation, where the severity of an event rises more rapidly than the probability of its occurrence declines. Which category best applies to climate change risks is unclear (Tol, 1994b).

Three main types of climate catastrophes are identified in the literature, all associated with strongly non-linear responses to changed forcing: (i) the runaway greenhouse effect, (ii) disintegration of the West-Antarctic Ice Sheet, and (iii) structural changes in ocean currents. These three categories have a small but unknown possibility to occur.

The runaway greenhouse effect refers to the scenario in which one or more of the positive feedbacks dominate the negative ones such that the climate changes much more and much faster than the common consensus indicates. The main causes are a rapid increase in the natural emissions of greenhouse gases, e.g., through methane and carbon dioxide releases from melting permafrost or methane clathrates, a shutdown of major greenhouse gas sinks, e.g., through reduced plankton activity or the reduction of growth or die-back of forests, and changes in atmospheric chemistry. The runaway greenhouse effect does not only bring much larger and faster climate change, it also considerably enlarges the possibility of other catastrophes and surprises. The disintegration of the West-Antarctic Ice Sheet refers to a rapid melting of this ice-sheet, which could be unstable, leading to an additional sea level rise of about 5 metres within the next century. Changes in ocean currents have more regional impacts. The Gulf Stream transports energy from the tropics to Western Europe thereby being responsible for its moderate climate. This 'conveyor belt' is driven by temperature contrasts and salinity near Iceland. Reconstructions of past climates and model experiments reveal that the energy transport can be weakened, start to fluctuate or even stop completely, possibly as a result of global warming. This would lead to a sharp drop in European mean temperatures. Another important ocean current is the Humboldt Stream (IPCC, 1995).

Rapid climate change brings forward the impact of long-term warming (see section 6.3), leaving less time to adapt and thereby increasing the impact enormously. Table 6.8 illustrated the impacts of a 10°C increase in the global mean temperature (4 times the temperature rise associated with 2xCO₂), and suggested that this might lead to about a sixfold increase in the costs compared to a 2.5°C rise. This figure cannot readily be applied to a 10°C temperature rise at the shorter term, though, since the estimates assume a moderate level of adaptation. Adaptation will be much less successful in the case of rapid climate change. Section 6.1.6 states the power of adaptation, preventing the larger part of the losses due to sea level rise in the OECD, and mitigating agricultural losses at a moderate cost. This adaptation cost is likely to be much higher for fast or sudden changes, and some measures might be impossible to implement. The long-term figure stated above thus at best represents the lower bound of the actual costs of a catastrophe.

Unfortunately, few attempts exist to quantify catastrophic impacts directly. One exception is Tol (1994b) who splits the damage costs of climate change *inter alia* into those due to the rate of change and those due to the change compared to present temperatures. The damage module of his model *FUND* yields tangible damages of 0.33%, 0.55% and 1.09% of Gross World Product for a 2.5°C warming in 2095, 2057 and 2031, respectively. However, no figures on a more rapid temperature increase are reported there. The *ICAM* model

(Dowlatabadi and Granger, 1993) also considers the pace as well as the amount of warming in the damage cost functions, but explicitly adds adaptation. A warming of 8°C at high latitudes and 2.8°C at low latitudes would lead to tangible losses of 6.0% of GDP in the industrialised countries and 6.6% of GDP in the less industrialised countries (Kandlikar, 1994). Nordhaus' (1994a) poll of experts provides the most direct information: a doubling of the warming by 2090 from 3°C to 6°C almost triples the costs of global warming. The probability of an impact catastrophe (i.e. damages greater than 25% of GNP) could also be considerable. The average probability stated in the survey varies between 4.8% and 17.5%, depending on the underlying warming scenario (see Table 6.7). Interestingly, natural scientists were again far more pessimistic in their assessment than economists (see also Section 6.2.15).

6.5 Regional Implications of Global Warming Damage

6.5.1 Regional Damage Estimates

Section 6.2 surveyed the available literature on comprehensive damage estimates of global warming. These are heavily biased toward the USA and to a lesser extent Europe, due to the concentration of work there. This section looks at case studies available for other regions. Focusing mostly on agricultural impacts and sea level rise, regional studies predict impacts ranging from slightly beneficial to truly catastrophic. It is difficult to compare studies across regions, though, due to different underlying assumptions in the GCMs used, the nature of the model runs (transient or equilibrium), the models' capabilities for simulating control conditions for the relevant country (e.g. precipitation), and differences in assumptions and scenarios. Some scenarios include assumed adaptation measures, others do not. Moreover, few studies examine interlinkages between areas, so that they are not truly integrated assessments.

6.5.2 Japan

In terms of *agriculture*, research has focused on the effects of climate change and increased CO₂ on rice production (Nishioka *et al.*, 1993). Laboratory experiments with increased CO₂ concentrations (a rather high 700 ppm), produced grain yield increases of 23-71%.

An increase in effective accumulated temperature (EAT) in most of the country (except parts of Hokkaido) would reduce the vulnerability of rice to cool summer weather in the North of Japan, perhaps stabilising production. Rice producing regions may themselves be extended. Commercial rice cultivation in Japan could shift northward by 200-500 km by the end of the next century. In the north, 2xCO₂ conditions could open up most of the land below 500m altitude for rice cultivation. Currently most cultivated areas are at elevations below 200m. In light of the altered climate predicted by the GISS model, the transplanting date of rice would be advanced by 20-30 days and the maturing period would be reduced by 25-50 days. For spring wheat and winter wheat respectively, the heading date would advance by 2-5 days and 30 days, and the maturing period would reduce by 3-5 days and 3-6 days. For *forests*, some replacement of the understorey is expected due to inability of forests to migrate in the short term.

Japan's economic activities are concentrated along the coast. Major cities like Tokyo, Osaka and Nagoya are all located in the coastal zone. Together the three cities account for more than 50% of Japan's industrial production. Already now, about 860 km² of coastal land is below mean high water level, an area supporting 2 million people and 54 trillion yen (\$450 billion) value of physical assets. For a 1 metre rise in sea level this area would expand by a factor of 2.7 to embrace 4.1 million people and assets worth 109 trillion yen (\$908 billion). The same sea level rise would expand the flood prone area from 6270 km² to 8,900 km², with an additional 3 million people at risk (Nishioka *et al.*, 1993). Coastal protection will be central to the country's response strategy. The costs of adjusting existing protection measures has been estimated at about \$80 billion. However, extensive coastal protection would put additional pressure on Japan's remaining natural shorelines (IPCC, 1992b).

6.5.3 Africa

Very little work on impact assessment in Africa has been done. Magazda (1991) predicts reduced precipitation in the rain forests of Zaire and Uganda under doubled CO₂ concentrations. Citing Cummings on general relationships between precipitation and herbivores, Magazda predicts reductions in large herbivores as Savannah productivity is reduced, affecting buffalos and elephants among others. Shallow lakes, such as Lake Abiata in Ethiopia and Lake Turkana in Kenya, and savannah wetlands are likely to be reduced, affecting resident wildlife and bird migrations.

Ominde and Juma (1991) emphasise the greater vulnerability of Africa to climate change due to the high *agricultural* dependence and the limited capacity for adaptation. For Egypt, Rosenzweig *et al.* (1993) predict aggregate yield losses in the order of 25-50% for 2xCO₂. The implications of agricultural damages on consumer welfare in Africa are expected to be negative even in the most optimistic scenarios (Reilly *et al.*, 1994).

Sea level rise is predicted to affect some 20% of Egypt's 35,000 km² of arable land. A 1 metre rise in sea level could destroy up to 25% of the Nile Delta's agricultural land and displace about 8 million people. Cotton and rice would be the main crops affected (El-Raey, 1990). Awosika *et al.* (1990) estimate that sea level rise would greatly exacerbate existing erosion at Lagos Beach in Nigeria, whilst even a modest rise will affect mangroves and wetlands which support timber and fishery industries. In the absence of protection a 1 metre rise in sea level could flood over 18,000 km² of Nigeria's land, damaging assets currently worth at least \$18 billion, including much of the country's oil industry which is mostly located near the coast. In addition, over 3 million people would have to be relocated. Protecting at least the highly developed areas would cost \$550-700 million (IPCC, 1994, 1992b). A similar case study for Senegal estimates that in the absence of protection over 6,000 km² of land would be lost under a 1 metre rise, some 3% of the total area. Two thirds of the population and 90% of the industry are located in the coastal zone. Protecting these areas would cost \$250-850 million, about three quarters of which would go toward beach nourishment (IPCC, 1994, 1992b).

6.5.4 Bangladesh

Climate change impacts in Bangladesh were analysed in detail in the context of a multi-country study on climate change in Asia (Asian Development Bank, 1994). Taking the coastal

zone of Bangladesh to be defined by districts with a maritime boundary, the zone is a delta of the combined Ganges-Jamuna-Meghna river system and accounts for some 22% of the total land area and 16% of the population (Asaduzzaman, 1994). It also accounts for 24% of agricultural value added, 40% of manufacturing fixed assets and 22% of manufacturing employment. A 45 cm rise in sea levels (SLR) along the Bay of Bengal coast would submerge some 15,700 km² of land (about 11% of the total land area), including some 75% of the Sundarban mangrove forests. Several ports would also be affected. A 1 metre rise would affect nearly 30,000 km² (about 21% of the land area) (Asaduzzaman, 1994). This is somewhat higher than earlier estimates by the Commonwealth Secretariat (1989) which predicted a loss of just under 16% of total land area for a 1 metre rise. 1 metre sea level rise would result in all the Sundarban mangrove forests disappearing. Sea level rise will result in saline intrusion further inland than the existing freshwater-saline water interface. Changes in cyclone frequency appear to be small and soil erosion effects appear to be unknown.

Impacts on *agriculture* remain difficult to predict. A study by the Bangladesh Institute of Development Studies suggests losses of rice output due to sea level rise as shown in Table 6.9.

[Table 6.9]

Asaduzzaman (1994) suggests that the overall macroeconomic impact of sea level rise would amount to some 30% of current GNP in the coastal zone, or some 5% of overall Bangladesh GNP. Damages in absolute terms would be perhaps \$4.8 billion in terms of 'lost' output in 2070.

The loss of the Sundarbans would impose a particularly severe loss on the poorest people of Bangladesh, relying as they do on the mangroves for fuelwood, timber, fish and many raw materials. Biodiversity losses are incalculable due to the extensive lack of knowledge about the ecological functioning of the Sundarbans. Many shrimp fisheries are likely to disappear, offset to some extent by the emergence of new estuarine fisheries as sea levels rise. Salinisation will also affect industries relying on freshwater intakes, including electricity generating plants, raising costs of production. Other industries would have to move and some would be irretrievably lost, e.g. those relying on shrimp processing. Road and rail links between Dhaka and Chittagong/Khulna would be disrupted by sea level rise, seriously affecting all international trade. Asaduzzaman (1994) suggests that 45 cm sea level rise would affect 195,000 jobs and some 790 km of roads; 100 cm rise would affect 735,000 jobs and 1460 km of roads.

Population displacement would be dramatic if impacts are assumed to be 'sudden'. Some 5% of people would be displaced by 45cm rise, and 13.5% for 1 metre rise, i.e. in terms of projected 2070 population 12 million and 32 million people, respectively. In practice, migration away from the likely to be affected areas is already taking place, partly for weather-related reasons.

6.5.5 India

A broad analysis of climate change impacts in India has been provided as a part of two multi-country studies on climate change in Asia, commissioned by ADB (1994) and SAARC

(1992). Some 70% of India's annual rainfall occurs in the June-September monsoon season. Chakraborty and Lal (1994) project increases in precipitation in most parts of India due to doubled CO₂ concentrations. The Central Plains and East Coast might expect pronounced increases in annual average precipitation (1 mm/day) and this may be 2 mm/day in the monsoon period in the former region. 2 mm/day is also estimated for West Bengal in the pre-monsoon season. Monsoons thus intensify for many regions and more frequent heavy rainfall events are predicted.

In *agriculture*, yields may be lowered due to the decrease in the number of growing degree days due to enhanced temperatures. Seshu and Cady (cited in SAARC, 1992) suggest a decline in rice yields of 0.7 t/ha for an increase in minimum temperature from 18°C to 19°C, a decrease of 0.4 t/ha for 22 to 23°C and 0.04 t/ha for 27 to 28°C. As for wheat, it has been estimated that each 0.5°C increase in temperature would reduce productivity in Punjab, Haryana and Uttar Pradesh by about 10%. In Central India, where productivity is lower, the decrease would be lower (SAARC, 1992). In comparison, the global study by Rosenzweig *et al.* (1993) predicts changes in aggregate agricultural yields of +3% to -33% under 2xCO₂ (including CO₂ fertilization).

Sea level rise will affect many regions, with the Andaman and Nicobar islands and the coral atolls of the Lakshadweep archipelago being among the most vulnerable areas. The east coast would be more subject to storm surges than the west coast. The western coastline south of 12° North is likely to become more eroded. No overall estimates of macroeconomic impact are available, though. In a case study of the Orissa and West Bengal region, IPCC (1992b) estimated that in the absence of protection a 1 metre sea level rise would inundate an area of 1,700 km², predominantly prime agricultural land, and displace 700,000 people. Protecting the area would require the construction of an additional 4,000 km of dikes and sea walls.

The Asian Development Bank country study for India (ADB, 1994) reports estimates by Asthana (1993) of the costs of 1 metre sea level rise for India. In the absence of protection, approximately 7 million people are estimated to be displaced, some 5,763 km² of land would be lost, and some 4,200 km of roads would also be lost. The dominant cost is land loss which accounts for 83% of all damages. While the annuitised cost is reported to be 0.18% of GNP it appears to be net of the value of land loss. Inclusive of land loss, the correct percentage appears to be 1% of GNP.

6.5.6 Indonesia

Based on calculations by the Commonwealth Scientific and Industrial Research Organisation (CSIRO), the ADB country study for Indonesia (Asian Development Bank, 1994) predicts an increase in mean annual temperature in Indonesia of 1.5°C (0.4-3.0°C) by 2070 under baseline conditions. Sea levels could rise by 45cm (15-90cm). In comparison, Parry *et al.* (1991) suggest that 2xCO₂ could raise the mean annual temperature by as much as 3°C and produce a rise in sea levels of 60 cm. Precipitation under 2xCO₂ is likely to decline in some regions, but might generally increase. Increases in rainfall could lead to a 30% increase in the irrigation area of Brantas and Citarum Basins in western Java. Soil erosion might increase by 14, 18 and 40% in the Citarum, Brantas and Saddan watersheds, with resulting soybean production losses of 2,000 to 2,700 tonnes in each region.

Enhanced temperatures and, at certain sites, reduced water availability could reduce rice yields, especially for early season rice. This could be offset to some extent by increases in late season rice. Net yields might decline by 4%. Soybean production might decline by around 10%, largely due to lower yields in the early season. Appropriate adaptive measures may lead to productivity increases which could offset potential losses, though, and overall yields may increase. The biggest yield effects are likely to be on maize output with declines of 25-65% (Parry *et al.*, 1991).

Indonesia is the world's largest archipelagic state, with nearly 17,000 islands and a shoreline of approximately 81,000 km (ADB, 1994). *Sea level rise* will affect coastal ecosystems, industrial production and agriculture alike. In the Krawang and Subang districts, 95% of the predicted reduction in local rice supply (about 300,000 tonnes) and half of the loss in maize output is due to the inundation of coastal land. As a consequence, over 81,000 farmers may lose their source of income in the Subang district alone, and about 43,000 farm labourers could lose their job (Parry *et al.*, 1991). Under the baseline assumption of a 15 - 90cm sea level rise by 2070, and assuming that the Indonesian population will stabilise between 2030 and 2045, ADB (1994) predicts that about 3.3 million people will be displaced. Some 800,000 households would have to be relocated at a cost of \$ 8 bn. In the absence of protection, a total area of 3.4 million hectares could be inundated.

Indonesia is one of the few countries for which tentative *health* impact estimates are available. ADB (1994) expects that the incidence of malaria could increase by about 20%, from 2,700 cases per 10,000 people in 1989 to 3,200 cases in 2070. The incidence of diarrhoea and dengue fever could each increase by as much as a factor 3 or 4. The resulting increase in health expenditures for all three diseases could amount to \$9 million per 10,000 people (excluding the costs of death and disrupted livelihoods).

6.5.7 Malaysia

The expected impact of $2\times\text{CO}_2$ on annual mean temperature in Malaysia ranges from 1-2°C (ADB, 1994; for carbon equivalent doubling) to 3-4°C (Parry *et al.*, 1991). Rainfall increases are likely in January-February in the coastal regions of Sarawak, and in March-May in Southwestern Peninsular Malaysia. Runs of the CERES rice model predict a 12-22% yield decline for rice in the largest rice growing region of Muda. A 10% reduction in solar radiation in the Serdang region could result in maize production losses of about 20%. Rainfall increases in March-May could increase oil palm productivity in alluvial coastal areas. Temperature and rainfall changes on the eastern coast of Malaysia could make the area too wet for rubber cultivation. Roughly, rubber yield is inversely proportional to total annual rainfall. A 10% increase in rainfall could reduce yields by 13%, a figure which could rise to 25-40% due to interference with tapping (ADB, 1994). Dry marginal rubber cultivations, for example in the northern states, may become uneconomic due to drought. National yield levels could decline by 15%, but improved varieties could more than offset this loss.

The frequency of peak discharges in the Kelantan river basin in NE Peninsular Malaysia could increase by 9% under $2\times\text{CO}_2$, implying more *flood damage* and a 5% increase in the population affected by floods. About 3 million people currently live in flood prone areas. In terms of flood occurrence, the present once-every-50-year flood would return every 30 years (ADB, 1994). Water deficits in the dry season, on the other hand, are likely to increase due

to higher evaporation, reducing water availability for irrigation.

About 70% of the total population of Malaysia live in the *coastal zone*, which is also the centre of most of the country's economic activities. In addition, important natural ecosystems are located along the coast, with 44 of the 1000 islands being designated as marine parks. Sea level rise could have significant consequences for the low lying coastal plains of Malaysia. Parry *et al.* (1991) report that a 1 metre rise could lead to a landward retreat of the shoreline of as much as 2.5 km. Midun and Lee (1989) suggest that such a rise could result in the near-total loss of existing mangroves with little chance of inland migration, in particular mangrove islands. Mangrove forests are already under severe stress from human interference. Sea level rise thus aggravates an already urgent environmental problem.

6.5.8 Thailand

Parry *et al.* (1991) suggest that $2\times\text{CO}_2$ could result in a 3-6°C mean annual temperature change in Thailand, probably a rather high estimate. GCM predictions for rainfall diverge, but generally show a reduction under the GISS scenario. Northern Thailand will tend to be drier in most months except July. For Ayuthaya Province, the GISS model predicts rainfall reductions in August-September but other models do not produce this result. With respect to agriculture, preliminary runs using current climate data with the CERES agricultural model for the Ayuthaya province showed higher yields for transplanted and lower than expected yields for direct seeded rice in comparison to observed values. Under the $2\times\text{CO}_2$ climate, rice yields in this province would generally increase. The analysis suggested an 8% increase in cultivation in the province, substantially less than the currently observed year-to-year fluctuations. Off-season rice showed average yield increases of 5%. Model validation is weak, however, and the results should be treated with caution. Results for Chiang Mai, for example, suggest average yield reductions of 5%.

For the Suratthani province in Southern Thailand, a case study calculated that 37% of the area would be affected by a 1 metre *rise in sea level*, with losses of over 4200 ha of agricultural land and many shrimp ponds (Parry *et al.*, 1991).

6.5.9 Latin America

IPCC (1992b, 1994) summarises *sea level rise* case studies for several Latin American countries, including, Argentina, Uruguay and Venezuela. In Argentina a 1 metre sea level rise would inundate an area of about 3,400 km² (0.1% of total area). Erosion would claim assets and land worth \$5 billion. Venezuela could lose about 5,700 km² or 0.6% of its area under a 1 metre rise (assuming no protection). Particularly at risk would be the country's low lying coastal plains and deltas. While only a small area would be at risk in Uruguay, the coastlines affected would be highly valuable tourist beaches. Uruguay's tourist industry creates over \$200 million in revenue per annum, and attracts over 1 million visitors each summer. Protecting the beaches would be expensive. The capital costs of developed areas protection (mainly beach nourishment) were estimated at \$2.9-8.6 billion, more than five times the costs expected for Venezuela. If spread over 50 years, this would correspond to annual investments of 6-19% compared to 1987 gross investments (Nicholls *et al.*, 1992).

The impacts of climate change on *agriculture* are less well studied. Using climate analogues Magalhães and Glantz (1992) illustrate the consequences of climate extremes on Brazilian agriculture and society. In the semi-arid Northeast of Brazil, agriculture is characteristically vulnerable to droughts. Drops in agricultural production cause mass unemployment in the agricultural sector, followed by malnutrition and hunger. Increased migration to urban centres is one of the consequences. In the global agricultural model of Rosenzweig *et al.* (1993), yield impacts in Brazil are among the most severe of all regions. Under $2\times\text{CO}_2$ yields are expected to fall by 17-33% with CO_2 fertilization, and 38-53% without. Similar reductions are also reported for Uruguay.

6.5.10 The Small Island States

The small island states (SISs) are self-evidently vulnerable to *sea level rise*. Table 6.10 summarises the results of computing a vulnerability index for different categories of countries. Vulnerability is defined in terms of exposure to foreign economic conditions (export dependence); insularity and remoteness; and proneness to natural disasters. In the full list for 113 countries, 9 out of the 10 most vulnerable countries are island states (Briguglio, 1993).

[Table 6.10]

Pernetta (1989) suggests a ranking of SISs in the Pacific in terms of their extreme vulnerability to sea level rise. 'Profound impacts', including non-existence in the worst cases, could be felt by Tokelau, Marshall islands, Tuvalu, Line Islands and Kiribati; severe impacts resulting in major population displacement would be experienced by Micronesia, Palau, Nauru, French Polynesia, Cook Islands, Niue and Tonga; moderate to severe impacts would be felt by Fiji, American Samoa, New Caledonia, Northern Marianas and the Solomon Islands; and local severe to catastrophic events would be experienced by Vanuatu, Wallis and Futuna, Papua New Guinea, Guam and Western Samoa.

Pernetta (1992) outlines various impacts that SISs may suffer. These include increased frequency of tropical cyclones in areas not normally affected by them; increases in altitudinal vegetation zones, affecting alpine grasslands in Papua New Guinea and threatening mid-montane rain forests as they come under pressure for cultivation; some increased capillarity in limestone soils, reducing soil fertility in some areas; some increases in disease due to drier conditions in some countries and longer wet seasons in others; increases in humidity and hence human discomfort and adaptation costs. Sea level rise will also affect *agriculture* since most agriculture occurs on the coasts. Agriculture will be pushed inland on to less suitable soils, increasing erosion. Exclusive economic zones based on outlying islands will be affected as some of the islands are submerged. Protection measures are limited and expensive. For the Marshall Island, for example, IPCC (1992b) reports that protecting the Majuro atoll alone would cost 1.5 to 3 times the present GDP.

Since many hermatypic corals are growing at their limit of thermal tolerance, any rise in sea water temperature could result in increased coral bleaching, with consequent loss of coral fishery resources and tourism. Although the reactions of corals to such changes appear not to be known in any detail, consequences could be significant. In the Maldives, for example, dependence on the corals is high: they are mined for building materials while fish and marine

products account for most of the island's exports. *Tourism* based on the corals is also vital. Coral deaths have already occurred probably due to increased lagoon temperatures, but pollution is also implicated.

6.5.11 Conclusions on Regional Impacts

Economic analyses of damage to developing countries from climatic change remain limited. Nonetheless, the preceding overview supports the general finding of the broader economic studies by showing that impacts on developing countries are likely to be more severe relative to the wealth of those countries. In some cases, sea level rise alone results in dramatic impacts on the economies. Summarising studies for Bangladesh, Brazil, China, Egypt, Malaysia, Nigeria and Senegal, for example, Nicholls *et al.* (1990) suggest that 1 metre sea level rise could displace nearly 100 million people in those countries alone (with China accounting for 75% of these). This is relevant to any discussion of the equity case for controlling climate change.

6.6 From Greenhouse Damages to Abatement Benefits

There is a distinction between *global warming damage* and the *benefits of policy measures*, although the two concepts are related. In general, the *benefits of greenhouse action are at least equal to the amount of damage avoided*, that is to the extra damage which would have occurred in the absence of action. In addition, there may also be ancillary benefits which are not related to climate change (see Section 6.7). The above principal rule is complicated somewhat by the dynamic character of global warming, however.

Figure 6.1 considers schematically the development of greenhouse gas emissions and damage over time under different scenarios. Under business-as-usual, emission levels are assumed to continue rising over the next 100 years or so (curve labelled "baseline" in the emissions chart). Global mean temperature levels will therefore rise as well, and so, too, will the level of global warming damage (including the influence of adaptation, see Section 6.1.7). The upper curve in the damage chart shows how annual damages may rise in the baseline. The estimates of benchmark warming damage of Section 6.2 relate to only one particular point on this time path: the point $t_{2\times\text{CO}_2}$, when the warming assumptions underlying the estimates are realized. In a business-as-usual scenario, this may for example be in the year 2060. If damage levels grow in proportion to GNP and assuming the earlier assessment is correct, damage at time $t_{2\times\text{CO}_2}$ will be in the order of 1 - 2 % of Gross World Product (GWP) (abstracting from possible differences between transient and equilibrium damage). Before this date, annual damage levels (relative to GNP) are lower. In subsequent decades they are higher, due to the rising atmospheric concentration.

[Figure 6.2]

The $2\times\text{CO}_2$ benchmark is contrasted with the consequences of a particular greenhouse gas abatement strategy, say a stabilisation of emissions at time t_0 (represented by the lower emission and damage curves). Due to the thermal inertia of the climate system, annual damage levels will react only gradually to this policy change, and will initially continue to grow unabated. Eventually, however, damage will start to deviate from the baseline. To

which level the trajectory will converge in the long run is unclear, and depends on the exact character and source of the damages.

What, then, are the benefits of the stabilisation policy? They are represented by the shaded area in Figure 6.1, which depicts the difference in annual damage levels between business as usual and the control scenario, summed up over the relevant time horizon. In each future time period damage is lower than it would have been otherwise, and the benefit of greenhouse gas abatement is the (discounted) sum of these avoided future damages.

As Figure 6.1 makes clear, there is thus no direct connection between *damage associated with $2xCO_2$* and the *benefits of greenhouse gas abatement*. The benefits of abatement occur as a *stream* of reduced damage over time, while $2xCO_2$ concerns only one point. Annual damage reduction levels will generally not coincide with the $2xCO_2$ assessment either, for two reasons: firstly, because even the most stringent abatement scheme is unlikely to succeed in avoiding all damage - some damages have already been done, i.e. they are irreversible; secondly, because damage reductions will chiefly concern years in which the business as usual damage would not be that of $2xCO_2$.

Despite this difference, $2xCO_2$ assessments still provide some indication of the size of abatement benefits. For a more precise assessment much more information would be necessary, though. A careful analysis would in particular require a better knowledge about the *slope* of the damage trajectory, that is about how global warming damage alters over time, as a consequence of both climate change and economic and population growth. A further need would be information about the degree of damage which can be avoided through a particular policy measure, that is the distance between the two damage trajectories of Figure 6.1. The answer here depends chiefly on the exact character of impacts - whether they are reversible or not, whether damage depends on the rate of change or on absolute temperature levels, whether damage is persistent or a transitional adjustment cost, and so on.

Knowledge about damage beyond the $2xCO_2$ benchmark is very limited. The small literature aiming at estimating the benefits of greenhouse gas abatement relies on several rather *ad hoc* assumptions. In older studies damage costs were typically specified as a polynomial (usually linear to cubic) function of global mean temperature, calibrated around the $2xCO_2$ estimates. Damage is usually fully reversible and typically assumed to grow with GNP. More recently, studies have started to emerge which explicitly incorporate regionally diversified temperatures and sea levels, model individual damage categories (e.g. agriculture) separately, or at least distinguish between damages related to absolute temperature level and those related to the rate of change (e.g. Morgan and Dowlatabadi, 1993; Hope *et al.*, 1993; Tol, 1994a, b).

Table 6.11 provides a list of estimates of the marginal benefits of CO_2 abatement. In terms of Figure 6.1 these numbers represent the shaded area that would occur if emissions were to deviate marginally from the baseline path, say by one tonne in period t_0 , but remain unaltered otherwise. The estimates are mostly based on models with simple polynomial damage functions. Several of them are derived from optimal control, or dynamic cost-benefit models. In these models, the marginal benefit from abatement, or the 'shadow price of carbon', is calculated as the carbon tax necessary to keep emissions on the trajectory which is considered socially optimal by the model. In other models the marginal benefits are calculated directly, as in Figure 6.1, by comparing the present value of the stream of

damages associated with a certain emissions scenario to that of an alternative scenario with marginally different emissions in the base period. Estimates vary widely, mainly as a consequence of different assumptions about the discount rate. They rise over time as a consequence of economic growth and increasing concentration levels.

[Table 6.11]

Using the base case in DICE, Nordhaus (1993a, b) finds that the shadow price begins at only about \$5 per tonne of carbon in 1995, rises to about \$10 by 2025, and reaches \$21 by 2095 (at 1990 prices). Peck and Teisberg (1992, 1993a, b) find only moderately higher values. These low shadow prices reflect the small amount of abatement that is found to be optimal in these two models. In contrast, Cline (1992b, 1993d) finds that with the sum of pure time preference and the elasticity of marginal utility (absolute value) set to 1.5%, the DICE model generates a path of shadow prices beginning at \$45 per ton, reaching \$84 by 2025, \$133 by 2055, and \$243 by 2105. Other parameter specifications provide even higher values.

In comparison, Fankhauser (1994a, b) identifies a lower and flatter trajectory for the shadow price of carbon, rising from \$20 per tonne 1991-2000 to \$28 per tonne by 2021-2030. An important source of the difference is that Fankhauser uses a probabilistic approach to the range of discount rates, in which low and high discount rates are given different weights. Conceptually Fankhauser's method also differs because it seeks to identify the shadow price on a basis of discounted greenhouse damages under probability-weighted scenarios of public action and inaction.

6.7 The Secondary Benefits of Abatement Strategies

The benefits of greenhouse gas abatement will not be limited to reduced climate change costs alone, but are likely to spill over to other sectors. This is a further reason why greenhouse damage is different to the benefits of greenhouse gas abatement (see Section 6.6). For example, if abatement is brought about by an environmental tax (e.g. a carbon tax), the resulting revenues can be used to lower other, distortionary taxes, such as those on labour. This will lower the welfare costs of governmental revenue raising - the so called *double dividend* of carbon abatement (see Chapter 8 of this report). Efforts to halt deforestation in order to reduce the emission of CO_2 will contribute to the conservation of the world's biological diversity. Other ancillary benefits could occur in the form of local and regional air quality improvements, a reduction in traffic related externalities like accidents or congestion, and the reduced risk of tanker accidents and oil spills. These problems are tied to global warming in that they are caused by largely the same activities, in particular the consumption of fossil fuels. Because no economical CO_2 -removal technologies currently exist, attempts to limit CO_2 emissions will by and large concentrate on reducing the use of fossil fuels. A reduction in CO_2 emissions will therefore also reduce other environmental problems related to fuel combustion. These effects are often called the *secondary benefits* of carbon abatement.

Secondary benefits from air quality improvements may be quite large. Table 6.12 provides estimates of benefits from reduced air pollution levels as a consequence of carbon abatement (see also Box 6.4). The estimates are not necessarily comparable since the assumed

abatement policies differ from study to study, although they all roughly aim at stabilising CO₂ emissions at about 1990 levels.

[Table 6.12]

[Box 6.4]

What is the value of these emission reductions? Estimates which measure the social costs of each pollutant vary widely between regions, depending on local factors like baseline air quality standards, ecosystem vulnerability, population at risk etc. Figures may also differ because impacts caused by a combination of gases are attributed to the initial sources in different ways. A selection of illustrative results is given in Table 6.13. The average secondary benefits implied by these estimates vary widely, from about \$2 per tonne of carbon abated to over 500 \$/tC. In absolute terms secondary benefits offset about 30-50% of the initial abatement costs in the case of Norway (Alfsen *et al.*, 1992) and over 100% in the UK (Barker, 1993).

[Table 6.13]

The figures in Table 6.12 relate to Europe or the United States. Amano (1994), has extended the Alfsen *et al.* (1992) study to several Asian regions, using the same benefit-abatement ratios (air quality benefits, in percent of GDP, per percentage cut in air pollution). The Amano calculations imply that secondary benefits could be similarly important in Asian countries. However, since the study uses the Norwegian ratios results should be interpreted with caution. For Japan and India estimated secondary benefits exceed the primary costs of stabilising emissions at 1990 levels. For China and the group of "Dynamic Asian Economies" (Hong Kong, Philippines, Singapore, South Korea, Taiwan and Thailand) secondary benefits are estimated to offset about one third of the initial abatement costs.

An alternative way to measure secondary benefits is by estimating the change in the costs of meeting air quality standards. Many industrialized countries are committed to significant cuts in the emission of air pollutants. The Helsinki protocol of 1985 required a cut in sulphur emissions of 30% by 1993, compared to 1980 levels, for selected European countries. Under the 'Second Sulphur Protocol' further reductions will be required up to 2010. The Sofia Protocol on nitrogen dioxide commits signatories to a freeze on emissions at 1987 levels. Greenhouse gas abatement will lower the amount of traditional air pollution abatement needed to meet these targets. Alfsen *et al.* (1993), for example, calculate that the introduction of a carbon/energy tax would reduce the cost of traditional SO₂ and NO_x abatement in the nine countries introducing the tax by 25 - 30% and 12 - 25 %, respectively, implying average secondary benefits of about 2.5 \$/tC for NO_x and 4.0 \$/tC for SO₂. These results are low compared to the previous estimation procedure.

It is important to underline the different character of secondary benefits compared to their primary (warming damage avoidance) counterpart. Most critically, secondary benefits do not depend on climate variables but only arise in connection with greenhouse gas abatement. They occur locally or regionally and do not share the global character of greenhouse damages. The question of secondary benefits from carbon abatement should also be distinguished from the more comprehensive issue of the optimal abatement mix with respect to all pollutants. The secondary benefit argument is characterized by an implicit primacy of

the greenhouse problem, in that improvements in other areas are seen as welcome side effects of a global warming policy, but are not considered or sought in their own right. This is not necessarily the ideal way to proceed. Strictly, each pollutant should be taxed in proportion to the environmental damage it causes. If there are interdependencies between them, as is the case with global warming and air pollution, these would have to be reflected in the relative tax rates. The currently considered abatement strategies may then no longer constitute the optimal approaches. Once secondary benefits are taken into account, location will also matter. Unlike for greenhouse gases, for most other air pollutants it matters where they are emitted. Emission reduction measures should therefore be concentrated to those places where the joint benefits of reducing all emissions is highest.

6.8 Comparing Benefits and Costs of Response Strategies

[this section may move to another chapter]

6.8.1 Social Efficiency of Abatement

Economic models comparing the costs and benefits of greenhouse gas abatement are discussed in Chapter 9. Among the most prominent examples are Cline (1992a), Nordhaus (1993a, b), Manne *et al.* (1993), Hope *et al.* (1993), and Peck and Teisberg (1992, 1993a, b).

Cline (1992a) analyses the time profile of abatement and damage costs under a policy of limiting carbon emissions to 4 GtC annually and similarly reducing other greenhouse gas emissions. The abatement cost curve is low at first, then peaks at about 3.5% of gross world product, and thereafter declines to a plateau of about 2.5% as a consequence of widening technological alternatives. On the damage side, Cline assumes that the damage profile for the United States is also representative of international effects. This assumption may be a moderate understatement, given the results of Table 6.6. The benefits of abatement are set at only 80% of greenhouse damage, under the assumption that a significant portion of warming cannot be avoided.

The cost-benefit decision for greenhouse policy involves a tradeoff between substantial abatement costs early in the horizon, in return for avoidance of potentially large damages later in the horizon. The discounting methodology is critical in such a trade off. Cline also stresses the importance of taking high damage and low damage cases into account instead of just the central case. On grounds that policy makers should be risk averse, Cline weights the representative high-damage case three times as heavily as the low-damage case. Discounting at a zero rate of pure time preference (see Section 6.1.5), he finds that the overall benefit-cost ratio for aggressive international action limiting carbon emissions to 4 GtC is a favourable 1.3.

Nordhaus (1993a, b - the DICE model) and, to a lesser extent, Peck and Teisberg (1992 - the CETA model), reach essentially the opposite conclusion: that only relatively small cutbacks of some 10% - 15% from the baseline of carbon emissions are economically optimal. Because the baseline under business-as-usual reaches many times today's emissions, this finding means that it would be optimal on economic grounds to permit emissions to rise

far beyond 1990 levels. Nordhaus (1993a, b) finds that freezing emissions at their current level would have net social costs equivalent to 0.7% of discounted future consumption. When he incorporates spillover benefits from greater tax efficiency, Nordhaus (1993a) raises the optimal cutback to some 35% from baseline, but even this result leaves the optimal emissions path above today's levels within a decade or two. In the CETA model significant emission reductions only occur for a sufficiently steep damage function.

Manne *et al.* (1993) have extended the earlier Manne and Richels (1992) carbon-economic-energy model (Global 2200) to incorporate a climate module for atmospheric concentrations and radiative forcing, and a damage module, to obtain an overall benefit-cost evaluation of greenhouse policy. Specified through the year 2200, their MERGE model has long-term properties (but does not report the extent of eventual warming expected). It adopts a relatively low damage function (0.25% of GDP for market-sector impact of 2.5°C, and a willingness to pay for avoiding non-market sector damage that peaks for rich countries at 2% of GDP but is less than 0.1% of GDP for middle- and low-income countries). The authors apply a pure rate of time preference of 3%. Under these assumptions, they conclude that a policy of freezing emissions at their 1990 levels would have a benefit/cost ratio of only about one-third; and a policy of setting a ceiling of 415 ppm on carbon concentrations, a benefit/cost ratio of only about 0.14.

Hope *et al.* (1993) obtained different results. For the aggressive abatement policy analysed in their study they obtained benefit/cost ratios close to one, and most likely above one, if non-market impacts are integrated. Once adaptive measures are taken into account these strong policy implications are reduced.

All model results are highly sensitive to the underlying parameter assumptions, in particular the rate used for pure time preference. This was shown by several authors who replicated the Nordhaus DICE model. If DICE is rerun placing the pure time preference rate at zero, for example, it generates an optimal abatement path that cuts emissions by about 50% from baseline by the year 2100 (Cline, 1992b, 1993d). Cline (1992b) therefore suggests that if other model differences are taken into account (e.g. the low long-term warming in DICE, the incorporation of risk-weighting), the Nordhaus dynamic optimization model could generate optimal abatement paths close to those suggested by Cline (1992a).

Other critical features of optimal control models include the availability of a carbon free backstop technology (Cline and Hsieh, 1993) and the treatment of non-market damages. Tol (1994a) has conducted alternative experiments with DICE by shifting intangible (non-market) sector damages from the production side of the DICE model to the utility side, on the argument that they have poor substitutability with standard production inputs. When he makes the additional assumption that valuation of unit intangibles rises proportionately with per capita income, he obtains optimal emissions cutbacks from baseline amounting to 27% in 2100 and 42% by 2300, even though he applies a pure rate of time preference of 3 percent.

An alternative to attempting a cost-benefit analysis of global warming policy is to adopt a hedging strategy that treats the problem as essentially binary - severe or mild damage - and undertakes limited action during an initial phase as a hedge until further research can confirm which case is valid. Manne and Richels (1992) explicitly apply their model in such an approach. They assume that scientific research will not demonstrate until 2020 whether the

problem is severe or mild. The model simulations show that the optimal amount of hedging (cutbacks from baseline emissions) will depend on the certainty of scientific advance, and on optimism or pessimism about future non-carbon energy technology. If we have little confidence that science will have a nearly definitive evaluation of climate change by 2020, and if we are pessimistic about non-carbon energy, then the model suggests it is best to take more action now, to spread the pain of carbon abatement more evenly over time in case it must be undertaken. If there is great confidence about future scientific clarification, and there is optimism about non-carbon energy supplies in the future, then there are large savings in adopting only modest action now and then intensifying or phasing out abatement in 2020 and after in the light of improved scientific knowledge. Even under the latter, favourable circumstances, their optimal hedging strategy involves a cutback of about 12% from baseline in carbon emissions by the year 2000.

6.8.2 Possible Implications of Benefit-Cost Models

There is a convergence of the various analyses on approaches to action in an initial decade. The Cline (1992a) aggressive action programme is a reduction of one-third; but he suggests a milder first phase, pending additional scientific confirmation, implying an initial cutback from baseline by some 10% - 15%. The Nordhaus (1993a, b) optimal cutback of 9% by 1995 is comparable. Similarly, the hedging strategy of Manne and Richels (1992) also leads to a cutback from baseline by about 12% by the year 2000. The carbon tax also tends to converge for this initial period. Thus, the figure suggested in Cline (1993d) of \$45 per tonne in the 1990s suggests that something like \$20 to \$25 per tonne would be applicable in the initial decade of more moderate contingent action. This range is consistent with the Fankhauser (1994a, b) initial marginal damage cost figure of about \$20 per tonne of carbon, and with the Monte-Carlo sensitivity results in Nordhaus (1994b), which place the optimal carbon tax at an expected (probability weighted) value of about \$12 per tonne of carbon in 1995, and at \$45 per tonne at the 95th percentile of the distribution. Considering the suggestion of Yohe (1993) that a reasonable risk aversion policy would focus on a scenario "which describes something around the 75th percentile of potential economic damage", an intermediate point between the two Nordhaus Monte-Carlo estimates would also tend to converge in the \$20-25 per tonne range for 1995. These policy prescriptions would begin to diverge more sharply beyond the first decade, assuming scientific confirmation of the seriousness of the problem. At that point it would become more essential to reach agreement on the fundamental issue of how heavily to discount effects on future generations.

6.9 Summary and Conclusions

This chapter has been concerned with the measurement of global warming damage and with the benefit of policies designed to reduce this damage.

Social cost estimates are necessarily *uncertain*. Apart from the scientific uncertainty of climate change, there are additional uncertainties associated with:

- (a) limited knowledge of regional and local impacts;
- (b) difficulties in measuring the economic value of impacts, even where the

1 impacts are known. This is particularly the case for non-market impacts and the
2 impacts in developing countries;

3 (c) difficulties in predicting future technological and socio-economic developments;

4 (d) the possibility of catastrophic events and surprises.

5 This uncertainty must be emphasised when interpreting the social cost figures in this chapter.

6 Most global warming impact studies have concentrated on the case of $2\times\text{CO}_2$, a doubling of
7 atmospheric CO_2 concentration levels. A *best guess* estimate of damage for $2\times\text{CO}_2$
8 concentrations is as follows:

9 World impact: 1.5 - 2.5% of world GNP

10 Developed country impact: 1 - 2% of GNP

11 Developing country impact: 2 - 9% of GNP

12 There is a large confidence interval around these figures. There will also be considerable
13 regional differences, with potentially higher impacts for some individual countries, e.g. small
14 island states. The regional variability of the social costs underlines the important issues of
15 equity discussed in Chapter 3.

16 These cost estimates are for $2\times\text{CO}_2$ concentrations. Global warming will not stop at this level
17 of concentrations if it is unconstrained. *Long term warming* damage may rise more than
18 linearly. The damage associated with 10°C could be 6% of world GNP or more. The
19 probability of a climate catastrophe also increases over time.

20 The *marginal damage*, i.e. the extra damage done by one extra tonne of carbon emitted now,
21 is estimated to be \$5 - 125 per tonne of carbon, with most estimates being at the lower end
22 of this range. The value will rise for marginal emissions in later periods. The range appears
23 wide but reflects variations in scenarios, models, discount rates etc. The numbers are
24 particularly sensitive to the choice of the discount rate. The models on which these estimates
25 are based remain simplistic and are limited representations of the actual processes. But they
26 represent the state of the art at this moment.

27 The marginal damage of an extra tonne of emissions is not necessarily the same as the
28 marginal benefits of abating an extra tonne. Abatement measures will yield additional benefits
29 besides avoided warming damage. These are the *secondary benefits*, which occur for example
30 in the form of local air quality improvements. The size of secondary benefits depends on
31 local circumstances. Studies for European countries and the United States indicate that
32 secondary benefits could offset between 30 and 100% of abatement costs. Whether the
33 benefits of climate policies are high enough to justify the costs of abatement is an issue
34 addressed in Chapter 9.

Box 6.1: Estimating the Value of a Statistical Life

1 Valuing statistical lives in monetary terms is controversial and raises a number of ethical
2 issues. The reality is, however, that human life is not 'beyond price'. If it were, most of the
3 world's wealth would be spent trying to save lives by reducing accidents and preventing
4 disease. Risks are taken every day, both voluntarily by individuals and by governments in
5 choosing their social and economic expenditures.

6 It is important to understand that no-one 'values human life' in monetary terms. It is a
7 *statistical life* that has an economic value. It would make no sense to ask an individual how
8 much he or she is willing to pay to avoid certain death. Nor is that the context of social
9 decision-making. But it does make sense to ask what individuals are willing to pay to reduce
10 the risk of death, or what they are willing to accept to tolerate an increased risk of death.

11 In the past, economic values of life risks have been estimated by the *human capital* approach.
12 This involves treating an individual as an economic agent capable of producing an output that
13 is valued in monetary terms. A life lost is then the loss of that output, less any consumption
14 that individual would have made. One immediate problem with the approach is that, if it is
15 applied literally, the very old would have negative values for their lives - they would not be
16 contributing to output, but they would be consuming. As with many other valuation
17 procedures, it is the value of a statistical life at a mean or median age group that is applied
18 'across the board' to young and old. But the real problem with the human capital approach
19 is that it has no particular relationship to an individual's willingness to pay to reduce his or
20 her risks of mortality. It is not properly founded in economic theory. Moreover, it tends to
21 produce extremely low values for those with low earnings, clearly discriminating against the
22 already poor.

23 The alternative is to estimate individuals' willingness to pay or accept for risk changes.
24 Willingness to pay measures include direct approaches such as *contingent valuation* where
25 the individual is asked how much they are willing to pay to reduce risks. Other measures
26 include finding out what people are willing to pay to adopt safety and disease preventing
27 measures. For willingness to accept, the *hedonic wage approach* can be used. For example,
28 if there are 100,000 workers and each is willing to accept \$5 to tolerate an increased risk of
29 mortality of 1/100,000 then the increased risk will result in one statistical death. The value
30 of that statistical life is then $\$5 \times 100,000 = \$500,000$.

31 Studies of the contingent valuation and hedonic wage risk approaches suggest 'values of
32 statistical lives' (VOSLs) of about \$3 million in the developed world. Since few studies exist
33 for the developing world it is difficult to say what the results would be for these techniques.
34 Since willingness to pay (WTP) is constrained by ability to pay (wealth and income) the
35 results are likely to be very much lower. The available studies place 'own valuations' at
36 perhaps \$10,000 (Parikh, 1994; Seroa da Motta, 1994).

37 'Borrowing' VOSLs from developed economy studies is hazardous. Various rough and ready
38 approaches have been tried. For example, developing country valuations could be estimated

as

$$VOSL_{dc} = VOSL_{dc} \cdot (Y_{dc}/Y_{dc})^E$$

where ldc = developing economy, dc = developed economy, E either denotes the income elasticity of demand or the elasticity of the marginal utility of income, and Y is income. Developing countries' VOSLs would simply be 'scaled down' by the ratio of incomes raised to the power E . If $E = 1$, then the scaling down is simply done by the ratio of incomes.

This formula results in lower VOSLs in poorer countries compared to rich countries. This appears to be 'unfair' since it could be taken to imply that for every dollar spent saving a life in the developed world, only a fraction of a dollar should be spent saving lives in the developing world. This is one reason for expressing VOSL losses as a percentage of GDP, i.e. what individual countries and regions are willing to pay out of their available resources. In terms of the above formula, if $E = 1$, and dividing both sides of the equation by Y_{dc} , the result is $VOSL_{dc}/Y_{dc} = VOSL_{dc}/Y_{dc}$, i.e. the VOSL in a developing country is the same proportion of income as it is in the developed economy.

But this still leaves the *absolute* VOSL lower in developing countries. Some people argue that the rich countries have caused the global warming problem and that the polluter-pays-principle therefore dictates that $VOSL_{dc}$ is the correct value for *all* lives. An example of such an approach is given by Hohmeyer and Gärtner (1992). One implication then is that mortality damage is the dominant climate change impact in developing countries, as is the case with the Hohmeyer and Gärtner estimates. Their figure is no longer a representations of a region's willingness to pay to avoid climate change, however.

Box 6.2 Damage Aggregation Across Countries and Individuals

Benefit-cost analysis assumes that the monetary values of damage can be aggregated across (a) individuals, and (b) countries. This aggregation process raises an important problem of so-called *interpersonal comparisons of utility*, where utility is simply another word for "welfare" or "wellbeing". Basically, introspection allows any one individual to assess his or her *own* preferences, but perhaps not *others'* preferences. Each individual knows by how much he or she is better off in situation X compared to situation Y, but he or she cannot assess how this change compares to the extent to which someone else is better off for the same change of situation. This inability to assess *other minds* produces the theorem that it is impossible to make comparisons of wellbeing between individuals, and hence by extension, between countries. There is therefore an endless number of ways in which *individuals'* assessment of their own wellbeing can be aggregated to yield a measure of *social welfare* change.

Measuring social welfare change requires interpersonal welfare comparisons, comparisons that require ethical judgements about individuals preferences. Such judgements could include one to the effect that preference measures should not be unduly influenced by income differences. In this case, the individual measures of preference - willingness to pay - could be weighted so as to reflect the preference of someone with an average income. One way to proceed is to indicate the outcomes of the benefit-cost analysis according to differing value judgements about the weights attached to preferences - a kind of "value sensitivity analysis". Thus, whether a change in the state of the world raises or lowers social welfare depends on the impacts on individual welfare as well as on normative criteria for making interpersonal welfare comparisons. Measures of social welfare change are, therefore, not objective but normative.

Global warming damage formulations usually present total damages (D) as the sum of individual impacts (d_i),

$$D = \sum_i d_i$$

Instead an alternative formulation could be to present the results in the following way,

$$D = \sum_i d_i \left(\frac{Y_i}{Y_i} \right)^E$$

where Y_i is now some reference level of income, say the global average income, or the income of the richer countries, and E is a factor correcting for differences in the utility of income between countries. In the literature, E is usually either the income elasticity of demand or the elasticity of the marginal utility of income (Pearce, 1986).

An example will indicate how the measures differ. Suppose there are just two countries. In country A, damage d_A is \$50 and in country B it is \$30. Country A has an income of \$5,000 and in country B it is \$1,000. The unweighted approach would make the global damage \$80. As a percentage of world income this is $80/6000 = 1.33\%$. Note however, that A's damage is 1% of its income, and B's is 3%.

Setting Y_A at the average world income of \$3000, and $E=1$ for convenience, the weighted procedure would produce the following result,

$$D = 50 \cdot \left(\frac{3,000}{5,000} \right) + 30 \cdot \left(\frac{3,000}{1,000} \right) = 30 + 90 = 120$$

Damage is now in "equity weighted" terms, and expressed as a fraction of world income it is 2%. The share of B's income has risen to 9% and the effect of equity weighting is therefore to make B's damage much more important.

How is the value of E selected? If logarithmic utility functions are chosen and E is interpreted as the elasticity of the marginal utility of income, then $E=1$, and we have the results shown above. Various alternative weights could be chosen, e.g. to reflect income elasticities of demand.

There are many problems involved in such procedures, but they illustrate the idea of "value sensitivity". The issue of interpersonal utility comparisons has been addressed above. There is also the question of what per capita income figure to use. Here the answer is probably purchasing parity rather than exchange-rate based per capita income. For low-income countries, the former tend to be about three times as high as the latter, whereas the two are approximately equal for rich countries. The use of exchange-rate based per capita income would inappropriately increase still further the multiple of the developing country welfare weight relative to the industrial country welfare weight. Further, what is the time reference of the per capita income? In principle it should be in the year for which the damage is calculated, and thus, say, 2050 and beyond. By then the per capita income multiple of rich relative to poor nations should have diminished from more rapid growth in the latter, reducing the differences among relative welfare weights.

Consideration of welfare-weighted impacts widens the array of policy implications. In one dimension, it helps show how extreme effects for some countries might count for relatively more than minor effects summed over a larger block of countries (e.g. welfare effects for an island state expected to be inundated might be larger than would be attributed solely on the basis of its income or even population). The reason is that the marginal utility rises as per capita income declines, so that utility-based damage for one country with a 30 percent loss in per capita income is greater than the sum for five other countries of equal size but with 6 percent income reduction each. In another dimension, consideration of welfare-weighting quickly leads to recognition of gains from trade in greenhouse effects. Income available is based on country shares in global income, whereas utility effects essentially involve population weighting. In a cooperative international abatement program, there is a resulting opportunity for efficient trades in which rich countries allocate some of their income

to defray the losses of poorer countries that are equivalent in absolute terms to the income transferred but much larger in terms of utility otherwise sacrificed. Of course, this same dynamic suggests that a utility-oriented approach would counsel larger amounts of grant aid to poor countries already today, irrespective of the greenhouse effect. That such larger flows do not presently occur (they would have to completely eliminate per capita income differences to remove the gain from utility trade) is not an argument for failing to consider welfare weighting in greenhouse damage analysis, if only because there is a qualitative and ethical difference between refraining from assisting on the one hand and imposing damage on the other.

Box 6.3 Relative Damage in Developing and Industrial Countries

Various factors influence global warming damage in less developed countries (LDCs) as opposed to industrial countries (DCs), as a fraction of (purchasing-power) GDP.

- **Location:** In general, warming is expected to be greater at higher latitudes. Because the developing countries tend to be located closer to the equator, from this standpoint one would expect *lesser* impact on developing than on industrial countries.
- **Economic Structure:** Because LDCs have a much higher share of GDP in agriculture, and therefore a larger share of output directly exposed to climatic influences, one would expect a *greater* impact on LDCs than on DCs from this standpoint.
- **Coastal Vulnerability:** The incidence of coastal vulnerability to sea level rise and possible increase in tropical cyclone damage is probably *greater* in LDCs than DCs. Although vulnerable areas can be found in industrial countries (for example, Louisiana), vulnerability is particularly high for such LDCs as Bangladesh, Egypt, and China. Low-lying island states tend to be LDCs. Of 50 countries or territories identified as having shore protection costs above 0.5 percent of GDP annually as a consequence of a 1-metre rise in sea level, all but one (New Zealand) are LDCs (IPCC, 1990b).
- **Rigidities:** Capacity to adapt to warming may be more limited in developing countries. Adaptation requires an investment outlay, and low-income communities tend to have lower savings rates and flexibility to undertake these investments. Thus, Rosenzweig *et al.* (1993) identify *greater* relative damage to agriculture in LDCs, partly because crops are already grown nearer to heat tolerance limits but also because of lesser expected capacity to adapt than in DCs. A possible consideration in the other direction is that the economy growing more rapidly has a lower fraction of past fixed investment in its total capital stock, and thus easier adjustment.
- **Human Life:** Because of poorer nutrition and health infrastructure, proportionate loss of life from global warming (from heat waves, increased hunger risk, possible tropical storm damage increase) seems likely to be *greater* in LDCs than in DCs. Valuation effects could go either way. Most statistical life valuation techniques would place a lower unit value in a country with lower per capita income (see Box 6.1). However, some would question this differentiation on ethical grounds. Moreover, income-related differences would tend not to affect impacts expressed as a fraction of GDP, as the base would also be proportionately lower.

Box 6.4 Valuation of Electricity-Related Externalities in California

The importance of secondary air quality benefits can be illustrated at least in part from the practices of some regulatory commissions in the United States. A growing number of these now require that electric utilities take into account the value of air emissions in their cost-benefit analysis of alternative supply and demand side resources.

The monetary air quality values used in these assessments do not usually represent actual marginal damages, however. CO₂ values, for example, are mostly based on avoided costs, e.g. the cost of planting trees on otherwise unforested land. The environmental cost adds for the other pollutants are also mostly based on control costs. The conceptual basis for this method is rather weak: using abatement costs as a proxy for the damage costs could involve substantial error. The use of damage control costs as a proxy is justified by many regulatory commissions on the basis that damage cost estimates are themselves uncertain.

A study commissioned by the California Energy Commission which does use consistently estimated damage-cost based externality values is shown below. The estimates imply that for every dollar in benefits resulting from the reduction of CO₂ emissions, there is another \$ 3 resulting from the reduction of conjoint pollutants. It is a reasonable conclusion, therefore, that joint benefits can significantly affect the overall cost-benefit assessment of climate policies.

	Environmental Benefits (\$/t)	Emission Rate (lbs/mwh)	Total Benefits (\$)
CO ₂	26 ¹	1,820	23
joint products			
NO _x	14,483	6	43
SO ₂	7,425	6	22
TSP	57,620	0.3	9
Total joint products			74

¹ based on avoided costs

Source: Emission rates based on a notional, new coal-fired plant meeting new source performance standards (NSPS). Externality values for NO_x, SO₂ and particulates (TSP) based on Hashem, Barakat and Chamberlin (1992).

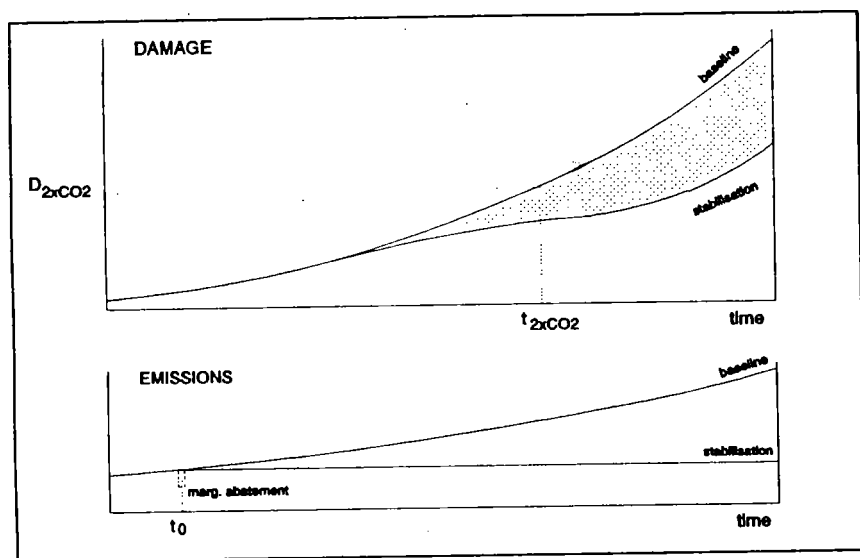


Figure 6.1 2xCO₂ Damage vs. Abatement Benefits. Under business-as-usual, greenhouse gas emissions will continue to rise over time (upward sloping line in the emissions graph). As a consequence annual global warming damages will rise over time as well (upper line in the damage graph). If instead emissions are stabilised at time t_0 (the horizontal "stabilisation" line in the lower graph), the annual damage curve will follow a more flat trajectory (the lower curve in the upper diagram). The benefit of this stabilisation policy is represented by the shaded area: the sum of avoided damages in all time periods. Stabilising emissions constitutes a significant change in policy. Analysts are often interested¹ in the benefits obtained through only a *marginal* deviation from the baseline - the marginal benefit per tonne abated, or the marginal cost of an additional tonne of emissions. Marginal changes are conceptually calculated in the same way, as the difference in the two damage trajectories with and without the abated tonne (not drawn in the figure). The two emission paths with and without marginal abatement would be identical, except for a slight deviation at time t_0 .

Table 6.1 Overview on Climate Change Impacts

Damages	Market Impacts				Non-Market Impacts		
	Primary economic sector damage	Other economic sector damage	Property loss	Damage from extreme events	Ecosystem damage	Human impacts	Damage from extreme events
Fully estimated based on willingness to pay	agriculture ¹				wetland loss		
Fully estimated, using approximations	forestry	water supply	dryland loss coastal protect.	hurricane damage	forest loss		hurricanes
Partially estimated	fisheries ²	energy demand leisure activity	urban infrastructure	damage from droughts ³	species loss	human life air pollution water pollution migration	
Not estimated		insurance construction transport energy supply		non trop. storms river floods hot/cold spells other catastrophes	other ecosystems loss	morbidity physical comfort polit. stability human hardship	non trop. storms droughts river floods hot/cold spells other catastrophes

¹ widespread disagreement

² often included in wetland loss

³ primarily agricultural damage

Table 6.2 *Preference Valuation for Endangered Species and Prized Habitats*

Country	Species or Habitat	Value (1990\$/year/person)
Norway	brown bear, wolf and wolverine	15.0
	conservation of rivers against hydroelectric development	59.0-107.0
United States	bald eagle	12.4
	emerald shiner	4.5
	grizzly bear	18.5
	bighorn sheep	8.6
	whooping crane	1.2
	blue whale	9.3
	bottlenose dolphin	7.0
	California sea otter	8.1
	northern elephant seal	8.1
	humpback whale ¹	40-48 (without information) 49-64 (with information)
	Grand Canyon (visibility)	27.0
	Colorado wilderness	9.3-21.2
Australia	Nadgee Nature Reserve (NSW)	28.1
	Kakadu Conservation Zone (NT) ²	40.0 (minor damages) 93.0 (major damages)
UK	nature reserves ³	40.0 (informed individuals)

¹ Respondents divided into two groups one of which was given video information

² Two scenarios of mining development damage were given to respondents

³ Survey of informed individuals only

Source: Pearce (1993).

Table 6.3 *Reported Fatalities due to Weather Events 1989-1992*

Region	Total Number 1989	1990	1991	1992	Average
Africa	31	138	> 621	> 360 > 69 ¹	> 288 > 215 ¹
Asia	> 4,300	> 3,280	> 142,000 > 3,000 ²	> 7,766 > 2,766 ²	> 39,337 > 3,337 ²
South America	> 35	26	> 117	108	> 72
Central & North America	> 75	> 57	> 86	> 131	> 87
South West Pacific	17	804	6,640 296 ³	90	1,888 302 ³
Europe	> 52	> 129	> 65	> 424	> 161
Total:					
all events	> 4,483	> 4,434	> 149,529	> 8,879	> 41,831
excl. major disasters	> 4,483	> 4,434	> 4,185	> 3,588	> 4,173

¹ Excluding the Madagascar 1992 drought and famine.

² Excluding the Bangladesh 1991 and Pakistan 1992 floods

³ Excluding the Philippines 1991 storm

Source: Limbert (1993).

Table 6.4 Economic Damages from Global Warming: US Economy at Present Scale
(base year 1990; billion \$)

	2xCO ₂		3	
	Cline (2.5°C)	Fankhauser (2.5°C) ¹	Titus (4°C)	Tol (2.5°C) ²
Agriculture	17.5	8.4	1.2	10.0
Forest Loss	3.3	0.7	43.6	-
Species Loss	4.0 + a	8.4	-	5.0
Sea Level Rise	7.0	9.0	5.7	8.5
Electricity	11.2	7.9	5.6	-
Non-Electric Heating	- 1.3	-	-	-
Human Amenity	+ b	-	-	12.0
Human Morbidity	+ c	-	-	-
Human Life	5.8	11.4	9.4	37.4
Migration	0.5	0.6	-	1.0
Hurricanes	0.8	0.2	-	0.3
Construction	± d	-	-	-
Leisure Activities	1.7	-	-	-
Water Supply availability	7.0	15.6	11.4	-
pollution	-	-	32.6	-
Urban Infrastructure	0.1	-	-	-
Air Pollution	-	7.3	-	-
tropospheric Ozone	3.5	-	27.2	-
other	+ e	-	-	-
Mobile Air Cond.	-	-	2.5	-
Total	61.1 +a+b+c+d+e (1.1)	69.5 (1.3)	139.2 (2.5)	74.2 (1.5) ²

¹ transformed from 1988 to 1990 base
² USA and Canada, base year 1988
 Sources: Cline (1992a), Fankhauser (1994a), Titus (1992), Tol (1994b).

59

Table 6.5 Quantitative 2xCO₂ Damages in Different World Regions (2.5°C warming)

Type of damage	Damage indicator	EU	USA	Ex USSR	China	Non-OECD	OECD	World
agriculture	welfare loss (% GNP)	0.21	0.16	0.24	2.10	0.28	0.17	0.23
forestry	forest area lost (km ²)	52	282	908	121	334	901	1,235
fishery	reduced catch (1000t)	558	452	814	464	4,326	2,503	6,829
energy	rise in electricity demand (TWh)	54.2	92.0	54.6	17.1	142.7	211.2	353.9
water	reduced water availability (km ³)	15.3	32.7	24.7	32.2	168.5	62.2	230.7
coastal protect.	annual capital costs (m\$/yr)	133	176	51	24	514	493	1,007
dryland loss	area lost (1000 km ²)	1.6	10.7	23.9	0	99.5	40.4	139.9
wetland loss	area lost (1000 km ²)	9.9	11.1	9.8	11.9	219.1	33.9	253.0
ecosystems loss	number of protected habitats lost, assuming 2% loss (section 3.2.12)	16	8	?	4	53	53	106
health/mortality	number of deaths (1000)	8.8	6.6	7.7	29.4	114.8	22.9	137.7
air pollution	equivalent increase in emissions (1000 t NO ₂)	566	1,073	1,584	227	2,602	1,943	4,545
troposph. O ₃	(1000 t sulphur)	285	422	1,100	258	1,864	873	2,737
SO ₂								
migration	additional immigrants (1000)	229	100	153	583	2,279	455	2,734
hurricanes								
casualties	number of deaths	0	72	44	779	7,687	313	8,000
damages	m\$	0	115	1	13	124	506	630

Source: after Fankhauser (1994a).

Table 6.6 Monetary 2xCO₂ Damage in Different World Regions

	Fankhauser (1994a)		Tol (1994b)	
	bn\$	%GDP ¹	bn\$	%GDP ¹
• European Union	63.6	1.4		
• United States	61.0	1.3		
• Other OECD	55.9	1.4		
• OECD America			74.2	1.5
• OECD Europe			56.5	1.3
• OECD Pacific			59.0	2.8
<i>Total OECD</i>	<i>180.5</i>	<i>1.3</i>	<i>189.5</i>	<i>1.6</i>
• E. Europe / Former USSR	18.2 ²	0.7 ²	- 7.9	-0.3
• Centrally Planned Asia	16.7 ³	4.7 ³	18.0	5.2
• South and South East Asia			53.5	8.6
• Africa			30.3	8.7
• Latin America			31.0	4.3
• Middle East			1.3	4.1
<i>Total Non-OECD</i>	<i>89.1</i>	<i>1.6</i>	<i>126.2</i>	<i>2.7</i>
<i>World</i>	<i>269.6</i>	<i>1.4</i>	<i>315.7</i>	<i>1.9</i>

¹ Note that the GDP base may differ between the studies

² Former Soviet Union only

³ China only

Sources: Fankhauser (1994a), Tol (1994b).

Table 6.7 Expert Opinion on Climate Change Damage

	Scenario A	Scenario B	Scenario C
	3°C warming by 2090	6°C warming by 2175	6°C warming by 2090
<i>Damage Relative to World GDP (% of GDP)</i>			
mean answer	3.6	6.7	10.4
median answer	1.9	4.1	5.5
range of answers	0.0 - 21.0	0.0 - 35.0	0.8 - 62.0
<i>Probability of Damage > 25% of GNP (%)</i>			
mean answer	4.8	12.1	17.5
median answer	0.5	3.0	5.0
range of answers	0.0 - 30.0	0.2 - 75.0	0.3 - 95.0

Source: Poll of experts, Nordhaus (1994a).

Table 6.8 *Illustrative Damages from Long Term Warming: US Economy at Present Scale*
(base year 1990; billion \$)

	Long Term Warming (10°C)
Agriculture	95.0
Forest Loss	7.0
Species Loss	16.0 + A
Sea Level Rise	35.0
Electricity	64.1
Non-Electric Heating	- 4.0
Human Amenity	+ B
Human Morbidity	+ C
Human Life	33.0
Migration	2.8
Hurricanes	6.4
Construction	± D
Leisure Activities	4.0
Water Supply availability pollution	56.0 -
Urban Infrastructure	0.6
Air Pollution tropospheric ozone other	19.8 + E
Total	335.7 + A + B + C ± D + E
(% of GDP)	(6.1)

Source: Cline (1992a).

Table 6.9 *Losses of Rice Output due to Sea Level Rise in Coastal Zones of Bangladesh*

Year	SLR by 2070:	45 cm	SLR by 2070:	100 cm
	(1000 tonnes)	(% coastal output)	(1000 tonnes)	(% coastal output)
2020	125	2	412	4
2050	2,122	28	7,708	49
2070	2,619	28	9,514	50

Source: Asaduzzaman (1994).

Table 6.10 *Vulnerability Index for Different Categories of Countries*
(High vulnerability is indicated by values closer to 1)

Country Categories	Number of Countries	Index
All countries	113	0.376
Developed Countries	22	0.208
Developing Countries	91	0.417
Small Island Developing Countries	20	0.590
Other Island Developing Countries	28	0.539

Note: The index for country j is $\sum_i V_{ij}/3$, where $V_{ij} = (X_{ij} - \min X_i) / (\max X_i - \min X_i)$. X is the value of the component variable in the index, and $i = 1$ to 3 the number of variables influencing the index.

Source: Briguglio (1993).

Table 6.11 The Social Costs of CO₂ Emissions in Different Decades
(current value (1990)/\$/tC)

Study	Type	1991-2000	2001-2010	2011-2020	2021-2030
Nordhaus (1991)	MC	7.3 (0.3-65.9)			
Ayres and Walter (1991)	MC	30 - 35			
Nordhaus (1993a, b)	CBA	5.3	6.8	8.6	10.0
Cline (1992b, 1993d)	CBA	5.8 - 124	7.6 - 154	9.8 - 186	11.8 - 221
Peck and Teisberg (1992)	CBA	10 - 12	12 - 14	14 - 18	18 - 22
Fankhauser (1994a, b)	MC	20.3 (6.2-45.2)	22.8 (7.4-52.9)	25.3 (8.3-58.4)	27.8 (9.2-64.2)
Maddison (1994)	CBA/M ^c	5.9-6.1	8.1 - 8.4	11.1-11.5	14.7-15.2

Note: MC = marginal social cost study,

CBA = shadow value in a cost-benefit study.

Figures in brackets denote 90% confidence intervals.

Sources: as indicated.

65

Table 6.12 Reduced Air Emissions due to CO₂ Abatement
(% reduction compared to baseline)

Country	Year	Policy/Scenario	CO ₂	SO ₂	NO _x	CO	Partic.	VOC	Secondary Benefits (\$/tC)	Sources
Europe ¹	2000	EU carbon/energy tax - current product. structure - cost efficient regime	9.4 9.7	7.4 9.3	6.2 6.4	n.a. n.a.	n.a. n.a.	n.a. n.a.	6.1 6.6	Alfsen <i>et al.</i> (1993)
Norway	2000	Emission stabilisation (at 1989 level)	15.0	20.8	10.8	24.1	4.3	n.a.	40 - 140 ²	Alfsen <i>et al.</i> (1992)
UK	2005	EU carbon/energy tax	12.1	38.3	10.6	9.6	30.3	1.1	40 - 1040	Barker (1993)
US	2000	Emission stabilisation - through carbon tax - through Btu tax	8.6 8.6	1.9 ³ 2.2 ³	6.6 6.6	1.5 3.4	1.0/1.8 ⁴ 1.6/2.2 ⁴	1.4 2.7	2.0 - 20 3.5 - 28	Scheraga and Leary (1994)

¹ Western and Eastern Europe (UN ECE region). Tax in 6 EU countries (France, Germany, UK, Italy, Netherlands, Denmark) and Scandinavia (Norway, Finland, Sweden) only

² including road traffic benefits (reduced congestion, noise, accident, and road damage costs)

³ SO₂

⁴ PM₁₀ / TSP

Sources: as shown.

Table 6.13 The Social Costs of Air Pollution (\$/tonne)

Country	SO ₂	NO _x	CO	Particulates	VOC	Source
UK	367	124	15	21,333	n.a.	Pearce (1994)
UN ECE ¹	637	490	n.a.	21,333	n.a.	Pearce (1994)
Norway	500 - 7,600	1,600 - 31,400	1 - 13	2,100 - 27,700	n.a.	Alfsen <i>et al.</i> (1992)
US	4,800	2,000	n.a.	2,700	n.a.	Ottinger <i>et al.</i> (1990)
US	300 - 1,800	10 - 100	n.a.	400 - 10,900	360 - 2,400	Scheraga and Leary (1994)

¹ Damage done by a tonne of UK emissions to Western and Eastern Europe, incl. UK (UN ECE region).

Sources: as shown.

Extended Bibliography

- Adams, R.M., C. Rosenzweig, R.M. Peart, J.T. Ritchie, B.A. McCarl, J.D. Glyer, R.B. Curry, J.W. Jones, K.J. Boote, and L.H. Allen Jr. (1990),
Global Climate Change and US Agriculture, in: *Nature* 345(17 May): 219-223.
- Adams, R.M., R.A. Fleming, C.C. Chang, B.A. McCarl and C. Rosenzweig (1993),
A Reassessment of the Economic Effects of Global Climate Change on US Agriculture, Report prepared for the US Environmental Protection Agency, Washington DC (September).
- Adger, N. and S. Fankhauser (1993),
Economic Analysis of the Greenhouse Effect: Optimal Abatement Level and Strategies for Mitigation, in: *International Journal of Environment and Pollution* 3(1-3): 104-119.
- Agarwal, A. and S. Narain (1991),
Global Warming in an Unequal World. A Case of Environmental Colonialism, Mimeo, Centre for Science and Environment, New Delhi.
- Amano, A. (1994),
Estimating Secondary Benefits of Limiting CO₂ Emissions in the Asian Region, Mimeo, School of Business Administration, Kobe University.
- Alfsen, K., H. Birkelund, and M. Aaserud (1993),
Secondary Benefits of the EC Carbon/Energy Tax, Research Department Discussion Paper No 104, Statistics Norway, Oslo.
- Alfsen, K.H., A. Brendemoen, and S. Glomsrød (1992),
Benefits of Climate Policies: Some Tentative Calculations, Discussion Paper No. 69, Norwegian Central Bureau of Statistics, Oslo.
- Ali, S. I. and S. Huq (1990),
International Sea Level Rise: National Assessment of Effects and Possible Responses for Bangladesh, Unpublished Report to the University of Maryland, College Park.
- Allen, Bruce D., and Roger Y. Anderson (1993),
Evidence from Western North America for Rapid Shifts in Climate During the Last Glacial Maximum, in: *Science* 260(25 June): 1920-23.
- Anderson, D. and R. Williams (1993),
The Cost Effectiveness of GEF Projects, Working Paper No. 6, Global Environment Facility, Washington DC.
- Anklin, M., *et al.* (1993),
Climate Instability During the Last Interglacial Period Recorded in the GRIP Ice Core, in: *Nature* 364 (15 July): pp. 203-07.
- Arnell, N.W. and W.R. Dubourg (1994),
Implications for Water Supply and Water Management, in: M.L. Parry and R. Duncan (eds.), *Economic Implications of Climate Change in Britain*, London: Earthscan, forthcoming.

- Arrow, K.J. and M. Kurz (1970),
Public Investment, the Rate of Return and Optimal Fiscal Policy, Baltimore: Johns Hopkins University Press.
- Asaduzzaman, S. (1994),
Economic and Social Impacts of Climate Change: a Case Study of Bangladesh Coastal Zone, Mimeo, Bangladesh Institute of Development Studies, Dhaka.
- Asian Development Bank (1994),
Climate Change in Asia, 8 Country Studies, Manila: Asian Development Bank.
- Asthana, V. (1993),
Report on Impact of Sea Level Rise on the Islands and Coasts of India, Report to the Ministry of Environment and Forests, Government of India, New Delhi.
- Awosika, L., A.Ibe, and M.Udo-Aka. (1990),
Impact of Sea Level Rise on the Nigerian Coastal Zone, in Titus, J.G (ed), *Changing Climate and the Coast*, Vol.2, US Environmental Protection Agency, Washington DC.
- Ayres, R. and J. Walter (1991),
The Greenhouse Effect: Damages, Costs and Abatement, in: *Environmental and Resource Economics* 1: 237-270.
- Baan, P.J.A., H. van der Most, G.B.M. Pedroli and H.. van Zuijlen (1993),
Systeemverkenning Gevolgen van Klimaatverandering (in Dutch: System Exploration Impact of Climatic Change), Delft: Delft Hydraulics.
- Barker, T. (1993),
Secondary Benefits of Greenhouse Gas Abatement: The Effects of a UK Carbon/Energy Tax on Air Pollution, Energy Environment Economy Modelling Discussion Paper No. 4, Department of Applied Economics, University of Cambridge.
- Batie, S.S. and H.H. Shugart (1989),
The Biological Consequences of Climate Changes: An Ecological and Economic Assessment, in: N.J. Rosenberg *et al.* (eds.), *Greenhouse Warming: Abatement and Adaptation*, Washington, DC: Resources for the Future.
- Bazzaz, F. A. and E.D. Fajer (1992),
Plant Life in a CO₂-Rich World, in: *Scientific American*, 266(1): 68-74.
- Berz, G. (1990),
Natural Disasters and Insurance/Reinsurance, in: *UNDRO News*, January/February: 18-19.
- Berz, G.A. and Conrad, K. (1993),
Winds of Change, in: *The Review*, June: 32-35.
- Bigford, T.E. (1991),
Sea Level Rise, Nearshore Fisheries, and the Fishing Industry, in: *Coastal Zone Management* 19: 417-437.

- Birdsall, N. and A. Steer (1993),
Act Now on Global Warming - But Don't Cook the Books, in: *Finance & Development* 30(1): 6-8.
- Blanchard, O.J. and S. Fischer (1989),
Lectures on Macroeconomics, Cambridge, MA: MIT Press.
- Bradford, D.F. (1975),
Constraints on Government Investment Opportunities and the Choice of Discount Rate, in: *American Economic Review* 65(50): 887-899.
- Briguglio, L. (1993),
The Economic Vulnerabilities of Small Island Developing States, Report to UNCTAD, Geneva.
- Broccoli, A.J. and S. Manabe (1990),
Can Existing Climate Models Be Used to Study Anthropogenic Changes in Tropical Cyclone Climate?, in: *Geophysical Research Letters* 17 (11): 1917-1920.
- Broome, J. (1992),
Counting the Costs of Global Warming, Cambridge: White Horse Press.
- Bryant, E.A. (1991),
Natural Hazards, Cambridge: Cambridge University Press.
- Canadian Climate Program Board (1988a),
Implications of Climate Change for Downhill Skiing in Quebec, Climate Change Digest Report, CCD 88-03, Downsview, Ontario.
- Canadian Climate Program Board (1988b),
Implications of Climate Change for Tourism and Recreation in Ontario, Climate Change Digest Report, CCD 88-05, Downsview, Ontario.
- Carson, R., R. Mitchell, W.M. Hanemann, R. Köpp, S. Presser and P. Ruud (1994),
Contingent valuation and Loss Passive Use: Damages from the Exxon Valdez, Discussion Paper 94-18, Resources for the Future, Washington DC.
- Chakraborty, B. and M. Lal (1994),
Monsoon Climate and its Change in Doubled Carbon Dioxide Atmosphere as Simulated by CSIRO9, Mimeo, unpublished.
- Changnon, S.A. and Changnon, J.M. (1992),
Temporal Fluctuations in Weather Disasters: 1950-1989, in: *Climatic Change*, 22: 191-208.
- Clark, K.M. (1988),
Predicting Insurance Getting Easier, in: *National Underwriter*, 29 August 1988.
- Clark, K.M. (1991),
Catastrophe Reinsurers Need More, Better Data, in: *National Underwriter*, September.

- Cline, W. (1991),
Scientific Basis of the Greenhouse Effect, in: *Economic Journal* 101(407): 904-919.
- Cline, W.R. (1992a),
The Economics of Global Warming, Washington, DC: Institute for International Economics.
- Cline, W.R. (1992b),
Optimal Carbon Emissions over Time: Experiments with the Nordhaus DICE Model, Mimeo, Institute for International Economics, Washington, DC.
- Cline, W.R. (1993a),
Give Greenhouse Abatement a Fair Chance, in: *Finance & Development* 30(1): 3-5.
- Cline, W.R. (1993b),
The Impact of Global Warming on the United States: A Survey of Recent Literature, Mimeo, Institute for International Economics, Washington, DC (April).
- Cline, W.R. (1993c),
The Costs and Benefits of Greenhouse Abatement: A Guide to Policy Analysis, Paper presented at the OECD/IEA Conference on "The Economics of Global Warming", June 1993, Paris.
- Cline, W.R. (1993d),
Modelling Economically Efficient Abatement of Greenhouse Gases, Paper presented at the United Nations University Conference on "Global Environment, Energy and Economic Development", September 1993, Tokyo.
- Cline, W.R. (1993e),
A Note on the Impact of Global Warming on Air Conditioning and Heating Costs, Mimeo, Institute for International Economics, Washington, DC (January).
- Cline, W.R. and C.T. Hsieh (1993),
Optimal Carbon Emissions in the Nordhaus DICE Model under Backstop Technology, Mimeo, Institute for International Economics, Washington, DC (July).
- Collard, D. (1988)
Catastrophic Risk: Or the Economics of Being Scared, in: D. Collard, D.W. Pearce and D. Ulph (eds.) *Economics, Growth and Sustainable Environments: Essays in Memory of Richard Lecomber*, New York: Macmillan.
- Commonwealth Secretariat (1989),
Climate Change: Meeting the Challenge, Report of a Commonwealth Group of Experts, Commonwealth Secretariat, London.

- CRU/ERL (1992),
Development of a Framework for the Evaluation of Policy Options to Deal with The Greenhouse Effect: Economic Evaluation of Impacts and Adaptive Measures in the European Community, A Report for the Commission of European Communities, Climate Research Unit (CRU), University of East Anglia, and Environmental Resources Limited (ERL), London.
- Daily, G.C., P.R. Ehrlich, H.A. Mooney, and A.H. Ehrlich (1991),
Greenhouse Economics: Learn before you Leap, in: *Ecological Economics* 4: 1-10.
- Dansgaard, W., J.W.C. White, and S.J. Johnsen (1989),
The Abrupt Termination of the Younger Dryas Climate Event, in: *Nature* 339 (15 June): 532-34.
- Darmstadter, J. and M.A. Toman, eds. (1993),
Assessing Surprises and Nonlinearities in Greenhouse Warming Washington, DC: Resources for the Future.
- den Elzen, M.G.J. and J. Rotmans (1992),
The Socio-Economic Impact of Sea-Level Rise on the Netherlands: A Study of Possible Scenarios, in: *Climatic Change* 20: 169-195.
- Dlugolecki, A., D. Clement, C. Elvy, G. Kirby, J. Palutikoff, R. Salthouse, C. Toomer, S. Turner and D. Witt (1994),
The Impact of Changing Weather Patterns on Property Insurance, Report, Chartered Insurance Institute, London.
- Dlugolecki, A.F., K.M. Clark, D. McCauley, J.P. Palutikof and W. Yambi (1995),
Financial Services, in: IPCC, Second Assessment Report of Working Group II, forthcoming.
- Doornkamp, (1993),
Clay Shrinkage Induced Subsidence, in: *Geographical Journal* 159(2): 196-202.
- Dowlatabadi, H. and G. Morgan (1993),
A Model Framework for Integrated Studies of the Climate Problem, in: *Energy Policy* 21: 209-221.
- Easterling III, W.E., P.R. Crosson, N.J. Rosenberg, M.S. McKenney, L.A. Katz and K.M. Lemon (1993),
Agricultural Impacts of and Responses to Climate Change in the Missouri-Iowa-Nebraska-Kansas (MINK) Region, in: *Climatic Change* 24(1/2): 23-62.
- Edmonds, J. and J. Reilly (1985),
Global Energy. Assessing the Future, New York: Institute for Energy Analysis.
- El-Reay, M. (1990),
Responses to the Impacts of Greenhouse-induced Sea Level Rise on the Northern Coastal Regions of Egypt, in Titus, J.G (ed), *Changing Climate and the Coast*, Vol.2, US Environmental Protection Agency, Washington DC.

- Emanuel, K.A. (1987),
The Dependence of Hurricane Intensity on Climate, in: *Nature* 326: 483-485.
- Erickson, J.D. (1993),
From Ecology to Economics: The Case against CO₂ Fertilization, in: *Ecological Economics* 8: 157-175.
- Evans, D.J. et al. (1991),
Policy Implications of Greenhouse Warming, Washington, DC: National Academy Press.
- Fankhauser, S. (1994a),
Valuing Climate Change. The Economics of the Greenhouse Effect, London: Earthscan, forthcoming.
- Fankhauser, S. (1994b),
The Social Costs of Greenhouse Gas Emissions: An Expected Value Approach, in: *Energy Journal* 15(2): 157-184.
- Fankhauser, S. (1994c),
Protection vs. Retreat. The Economic Costs of Sea Level Rise, in: *Environment and Planning A*, forthcoming.
- Fankhauser, S. and C. Hope (1994),
Greenhouse Policies and the Costs of Mitigation, in: M.L. Parry and R. Duncan (eds.), *Economic Implications of Climate Change in Britain*, London: Earthscan, forthcoming.
- Fellner, W. (1967),
Operational Utility: The Theoretical Background and a Measurement, in: *Ten Economic Studies in the Tradition of Irving Fisher*, New York: John Wiley & Sons.
- Fisher, A.C. and W.M. Hahnemann (1993),
Assessing Climate Change Risks: Valuation of Effects, in: J. Darmstadter and M. Toman (eds.), *Assessing Surprises and Non-Linearities in Greenhouse Warming*, Washington, DC: Resources for the Future.
- Gleick, P.H. (1987),
Regional Hydrologic Consequences of Increases in Atmospheric CO₂ and Other Trace Gases, in: *Climatic Change* 10: 137-61.
- Gleick, P.H. (1992),
Water and Conflict, Project on Environmental Change and Acute Conflict, University of Toronto.
- Gleick, P.H. and E.P. Maurer (1990),
Assessing the Costs of Adapting to Sea Level Rise. A Case Study of San Francisco Bay, Mimeo, Pacific Institute for Studies in Development, Environment and Security, and Stockholm Environment Institute, Berkeley, CA and Stockholm.
- Glynn, P.W. and W.H. de Weerd (1991),
Elimination of Reef-building Hydrocorals Following the 1982-83 El Niño Warming Event, in: *Science* 253 (5 July): 69-71.

- Goering, J.M. (1990),
The Causes of Undocumented Migration to the United States: A Research Note, Working Papers No. 52, Commission for the Study of International Migration and Cooperative Economic Development.
- Goklany, I.M. (1989),
Climate change Effects on Fish, Wildlife and other DOI Programs, in: J.C. Topping, Jr. (ed.), *Coping with Climate Change*.
- Graßl, H. et al. (1995),
Catastrophes and Extreme Events, in: IPCC, Second Assessment Report of Working Group I, forthcoming.
- Grubb, M. (1993),
The Costs of Climate Change: Critical Elements, in: Y. Kaya, N. Nakićenović, W.D. Nordhaus and F. Toth (eds.), *Costs, Impacts and Benefits of CO₂ Mitigation*, IIASA Collaborative Paper Series, CP93-2, Laxenburg, Austria.
- Gutowski, W.J., G.F. McMahon, S.S. Schlachter, and P.H. Kirshen (1992),
Effects of Global Warming on Hurricane-Induced Flooding, Paper prepared for US Department of Energy, Washington, DC.
- Haarsma, R.J., J.F.B. Mitchell and C.A. Senior (1993),
Tropical Disturbances in a GCM, in: *Climate Dynamics* 8: 247-257.
- Haines, A. and C. Fuchs (1991),
Potential Impacts on Health of Atmospheric Change, in: *Journal of Public Health Medicine* 13(2): 69-80.
- Haines, A. and M. Parry (1993),
Climate Change and Human Health, in: *Journal of the Royal Society of Medicine* 86(December): 707-711.
- Han, M., J.Hou and L.Wu (1990),
Adverse Impact of Projected One Meter Sea Level Rise on China's Coastal Environment and Cities, University of Maryland, Maryland, *mimeo*.
- Hansen, J. et al. (1989),
Regional Greenhouse Climate Effects, in: J.C. Topping, Jr. (ed.), *Coping with Climate Change*, pp. 68-81.
- Hasham, Barakat and Chamberlin (1992),
..., California State Summary, EPRINET Environmental Externalities Clearing House. [full ref to follow]
- Heathcote, R.L. (1985),
Extreme Event Analysis, in: R.W. Kates, J.H. Ausubel and M. Berberian (eds.), *Climate Impact Assessment*, Chichester: John Wiley and Sons.

- Hoffert, M.I. and C. Covey (1992),
Deriving Global Climate Sensitivity from Paleoclimate Reconstructions, in: *Nature* 360(10 December): 573-76.
- Hohmeyer, O. and M. Gärtner (1992),
The Costs of Climate Change, Report to the Commission of the European Communities, Fraunhofer Institut für Systemtechnik und Innovations-Forschung, Karlsruhe (Germany).
- Homer-Dixon, T.F., J.H. Boutwell, and G.W. Rathjens (1993),
Environmental Change and Violent Conflict, in: *Scientific American*, 268(2): 38-45.
- Hope, C., J. Anderson, and P. Wenman (1993),
Policy Analysis of the Greenhouse Effect. An Application of the PAGE Model, in: *Energy Policy* 21(3): 327-338.
- Houghton, J. (1994),
Global Warming. The Complete Briefing, London: Lion Book.
- Howarth, R.B. (1992),
International Justice and the Chain of Obligation, *Environmental Values*, 1, 133-140.
- Howarth, R.B. and P.A. Monahan (1992),
Economics, Ethics, and Climate Policy, Mimeo, Lawrence Berkeley Laboratory, Berkeley, CA.
- Idso, S.B., R.C. Balling Jr. and R.S. Cerveny (1990),
Carbon Dioxide and Hurricanes: Implications of Northern Hemispheric Warming for Atlantic/Caribbean Storms, in: *Meteorology and Atmospheric Physics* 42: 259-263.
- Intergovernmental Panel on Climate Change (1990a),
Climate Change, the IPCC Scientific Assessment. Report from Working Group I, Cambridge: Cambridge University Press.
- Intergovernmental Panel on Climate Change (1990b),
Climate Change, the IPCC Impacts Assessment. Report from Working Group II, Canberra: Australian Government Publishing Service.
- Intergovernmental Panel on Climate Change (1990c),
Strategies for Adaptation to Sea Level Rise. Report of the Coastal Zone Management Subgroup, The Hague.
- Intergovernmental Panel on Climate Change (1992a),
Climate Change 1992. The Supplementary Report to the IPCC Scientific Assessment, Cambridge: Cambridge University Press.
- Intergovernmental Panel on Climate Change (1992b),
Global Climate Change and the Rising Challenge of the Sea. Supporting Document for the IPCC Update 1992, Geneva: WMO and UNEP.

- Intergovernmental Panel on Climate Change (1994),
Preparing to Meet the Coastal Challenges of the 21st Century. Conference Report of the World Coast Conference, Noordwijk, November 1993, Geneva: WMO and UNEP.
- Intergovernmental Panel on Climate Change (1995),
Second Assessment Report of Working Group I, forthcoming.
- Jansen, H.M.A. (1993),
Are We Underestimating, When Valuing the Benefits of Greenhouse Gas Reduction? in: Y. Kaya, N. Nakićenović, W.D. Nordhaus and F. Toth (eds.), *Costs, Impacts and Benefits of CO₂ Mitigation*, IIASA Collaborative Paper Series, CP93-2, Laxenburg, Austria.
- Kaiser, H.M., S.J. Riha, D.S. Wilks, D.G. Rossiter, and R. Sampath (1992),
A Farm-level Analysis of the Economic and Agronomic Impacts of Gradual Climate Warming, Mimeo, Department of Agricultural Economics, Cornell University, Syracuse, NY (May).
- Kalkstein, L.S. (1989),
The Impact of CO₂ and Trace Gas-Induced Climate Changes upon Human Mortality, in: J.B. Smith and D.A. Tirpak (eds.), *The Potential Effects of Global Climate Change on the United States. Appendix G: Health*, Washington DC: EPA.
- Kandlikar, M. (1994),
Catastrophic Climate Damage: Results from ICAM-2, Mimeo, Carnegie Mellon University, Pittsburgh.
- Kane, S., J. Reilly, and J. Tobey (1992),
An Empirical Study of the Economic Effects of Climate Change on World Agriculture, in: *Climatic Change* 21: 17-35.
- Kimball, B. and N.J. Rosenberg, eds. (1990),
The Impact of CO₂, Trace Gases, and Climate Change, Publication No. 53, American Society of Agronomy, Madison, WI.
- Kirshen, P. H. and N.M. Fennessey (1992),
Potential Impacts of Climate Change upon the Water Supply of the Boston Metropolitan Area, Mimeo, US Environmental Protection Agency, Washington, DC (October).
- Klinedinst, P.L., D.A. Wilhite, G.L. Hahn, and K.G. Hubbard (1993),
The Potential Effects of Climate Change on Summer Season Dair Cattle Milk Production and Reproduction, in: *Climatic Change*, 23(1): 21-36.
- Knox Lovell, C.A. and V.K. Smith (1985),
Microeconomic Analysis, in: R.W. Kates, J.H. Ausubel and M. Berberian (eds.), *Climate Impact Assessment*, Chichester: John Wiley and Sons.
- Körner, C. and J.A. Arnone III (1992),
Responses to Elevated Carbon Dioxide in Artificial Tropical Ecosystems, in: *Science* 257 (18 September): 1672-75.

- Krause, F., W. Bach, and J. Kooney (1989),
Energy Policy in the Greenhouse, London: Earthscan.
- Kunst, A.E., C.W.N. Looman and J.P. Mackenbach (1993),
Outdoor Air Temperature and Mortality in the Netherlands: A Time-Series Analysis, in:
American Journal of Epidemiology 137(3): 331-341.
- Langford, I.H. and G. Benthall (1993),
The Potential Effects of Climate Change on Winter Mortality in England and Wales,
Centre for Social and Economic Research on the Global Environment (CSERGE),
Working Paper GEC 93-25, University of East Anglia and University College London.
- Leary, N. (1994),
*The Amenity Value of Climate: A Review of Empirical Evidence from Migration, Wages
and Rents*, US Environmental Protection Agency, Discussion Paper, July.
- Leggett, J. (1993),
Climate Change and the Insurance Industry. Solidarity among the Risk Community,
Greenpeace International, Amsterdam.
- Limbert, D.W.S. (1993),
The Human and Economic Impacts of Weather Events in 1992, in: *WMO Bulletin* 42(4):
333-341.
- Lind, R.C., ed. (1982),
Discounting for Time and Risk in Energy Policy, Washington, DC: Resources for the
Future.
- Loveland, J.E. and G.Z. Brown (1992),
Impacts of Climate Change on the Energy Performance of Buildings in the United States,
Mimeo, US Office of Technology Assessment, Washington, DC.
- MacDonald, G.J. (1990),
Role of Methane Clathrates in Past and Future Climates, in: *Climatic Change* 16: 247-81.
- Maddison, D.J. (1994),
The Shadow Price of Greenhouse Gases and Aerosols, Mimeo, Centre for Social and
Economic Research on the Global Environment (CSERGE), University College London
and University of East Anglia, Norwich.
- Magadza, C.H.D. (1991),
Some Possible Impacts of Climate Change on African Ecosystems, in: J. Jäger and H.L.
Ferguson (eds), *Climate Change. Science, Impacts and Policy. Proceedings of the Second
World Climate Conference*, Cambridge: Cambridge University Press.
- Magalhães, A.R. and M.H. Glantz, eds. (1992),
Socioeconomic Impacts of Climate Variations and Policy Responses in Brazil, United
Nations Environmental Programme, Nairobi, and Esquel Brazil Foundation, Brasilia.

- Manabe, S. and R.J. Stouffer (1993),
Century-scale Effects of Increased Atmospheric CO₂ on the Ocean-Atmosphere System,
in: *Nature* 364(15 July): 215-218.
- Manne, A.S., R. Mendelsohn, and R.G. Richels (1993),
*MERGE - A Model for Evaluating Regional and Global Effects of Greenhouse Gas
Reduction Policies*, Mimeo, Electric Power Research Institute, Palo Alto, CA.
- Manne, A.S. and R.G. Richels (1992),
Buying Greenhouse Insurance, Cambridge MA: MIT Press.
- Markandya, A., and D.W. Pearce (1988),
Environmental Considerations and the Choice of Discount Rate in Developing Countries,
Environment Department, World Bank, Washington DC.
- Maunder, W.J. (1994),
*Tropical Cyclones in the South Pacific: An Historical Overview Regarding the Intensity,
Tracks, and Frequency of Tropical Cyclones in the South Pacific during the Last 100
Years, and an Analysis of any Changes in these Factors*, Institute for Environmental
Studies, Free University Amsterdam.
- McLean, D.M. (1989),
A Mechanism for Greenhouse-Induced Collapse of Mammalian Faunas in: J.C. Topping
Jr. (ed.), *Coping with Climate Change*, pp. 263-67.
- Mearns, L.O., R.W. Katz and S.H. Schneider (1984),
Extreme High Temperature Events: Changes in their Probabilities with Changes in Mean
Temperature, in: *Journal of Climate and Applied Meteorology* 23: 1601-1613.
- Mendelsohn, R., W. Nordhaus, and D. Shaw (1992),
The Impact of Climate on Agriculture: A Ricardian Approach, Discussion Paper No. 1010,
Cowles Foundation, New Haven, Conn.
- Midun, Z. and S. Lee (1989),
Effect of Climate Change and Sea Level Rise on Bangladesh, Report to the
Commonwealth Group of Experts, Commonwealth Secretariat, London.
- Milliman, J.D., J.M. Broadus, and F. Gable (1989),
Environmental and Economic Implications of Rising Sea Level and Subsiding Deltas: The
Nile and Bengal Examples, in: *Ambio* 18(6): 340-345.
- Morgenstern, R.D. (1991),
Towards a Comprehensive Approach to Global Climate Change Mitigation, in: *American
Economic Review, Papers and Proceedings* 81(2): 140-145.
- Munich Re (1993),
Winter Storms in Europe - Analysis of 1990 Losses and Future Loss Potential, Munich Re:
Munich.

- Nicholls, R., K. Dennis, and S. Leatherman (1990),
Impacts of Sea level Rise on Selected Developing Countries, Proceedings of 3rd European Workshop on Coastal Zones, Cyprus, September 1990.
- Nicholls, R., K. Dennis, C. Volonte and S. Leatherman (1992),
Methods and Problems in Assessing the Impacts of Accelerated Sea level Rise, Proceedings of the Workshop "The World at Risk: Natural Hazards and Climate Change", American Institute for Physics, New York.
- Nishioka, S., H. Harasawa, H. Hashimoto, T. Ookita, K. Masuda, and T. Morita (1993),
The Potential Effects of Climate Change in Japan, Centre for Global Environmental Research, and National Institute for Environmental Studies, Tsukuba (Japan).
- Nordhaus, W.D. (1991),
To Slow or not to Slow: The Economics of the Greenhouse Effect, in: *Economic Journal* 101(407): 920-937.
- Nordhaus, W.D. (1992),
The DICE Model: Background and Structure of a Dynamic Integrated Climate Economy Model of the Economics of Global Warming, Discussion Paper No. 1009, Cowles Foundation, New Haven, Conn.
- Nordhaus, W.D. (1993a),
Optimal Greenhouse Gas Reductions and Tax Policy in the "DICE" Model, in: *American Economic Review, Papers and Proceedings* 83(2): 313-317.
- Nordhaus, W.D. (1993b),
Rolling the "DICE": An Optimal Transition Path for Controlling Greenhouse Gases, in: *Resources and Energy Economics* 15(1): 27-50.
- Nordhaus, W.D. (1993c),
Reflections on the Economics of Climate Change, in: *Journal of Economic Perspectives*, 7(4): pp. 11-25.
- Nordhaus, W.D. (1994a),
Expert Opinion on Climate Change, in: *American Scientist*, January-February.
- Nordhaus, W.D. (1994b),
Managing the Global Commons: The Economics of Climate Change, Cambridge, MA: MIT Press, forthcoming.
- Nordhaus, W.D. and G.W. Yohe (1983),
Future Carbon Dioxide Emissions from Fossil Fuels, in: National Research Council, *Changing Climate*, Washington: National Academy Press.
- Office of Management and Budget (OMB) and US Department of Agriculture (USDA) (1989),
Climate Impact Response Functions, Report of a Workshop Held at Coolfont, West Virginia, Sept. 11-14.
- Ominde, S.H. and C. Juma (1991),
A Change in Weather, African Centre for Technology Studies, Nairobi: ACTS Press.

- Ottinger, R.L., D.R. Wooley, N.A. Robinson, D.R. Hodas and Susan E. Babb (1990),
Environmental Costs of Electricity, Pace University Centre for Environmental and Legal Studies, New York: Oceana Publications.
- Page, T. (1977),
Conservation and Economic Efficiency, Baltimore: Johns Hopkins University Press.
- Parikh, J (1994), [REF TO COME]
- Parry, M. (1990),
Climate Change and World Agriculture, London: Earthscan.
- Parry, M. (1993),
Climate Change and the Future of Agriculture, in: *International Journal of Environment and Pollution* 3(1-3): 13-30.
- Parry, M.L., M. Blamant de Rozari, A.L. Chong and S. Panich (1991),
The Potential Socio-Economic Effects of Climate Change in South-East Asia, Nairobi: United Nations Environmental Programme, Nairobi.
- Parry, M.L., T.R. Carter, and N.T. Konijn, eds. (1988),
The Impacts of Climate Variations on Agriculture, 2 Volumes, Dordrecht: Kluwer.
- Pearce, D.W. (1986),
Cost-Benefit Analysis, London: Macmillan.
- Pearce, D.W. (1992),
The Secondary Benefits of Greenhouse Gas Control, Global Environmental Change Working Paper GEC 92-12, Centre for Social and Economic Research on the Global Environment, University College London and University of East Anglia, Norwich.
- Pearce, D.W. (1993),
Economic Values and the Natural World. London: Earthscan.
- Pearce, D.W. (1994),
Costing the Environmental Damage from Energy Production, Mimeo, Centre for Social and Economic Research on the Global Environment, University College London and University of East Anglia, Norwich.
- Pearce, D.W., G. Atkinson and R. Dubourg (1994),
What is Sustainable Development?, in: *Annual Review of Energy*, forthcoming.
- Pearce, D.W., and D. Ulph (1994),
Estimating a Social Discount Rate for the United Kingdom, Mimeo, Centre for Social and Economic Research on the Global Environment, University College London and University of East Anglia.
- Peck, S.C. and T.J. Teisberg (1992),
CETA: A Model for Carbon Emissions Trajectory Assessment, in: *Energy Journal* 13(1): 55-77.

- Peck, S.C. and T.J. Teisberg (1993a),
CO₂ Emissions Control: Comparing Policy Instruments, in: *Energy Policy* 21(3): 222-230.
- Peck, S.C. and T.J. Teisberg (1993b),
Global Warming Uncertainties and the Value of Information: An Analysis Using CETA, in: *Resource and Energy Economics* 15(1): 71-97.
- Penner, J.E., R.E. Dickinson, and C.A. O'Neill (1992),
Effects of Aerosol from Biomass Burning on the Global Radiation Budget, in: *Science* 256(5 June): 1432-33.
- Pernetta, J.C. (1989),
Projected Climate Change and Sea-Level-Rise: A Relative Impact Rating for the Countries of the Pacific Basin, in: J.C. Pernetta and P.J. Hughes (eds.), *Implications of Expected Climate Changes in the South Pacific: An Overview*, UNEP Regional Seas Reports and Studies 128, United Nations Environmental Programme, Nairobi.
- Pernetta, J.C. (1992),
Impacts of Climate Change and Sea Level Rise on Small Island States, *Global Environmental Change*, 2(1), 19-31
- Peters, R.I. and T.E. Lovejoy, eds. (1992),
Global Warming and Biological Diversity, New Haven: Yale University Press.
- Pezzey, J. (1994),
The Optimal Sustainable Depletion of Non-renewable Resources, Mimeo, Department of Economics, University College London.
- Ramsey, F.P. (1928),
A Mathematical Theory of Saving, in: *Economic Journal* 138(152): 543-559.
- Raper, S.C.B. (1993),
Observational Data on the Relationships between Climate Change and the Frequency and Magnitude of Severe Tropical Storms, in: W.W. Warrick, E.M. Barrow and T.M.L. Wigley (eds.) *Climate and Sea Level Change*, Cambridge University Press, Cambridge.
- Reilly, J., J.A. Edmonds, R.H. Gardner, and A. L. Brenkert (1987),
Uncertainty Analysis of the IEA/ORAU CO₂ Emissions Model, in: *Energy Journal*, 8(3): 1-29.
- Reilly, J. and N. Hohmann (1993),
Climate Change and Agriculture: The Role of International Trade, in: *American Economic Review, Papers and Proceedings* 83(2): 306-312.
- Reilly, J., N. Hohmann and S. Kane (1994),
Climate Change and Agricultural Trade: Who Benefits, Who Loses?, in: *Global Environmental Change* 4(1): 24-36.

- Revelle, R.R. (1983),
Probable Future Change in Sea Level Resulting from Increased Atmospheric Carbon Dioxide, in: National Research Council, *Changing Climate*, Washington, DC: National Academy Press.
- Rijkswaterstaat (1991),
Rising Waters. Impacts of the Greenhouse Effect for the Netherlands, Dutch Ministry of Transport and Public Works, The Hague.
- Rijsberman, F. (1991),
Potential Costs of Adapting to Sea Level Rise in OECD Countries, in: OECD, *Responding to Climate Change: Selected Economic Issues*, Paris: OECD.
- Rijsberman, F. and R.J. Swart, eds. (1990),
Targets and Indicators of Climate Change, Stockholm Environment Institute, Stockholm.
- Rind, D., D. Glodberg, J. Hansen, C. Rosenzweig, and R. Ruedy (1990),
Potential Evapotranspiration and the Likelihood of Future Drought, in: *Journal of Geophysical Research* 95(D7): 9,983-10,004.
- Ritchie, J.T., B.D. Baer, and T. Y. Chou (1989),
Effect of Global Climate Change on Agriculture: Great Lakes Region, in: US Environmental Protection Agency, *The Potential Effects of Global Climate Change on the United States*, Washington, DC: EPA.
- Roberts, L. (1991),
Costs of a Clean Environment, in: *Science* 251 (8 March): 1182.
- Rosebrock, J. (1993),
Time-Weighting Emission Reductions for Global Warming Projects - A Comparison of Shadow Price and Emission Discounting Approaches, Mimeo, The World Bank, Washington, DC.
- Rosenberg N.J. (1992),
Adaptation of Agriculture to Climate Change, in: *Climatic Change* 21(4): 385-405.
- Rosenberg, N.J. et al. (1989a),
Policy Options for Adaptation to Climate Change, Resources for the Future Discussion Paper ENR 89-05, RFF, Washington, DC.
- Rosenberg, N.J., W.E. Easterling III, P.R. Crosson, and J. Darmstadter, eds. (1989b),
Greenhouse Warming: Abatement and Adaptation, Washington, DC: Resources for the Future.
- Rosenberg, N.J., and P.R. Crosson (1991a),
Processes for Identifying Regional Influences of and Responses to Increasing Atmospheric CO₂ and Climate Change - the MINK Project, Resources for the Future, for US Department of Energy, TR052A, Washington, DC.

- Rosenberg, N.J. and P.R. Crosson (1991b),
The MINK Project: A New Methodology for Identifying Regional Influences of, and Responses to, Increasing Atmospheric CO₂ and Climate Change, in: *Environmental Conservation* 18(4): 313-322.
- Rosenthal, D.H., H.K. Gruenspecht, and E.A. Moran (1994),
Effects of Global Warming on Energy Use for Space Heating and Cooling in the United States, Mimeo, US Department of Energy, Washington, DC (March).
- Rosenzweig, C. and D. Hillel (1993),
Agriculture in a Greenhouse World, in: *National Geographic Research & Exploration* 9(2): 208-21.
- Rosenzweig, C. and M.L. Parry (1994),
Potential Impact of Climate Change on World Food Supply, in: *Nature* 367(13 January): 133-138.
- Rosenzweig, C., M. Parry, K. Froberg, and G. Fisher (1993),
Climate Change and World Food Supply, Environmental Change Unit, Oxford.
- Rothenberg, J. (1993),
Economic Perspectives on Time Comparisons, in: C. Nazli (ed.), *Global Accord: Environmental Challenges and International Responses*, Cambridge, MA: MIT Press.
- Ryan, B.F., I.G. Watterson and J.L. Evans (1992),
Tropical Cyclone Frequencies Inferred from Gray's Yearly Genesis Parameter: Validation of GCM Tropical Climates, in: *Geophysical Research Letters*, 19 (18): 1831-1834.
- SAARC (1992),
Regional Study on Greenhouse Effect and its Impact on the Region, Report, South Asian Association for Regional Cooperation, Kathmandu.
- Schelling, T.C. (1983),
Climatic Change: Implications for Welfare and Policy, in: National Research Council, *Changing Climate*, Washington, DC: National Academy Press.
- Schelling, T.C. (1992),
Some Economics of Global Warming, in: *American Economic Review* 82(1): 1-14.
- Schelling, T.C. (1993),
Intergenerational Discounting, Mimeo, University of Maryland, College Park (November).
- Scheraga, J.D. and N.A. Leary (1994),
Costs and Side Benefits of Using Energy Taxes to Mitigate Global Climate Change, in: *Proceedings of the 86th Annual Conference*, National Tax Association, Washington, DC.
- Scheraga, J.D., N.A. Leary, R.J. Goettle, D.W. Jorgenson, and P.J. Wilcoxon (1993),
Macroeconomic Modelling and the Assessment of Climate Change Impacts, in: Y. Kaya, N. Nakićenović, W.D. Nordhaus and F. Toth (eds.), *Costs, Impacts and Benefits of CO₂ Mitigation*, IIASA Collaborative Paper Series, CP93-2, Laxenburg, Austria.
- Schlesinger, M.E. and X. Jiang (1990),
Simple Model Representation of Atmosphere-Ocean GCMs and Estimation of the Time Scale of CO₂-induced Climate Change, in: *Journal of Climate* 3(December): 12.
- Schneider, S.H. (1994),
Detecting Climatic Change Signals: Are There Any "Fingerprints?", in: *Science* 263(21 January): 341-47.
- Schneider, S.H. and R. S. Chen (1980),
Carbon Dioxide Warming and Coastline Flooding: Physical Factors and Climatic Impact, in: *American Review of Energy* 5: 107-40.
- Schneider, S.H. and N.J. Rosenberg (1989),
The Greenhouse Effect: Its Causes, Possible Impacts, and Associated Uncertainties, in: N.J. Rosenberg, W.E. Easterling III, P.R. Crosson, and J. Darmstadter (eds.), *Greenhouse Warming: Abatement and Adaptation*, Washington, DC: Resources for the Future.
- Scott, M.F. (1989),
A New View of Economic Growth, Oxford: Clarendon Press.
- Sedjo, R.A. and A.M. Solomon (1989),
Climate and Forests, in: N.J. Rosenberg, W.E. Easterling III, P.R. Crosson, and J. Darmstadter (eds.), *Greenhouse Warming: Abatement and Adaptation*, Washington, DC: Resources for the Future.
- Seroa da Motta, R. (1994), [REF TO COME]
- Smith, J.B., S. Ragland, and E. Trabka (1993),
Standardized Estimates of Climate Change Damages for the United States, Mimeo, RCG/Hagler Bailly, Boulder, CO (December).
- Smith, J.B., F.D. Stern, C.A. Yermoli, and W.S. Breffle (1994),
The Impact of Climate change on Thermoelectric Power Use in Egypt and Poland, Mimeo, RCG/Hagler Bailly, Boulder, CO (February).
- Smith, K. (1992),
Environmental Hazards. Assessing Risk and Reducing Disaster, London: Routledge.
- Solomou, S. (1990),
The Impact of Climatic Variations on Construction Cycles and Economic Activity, 1856-1913, Mimeo, University of Cambridge (August).
- Spash, C. (1994),
Double CO₂ and Beyond: Benefits, Costs and Compensation, *Ecological Economics*, 10, 27-36.
- Sundquist, E.T. (1990),
Long-Term Aspects of Future Atmospheric CO₂ and Sea-Level Changes, in: R.R. Revelle et al., *Sea-Level Change*, National Research Council, Washington, DC: National Academy Press.

- Titus, J.G. (1987),
The Causes and Effects of Sea Level Rise, in: H.G. Wind, *Impact of Sea Level Rise on Society*.
- Titus, J.G. (1991),
Greenhouse Effect and Coastal Wetland Policy: How Americans Could Abandon an Area the Size of Massachusetts, in: *Environmental Management Journal* 15(1): 39-58.
- Titus, J.G. (1992),
The Cost of Climate Change to the United States, in: S.K. Majumdar, L.S. Kalkstein, B. Yarnal, E.W. Miller, and L.M. Rosenfeld (eds.), *Global Climate Change: Implications Challenges and Mitigation Measures*, Pennsylvania: Pennsylvania Academy of Science.
- Titus, J.G., R.A. Park, S.P. Leatherman, J.R. Weggel, M.S. Greene, P.W. Mausel, S. Brown, C. Gaunt, M. Trehan, and G. Yohe (1991),
Greenhouse Effect and Sea Level Rise: The Cost of Holding Back the Sea, in: *Coastal Zone Management* 19: 172-204.
- Tol, R.S.J. (1994a),
The Damage Costs of Climate Change: A Note on Tangibles and Intangibles Applied to DICE, in: *Energy Policy* 22(5): 436-438.
- Tol, R.S.J. (1994b),
The Damage Costs of Climate Change: Towards More Comprehensive Calculations (revised version), Working Document W94/7, Free University Amsterdam, forthcoming.
- Tol, R.S.J., C. Dorland, E. van der Hul, F.P.M. Leek, A.A. Olsthoorn, P. Velinga and P.E. van der Werff (1994),
Climate, Extremes, Risk and Risk Management, Mimeo, Institute for Environmental Studies, Free University Amsterdam.
- Turner, R.K., P. Doktor, and N. Adger (1993),
Sea Level Rise and Coastal Wetlands in the UK: Mitigation Strategies for Sustainable Management, in: A.M. Jansson, C. Folke, R. Costanza, and M. Hammer (eds.), *Investing in Natural Capital: The Ecological Economic Perspective*, Covelo, CA: Island Press.
- Turner, R.K., S. Subak, N. Adger and J. Parfitt (1994),
How are Socio-Economic Systems Affected by Climate-Related Changes in the Coastal Zone? A Report to IPCC Working Group II, Subgroup B, Centre for Social and Economic Research on the Global Environment (CSERGE), University of East Anglia and University College London.
- UK Climate Impact Review Group (1991),
The Potential Effects of Climate Change in the United Kingdom, Report prepared at the Request of the Department of the Environment, London: HMSO.
- US Environmental Protection Agency (1989),
The Potential Effects of Global Climate Change on the United States, J.B. Smith and D. Tirpak, eds., Washington, DC: EPA.

- US Environmental Protection Agency (1990a),
Progress Reports on International Studies of Climate Change Impacts, Draft, EPA, Washington, DC (November).
- US Environmental Protection Agency (1990b),
Environmental Investments: The Cost of a Clean Environment, EPA, Washington DC.
- US FEMA-FIA (1991),
Projected Impact of Relative Sea Level Rise on the National Flood Insurance Programme, Federal Emergency Management Agency and Federal Insurance Administration, Washington DC.
- Waggoner, P.E. (1990),
Climate Change and US Water Resources, New York: Wiley.
- Waggoner, P.E. et al (1992),
Preparing US Agriculture for Global Climate Change, Report No. 119, Council for Agricultural Science and Technology, Ames, Iowa.
- Waggoner, P.E. (1994),
How Much Land Can Ten Billion People Spare for Nature? Report No. 121, Council for Agricultural Science and Technology, Ames, Iowa.
- Waters, S. (1990),
The Travel Industry World Yearbook: The Big Picture, Madrid: World Tourism Organization.
- Wendland, W.M. (1977),
Tropical Storm Frequencies Related to Sea Surface Temperatures, in: *Journal of Applied Meteorology* 16(5): 477-81.
- Wigley, T.M.L., and S.C.B. Raper (1992),
Implications for Climate and Sea Level of revised IPCC Emissions Scenarios, in: *Nature* 357: 293-300.
- World Health Organisation (1990),
Potential Health Effects of Climatic Change, Geneva: WHO.
- World Resources Institute (1990),
World Resources 1990-91: A Guide to the Global Environment, Vol. 4. World Resources Series. New York: Oxford University Press.
- World Resources Institute (1992),
World Resources 1992-93: A Guide to the Global Environment, Vol. 5. World Resources Series. New York: Oxford University Press.
- Yohe, G.W. (1993),
Sorting Out Facts and Uncertainties in Economic Response to the Physical Effects of Global Climate Change, in: J. Darmstadter and M. Toman (eds.), *Assessing Surprises and Non-Linearities in Greenhouse Warming*, Washington, DC: Resources for the Future.

A Generic Assessment of Response Options

C.J. JEPMA, M. ASADUZZAMAN, I. MINTZER, S. MAYA,
M. AL-MONEEF

Contributors:

*J. Byrne, H. Geller, C.A. Hendriks, M. Jefferson, T.B. Johansson,
G. Leach, A. Qureshi, W. Sassin, R.A. Sedjo, A. van der Veen.*

Draft, 3 October, 1994

CONTENTS

Executive Summary	-
1. Introduction	1
2. A Conceptual Framework	1
2.1 Mitigation Options	2
2.2 Adaptation Options	3
2.3 Indirect Policy Options	3
3. Criteria for Assessment	4
4. Mitigation Options	7
4.1 Energy Conservation and Efficiency Improvement	7
4.2 Fuel Switch between Fossils	11
4.3 Renewable Energy Technologies	13
4.4 Nuclear Energy	14
4.5 Capture and Disposal	15
4.6 Enhancing Sinks: Forestry Options	16
4.6.1 Costs	18
4.7 Methane	21
5. Adaptation Options	21
5.1 Adaptation to what?	21
5.2 How to adapt	22
5.3 Modeling Adaptation	24
6. An Integrated Approach	24
7. Regional Differences and International Policy Cooperation	26
Notes	29
References	

1. Introduction

In recent years a host of response options has been proposed in order to cope with possible climate change. These options can be classified in many ways, including by technology, by sector, by impact, and by strategic approach. This chapter is based on classification by strategic approach, i.e., Mitigation, Adaptation, and Indirect Policy Options. Many response options were thoroughly discussed in WG II (notably WG IIa, Second Assessment Report, Energy Supply Mitigation Options) with a major emphasis on technological feasibility. Some aspects of these options will be taken up here and generically assessed, i.e. not only from an engineering efficiency but also from a welfare economic point of view.¹

The present chapter focuses on a generic assessment of response options to deal with the greenhouse problem, and aims to survey the set of options feasible from a comparative economic perspective in order to assess scope and priorities of the policies. The main purposes are:

- to set up a structure so that the various options can be put into proper perspective and the assessment to be made can be truly generic (section 2);

- to discuss the various criteria that can be used in assessing the options, and the degree to which different criteria can produce different choices in terms of optimal use of the options (section 3);

- to review the various options in terms of (technical and practical) applicability, cost-effectiveness, and social acceptability, both as far as mitigation options (section 4), and adaptation options (section 5) are concerned. Special attention will be given to the case of the developing countries and countries in transition, because of their particular circumstances;

- to evaluate the scope for integrating response options, in particular with respect to mitigation options, on the basis of information about regional cost functions (section 6);

- to analyze to what extent information currently available about various options might provide a

basis for international policy cooperation (section 7).

Sections 1-3 therefore provide the methodological base; sections 4-5 survey the mitigation and adaptation options, and sections 6-7 deal with response options and policy application.

2. A Conceptual Framework

The next conceptual diagram shows the various feedbacks and policy options available to counter the greenhouse effect.

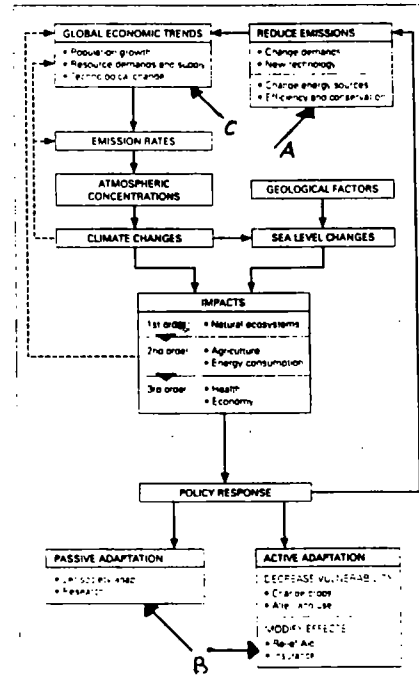


Figure 1. Schematic overview of options available to counter the greenhouse effect and their feedbacks.

Source: Viner and Hulme, 1994, p.7.

The diagram may serve to illustrate, that one can basically distinguish between three strategic categories of options in order to deal with the greenhouse issue:

a) mitigation options (block A in the figure), i.e. options that amongst others strive to prevent climate change, or combat any reinforcement thereof, by reducing the net emissions of greenhouse gases into the atmosphere either by reducing greenhouse gas emissions (source oriented measures), or by increasing the sinks for greenhouse gases (effect oriented measures);

b) adaptation options (block B), i.e. options that focus on reducing the damages due to rapid climate change by combating or avoiding their detrimental effects;

c) indirect policy options (block C), i.e. options that are not directly related to the emission or capture of greenhouse gases, but that can have a considerable indirect effect on energy consumption, greenhouse gas emissions, or greenhouse gas uptake.

Obviously, the various types of options are not mutually exclusive, nor can they be fully separated. Indirect policy options, adaptation options and mitigation options may even reinforce each other, as the following examples may illustrate. A population policy, as part of a broader policy mix, resulting in slowing down population growth in a densely populated country may contribute to finding cost-effective and acceptable opportunities for mitigation options. Similarly, if policies designed to decrease the energy and materials' intensity of economic activity are instituted in a country, many technically feasible options for emission reductions may become cost-effective. Technological progress will obviously improve the scope for adaptation options, etc. For conceptual reasons, however, the above distinction between the various types of options seems a useful starting point.

2.1 Mitigation Options

In the literature about greenhouse policy options, mitigation options receive by far the most attention. Most commonly the various options are discussed separately, and from the engineering perspective. Information about the cost-effectiveness

of the various options, e.g. in terms of \$/tC released into the atmosphere, is rapidly increasing. The marginal cost-effectiveness of the various options is probably highly dependent on the scale of application, the sector and country/region of application, and whether or not additional options are applied. Moreover learning curves, and therefore cumulative application and time, almost invariably play a dominant role in determining the options' economic viability. All these factors point in the same direction, namely that the mitigation options' cost functions may (suddenly) change in the course of time. The same applies with respect to the various options' social and political acceptability. Conclusions about the economic, social and political viability of various are therefore highly scale-, time- and location-specific.

In discussing the potential of the various mitigation options a distinction has been made between measures concerning CO₂ and measures concerning other greenhouse gases, because largely the former are related to the energy-related activities (both energy production and consumption) and the latter to other types of activities. A subsequent distinction is between source-oriented and sink-enhancement measures.

The various categories of mitigation options are (except for some 'exotic', mainly effect-oriented options such as geoengineering, orbital shades, iron fertilization, creating algal blooms and weathering rocks):

a. measures concerning CO₂

1. energy conservation and efficiency improvement
2. fossil fuels switch
3. renewable energy
4. nuclear energy

(1-4 = source-oriented)

5. capture and disposal of CO₂
6. enhancing sinks: forestry options

(5-6 = sink-enhancement)

b. measures concerning other greenhouse gases, such as phasing out HFCs (in addition to (H)-

CFCs, via the Montreal Protocol), and reducing emissions of methane (CH₄), nitrous oxide (N₂O), and other greenhouse gases.

Since the energy sector (in terms of both energy production and consumption) is the single largest source of carbon, much of the mitigation effort can be concentrated here. Options 1-4 each address elements of the energy conversion process from primary energy to end-use services.

Energy conservation and efficiency improvement have in common that both measures aim to reduce total energy use, without changing the current fuel mix or the fundamental structure of the energy conversion process. Here energy conservation is understood as reductions in energy needs resulting from altering, e.g. on the basis of behavioral change, the nature or level of the required energy services. In contrast, energy efficiency improvement will denote reductions in energy needs given these services. Since energy conservation is strongly linked to consumer preferences and behaviour, which makes policies aimed at achieving it more difficult to quantify, most studies focus on energy efficiency.²

A fossil fuel switch alters the mix of fossil fuels in favour of the less carbon-intensive natural gas (and perhaps oil). Nuclear energy substitutes for fossils as primary energy. Renewable energy is characterized by a practically unlimited natural supply, but often potentially severe local environmental impacts. Removal technologies extract carbon from an energy conversion process even before it has entered the atmosphere. Subsequently, the carbon has to be utilized, stored or disposed of.

Option 6 is in essence outside the energy area. It aims at binding carbon after it is combusted and dispersed throughout the atmosphere by combating deforestation or by afforestation.³ It may also refer to activities designed to preserve or enhance carbon uptake by soils.

2.2 Adaptation Options

Adaptation options have two purposes:

- 1) to reduce the damages from climate change
- 2) to increase the resilience of societies and ecosystems to the aspects of climate change that cannot be avoided.

Clearly, adaptation measures are interlinked with mitigation measures. The more one succeeds in limiting climate change, the easier it will be to adapt to it and vice versa. This is notwithstanding the fact that there can be reasons for supporting adaptation measures in their own right.

Three types of adaptation measures are commonly distinguished: protection, retreat, and accommodation.

As far as the costs of adaptation options are concerned, one can either focus on the opportunity cost, i.e. assessing the welfare implications of no action scenarios, or focus on the net investment cost involved with adaptation measures. Since chapter 6 of this report focuses on the former, in section 5 of this chapter we will mainly focus on the latter.

2.3 Indirect Policy Options

Potential climate change is perceived as a problem, mainly because it would interfere with the economic, social, ecological and eventually political system. Just as the precise scope and risks of climate change are subject to uncertainty, so is the future development of technology, resources, organization and structure of the economic and the social and the political system. However, it seems most likely that the changes of the global climate and the structural changes of the economic and political system differ significantly in at least one respect: the speed/time lag of changes to be expected. Whereas possible climate change generally is expected to develop slowly compared to a human lifespan (although exceptions can be possible), the economic, social and political systems change several times within a human lifespan and, as it seems, increasingly so as time progresses.

This poses two fundamental dilemmas when assessing the various response options to climate change: the slowly changing climate system has to be superimposed on a rapidly changing economic, social and political system, and the latter system is in constant flux due to numerous factors, with (potential) climate change being only one of them. Both dilemmas significantly complicate the assessment process, and even more the process of formulating policy options based thereon. However, recent history has taught that if there is a strong political consensus about the need to take action, such actions can well be undertaken rather vigorously (e.g. Montreal Protocol, CITES).

Indeed, climate and ecological change are by no means the only factors that will enforce a deep modification of the present economic situation, and that may pose serious dilemmas to society. Other evolutionary trends and structural adjustment processes - e.g., due to: population growth, urbanization, information technologies and their dissemination, the international mobility of labour and capital, the competition for natural resources, and the pattern and speed of technological progress - may be expected also to play an important role in shaping the economic, political and social system of tomorrow, especially if policy makers' time horizon is at most a few decades if not shorter. To illustrate, Western nations may well face a combination of problems such as urban decay, unemployment, massive international migration, changing patterns of economic competitiveness, that may easily attract more public and political attention than the climate change issue.

All these problems already call for response options, for instance in the sphere of consumption and lifestyle policies, population and migration policies, technology and environmental policies, structural and sectoral adjustments or trade policies, or of redistribution policies. Virtually all these policies will also, albeit indirectly, greatly affect energy use and thus the global climate.

An effective climate change response strategy should therefore pay attention to possibilities to join climate change response options with responses to other socio-economic transition phenomena, so as to increase the probabilities of implementing 'no-regrets' policies, i.e. climate change policies that will not be regretted even if climate change would not occur.⁴

Examples of the latter can especially be found in applications of the integrated systems approach. For instance, at present in many developing countries crop agriculture is highly dependent on energy use, both directly and indirectly, for much of which farmers have to depend on outside sources; in addition, such agricultural systems like those based on high-yielding varieties of wheat and rice are often monocultures. Other options, like low-external input sustainable agriculture, are proclaimed to not only lower the need for external and energy-intensive inputs, but also to increase productivity in farming, while at the same time taking care of any concern for national food security (Reijntjes et al., 1992).

3. Criteria For Assessment

In discussing the assessment of response options, the application possibilities of the options themselves are evaluated, not the policies, such as imposing performance standards, that may be expected to cause the various options to be applied or withdrawn. Insofar as the assessment of the policies is concerned, the reader is referred to chapter 8.

From a methodological point of view one can basically distinguish between two fundamentally different approaches for assessing response options. On the one hand the financial costs of the various technologies can be expressed in terms of CO₂ emission reduction/absorption. This could be called the 'engineering efficiency' approach. On the other hand an assessment of the various options could be made in the tradition of welfare economics. According to this line of thinking,

determining the costs and benefits of the application of any particular technology should include an assessment of the opportunities foregone by the allocation of the resources. This could be called the 'welfare economic' approach.

An afforestation program may serve to illustrate the above point. What investment has to be made to achieve a predetermined target in terms of net CO₂ absorption during some time interval? In the tradition of the engineering efficiency approach, one will then try to determine the discounted value of the costs of disposing of the land, tree planting, maintenance, guarding etc. Any future (sustainable) harvesting returns will equally be discounted, so that the net levelized costs can be determined in dollars. On the basis of this information, and by comparing this option with other options' cost-efficiencies, one can decide whether or not to proceed.

However, if the welfare economic approach is taken, the overall assessment may be quite different. By using the land for afforestation purposes, the possibility to use the same land for agricultural purposes is foregone. It therefore matters a great deal if the area has agricultural potential or not. If so, the local population may well be forced to migrate or else to suffer income losses. Moreover, the afforestation program if applied at a large scale may have additional impacts, either positive or negative, e.g. through its effect on the local climate and soil fertility, on the social and cultural life, on the infrastructure, on tourism, etc. In the assessment attention can also be paid to the distortionary impact of government measures, such as subsidies and taxes, on the efficiency of the forestry option. If all the direct and indirect welfare consequences of the envisaged afforestation program are going to be assessed, an extensive and complicated social cost-benefit type of analysis may well be called for, accepting that not all aspects can be quantified or monetized.

A priori, there is no reason why the outcomes of the engineering efficiency and welfare economic

assessment of the same project would coincide. The costs of the land in money terms may not fully reflect the land-use opportunity costs in welfare terms because in the former no full account is taken of: indirect effects, immaterial consequences, distributional impacts, and externalities.

In short, the major distinction between the cost assessment methodology in both approaches is, that the engineering efficiency approach basically starts from the evaluation of a project from the narrow perspective determined by the project boundaries, whereas the welfare economic approach attempts to fully take account of the various interests within and between societies, including the external effects, and of the social and political acceptability of options.

In actual practice, even public agents may not be fully aware of the various externalities and indirect, immaterial and distributional impacts of the application of response options. For one reason they may not want to take the various aspects into account, for instance under the influence of particular pressure groups; for another reason the information required for a full welfare assessment may simply be insufficient, so that decision making is hampered. What is more, even if all information for assessing the various options is available, obstacles in setting up the institutional capacities can pose serious bottlenecks, so that appropriate action will not follow, a process which also may contribute to explaining the existence of private no-regrets options.

The practical obstacles for a welfare economic assessment of climate change response options are large, particularly in the developing countries and countries in transition. One, the policy priorities especially with respect to the greenhouse issue will often differ from those in industrialized countries. Two, information about externalities at the local level may not or not fully reach the public sector due to limitations in communication and data; vice versa policies dealing with externalities may fail to reach part of the local population for various rea-

sons. Three, virtually all developing countries face a severe lack of human capacity to deal with these issues.

The general impression arises that optimism about technology potential is larger in the engineering efficiency approach than in the welfare economic approach; in the latter approach the emphasis is more on the obstacles in society to absorb and apply new technologies. This distinction can be related to the various aspects of the economies of scale concept:

- average costs may diminish at a larger scale of application (internal economies of scale);
- costs may diminish at a larger scale of application of other options, because of positive external effects (external economies of scale);
- costs may diminish as the application time progresses (learning effects);
- costs may increase at a larger scale of application due to increasing resistance and bottlenecks, related to social, political and environmental concerns, and to increasing opportunity costs;
- costs may increase, because achieving the required rate of diffusion of technologies, public education and lifestyle changes may become increasingly difficult at larger scale.

If one would focus on a-c mainly, optimism about the options' economic potential may rise. This is the perspective taken by the engineering efficiency approach. If, however, one would instead focus on a-e, one might easily tend to take a much more pessimistic view, exemplifying the welfare economic perspective.

A separate issue in comparing the feasibility of the various options is that the various studies differ in the extent to which energy costs and benefits of the options are taken into account. The application of some options, such as capture and disposal, requires a significant amount of energy inputs, often denoted energy penalties; other options, such as nuclear or renewable energy, besides achieving

a carbon emission target, also produce energy and are therefore substituting for traditional fossil energy resources. The former implies that one could distinguish between gross and net energy costs, the latter being gross costs minus the benefits of avoided fossil energy production. In TNO (1992) both cost functions have been derived for the EU; differences between gross and net costs turned out to be notably relevant for the options of energy saving, renewables, nuclear energy and energy farming (see figure 2).

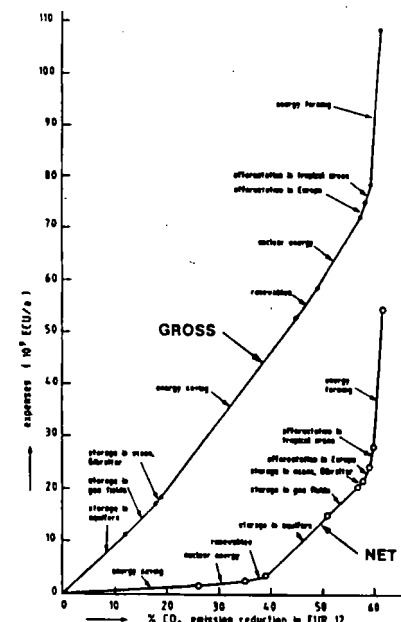


Figure 2. Options for CO₂ emission reduction in the EU, net and gross costs, and effectiveness.

Source: TNO, 1992, p.5.

A comparable issue is how costs have to be ascribed to the various targets that are achieved with the help of the investment made. More often

than not, investments made for economic and/or environmental reasons, have changes in greenhouse gas emission as a side-effect. Many no-regrets options belong to this category. The question then becomes how to precisely relate the investment costs to the greenhouse effect.

In any case, from the above it is clear that an assessment based on the engineering efficiency approach alone may easily create a biased view. A more complete assessment must recognize different priorities within countries, the impact of externalities, the political acceptability at various levels, and distributional aspects. In this respect it seems that, although both approaches raise analytical concerns which need to be addressed, a high priority item for both should be to pay attention to the special position of developing countries as well as of countries in transition.

4. Mitigation Options

This section will treat mitigation options as listed in section 2 in some detail, along with their costs and potential.

4.1 Energy Conservation And Efficiency Improvement

In order to put the energy efficiency option into a proper perspective, the Kaya identity (Yamaji et al., 1991) may provide a useful starting point for discussing energy:

$$CO_2 = (CO_2/E) \times (E/GDP) \times (GDP/P) \times P,$$

E = energy consumption; GDP = gross domestic product; P = population.

If population growth is given, and the future levels of GDP per capita are predetermined, a given CO₂ emission reduction target can only be achieved by a reduction in carbon intensity (CO₂/E) and/or energy intensity (E/GDP). The need to reduce carbon and energy intensities becomes stronger, the higher the growth rate of

population and the more ambitious targets are set with respect to GDP increase. The latter points obviously reinforce the need to pay specific attention to developing countries.

Historically, in most countries carbon and energy intensities have tended to decline due to ongoing technological change and evolution. Energy intensity per unit of value added has been decreasing at a rate of about 1% per year since the 1860s and at about 2% per year (even 2.6% in IEA member countries during 1980-1984) in most Western countries since the 1970s (Nakicenovic et al., 1993, p. 406). However, the differences between the various countries are enormous, both in terms of the levels of energy intensity and its direction in the course of time. The differences between a number of developing countries and most of the industrialized countries are particularly striking: the current energy intensity in China, to give just an example, is much higher than in virtually all presently industrialized countries a century ago; the same applies, albeit to a lesser extent, to a country like India (Nakicenovic et al., 1993, p. 408). Moreover, in contrast to the postwar trend noticed in industrialized countries, some developing countries do not succeed in reducing energy intensities.

Indeed, within each group, countries do vary in terms of the capacity, whether potential or realized, to restrict carbon emission through energy efficiency. Moreover, within a given country, not all sectors have similar energy efficiency. During 1973-1988 the estimated energy intensity in Japan fell by more than 35% (Ogawa, 1992); to illustrate, during 1973-1987 energy intensity of electric refrigerators fell by nearly 67% more efficient; the efficiency of motorcars increased from around 9.4 to about 13 km/litre (49%). During the same period, the USA, (the then) West Germany and France lowered their energy intensities by 27%, 22% and 17% (IEA member countries by 25%, IEA/OECD, 1991). In most cases it is industry where changes have been most apparent.

Over the 1980s, various developing countries managed to lower industrial energy intensity: China by more or less than 30% (Huang, 1993), Taiwan between 1970-1985 by some 40% (Li, Shrestha and Foell, 1990), and the Republic of Korea by 44% (Park, 1992). However, in other countries, such as Nigeria (Nakicenovic et al., 1993), Egypt (Abdel-Khalek, 1988), Mexico (Guzman et al., 1987), and during 1970-1988 (Imran and Barnes, 1990) Brazil (+20%), Pakistan (+26%), India (+25%), and Malaysia (+48%), energy intensity in the past actually increased.

Changes in aggregate energy intensity must be viewed with caution, however, as they depend on how energy use and economic output are measured. In Brazil, for example, official figures show overall energy intensity remaining roughly constant during 1973-1988. However, if hydropower is counted based on its direct energy content and GDP is corrected to reflect purchasing power parity with the dollar, then overall energy intensity declined 21% during 1973-1988 (Geller and Zylbersztajn, 1991).

Global carbon intensity, the other variable in the Kaya identity, also shows a declining trend: during 1860-present carbon emissions per unit of primary energy consumed have come down by about 0.3% per year, or from over 0.8 to somewhat over 0.5 tC/kWyr (Nakicenovic et al., 1993). Clearly, decarbonization can be achieved by a variety of options, such as a fossil fuels switch and substituting fossil fuels by nuclear and renewable energy. However, various projections with respect to developing countries indicate that without serious policies and changing trends, not only total emissions will increase rapidly, but also that carbon emissions may increase faster than GDP because demand for energy services is switching from regenerating biofuels to fossil fuels (for India for instance see Mongia, Bhatia, Sathaye and Mongia, 1991).

The two underlying factors of reduced energy intensities are improved energy efficiency of ind-

vidual production processes and structural changes in the economy (in particular, the increasing weight of less energy intensive sectors and the energy efficiency of the spatial structure). Only a few studies explicitly incorporate the impact of structural changes (most focus on energy efficiency measures).³ For example, it was estimated that energy efficiency improvements were responsible for about three-quarters of the 26% reduction in US energy intensity during 1973-1986 (Schipper, Howarth and Geller, 1990).

Disregarding the impact of structural shifts on the energy intensity in an intercountry comparison may easily create a biased view, because the present industrialized nations generally experience a structural shift of the economies from a highly energy-intensive secondary to less energy-intensive tertiary sectors ('dematerialization'), whereas the developing countries in general are entering more and more the secondary sectors.

Among virtually all studies, there is broad consensus on the virtue of energy efficiency improvement. Moreover, it is seen as directly beneficial irrespective of greenhouse warming coming true, so emissions reductions are achieved at a negative net cost (no regrets policy).

One basic reason why the energy efficiency improvement potential is considered substantial is that the useful energy (i.e. energy insofar as it provides useful services) to overall primary energy (i.e. energy as recovered or gathered directly from natural sources) ratio is estimated at 34% only at a global level; lowest with 22% in the developing countries and the highest in the countries in transition with 42% (Nakicenovic and Grübler, 1993). These data reflect the final energy (energy carriers delivered to the point of consumption) to primary energy ratio (global average: 74%; highest in the developing countries: about 80%; lowest in the countries in transition: 69%) times the much smaller, on the average, useful to final energy ratio (global average 46%; only 28% in the developing countries, some 60% in the countries in transition,

and almost 53% in the industrialized countries). This suggests that the scope for energy efficiency improvement is particularly promising with regards to increasing useful to final energy. Efficiencies are lowered further if seen from an 'exergy' point of view, i.e. if the actual services (work) supplied by the energy source are related to the corresponding inputs minimally required: exergy efficiency of primary inputs in the market economies is only a few percent!

Indeed, a back-of-the-envelope calculation shows, that if energy efficiencies of the current vintage structure of the OECD would be disseminated throughout the world, global primary energy requirements would come down by 17% from 12 to 10 TWyr/yr; if instead the best available technologies would replace instantaneously the current energy system worldwide, without altering the energy system structure, global annual primary energy requirements would decline to 7.2 TWyr/yr (Nakicenovic and Grübler, 1993). A similar exercise assuming that Japanese industrial efficiency levels were to diffuse globally, shows an estimated industrial carbon reduction potential of some 730 MtC worldwide, mainly in steel, chemical and cement industries (Matsuo, 1991).

Clearly, energy end use is the least efficient part of energy systems, and it is in this area that improvement would bring the greatest benefits. Most studies suggest that a large potential exists in many sectors and regions, while at the same time acknowledging that institutional, economic, and social barriers may delay or inhibit the achievement of full efficiency potentials in the near future. A review of twelve studies of long-term energy efficiency potential found that in many regions of the world, full adoption of cost-effective energy efficiency measures could reduce carbon emissions by 40% or more over the medium- to long-term compared to business-as-usual trends (Geller 1994). An illustrative example is IEA/OECD (1991) as shown in table 1. In this respect it should be mentioned that there have recently been consider-

able policy and regulatory reforms which have begun to address some of these barriers. In the US, for example, more than 30 states have adopted or experimented with regulatory reforms since 1989 to promote demand-side management (DSM) opportunities and to encourage integrated resource planning (IRP).

Other studies focus on the energy efficiency improvement potential by analyzing major energy end use, e.g. Blok et al. (1991), OTA (1991), COSEPUP (1991), Goldemberg (1988), Kaya et al. (1991), Gupta and Khanna (1991), ESCAP (1991), or focus on specific sectors. To illustrate, recent estimates for the US show energy saving potentials of 45% in buildings, 30% in industries, and 30% in cars (Rubin et al., 1992; DeCicco and Ross, 1993). In rural areas of developing countries, to give another example, the efficiency of wood and charcoal-fueled cook-stoves can be increased from 10-20% to 25-35% using improved stove designs at a capital cost of under \$10. Cooking efficiency can be further increased to 40-65% by shifting from biomass-based fuels to kerosene, LPG, or electricity, but at a significantly higher capital cost (US Congress, 1992).

Energy efficiency gains may be particularly promising in the following sectors: power production, transportation, steel and cement production, and residential. However, the relative ranking of sectors in terms of energy efficiency improvement potential is highly dependent on whether or not both the direct and indirect requirements of energy are taken into account, i.e. if interindustry demands are included during sectoral comparisons. A comparative study on India (Parikh and Gokarn, 1993) shows for instance that if direct carbon emission due to fossil fuel use is considered, then electricity generation tops the list of the total emission (1/3 of total). However, if direct and indirect emissions are taken into consideration, the construction sector emerges as the largest carbon emitting sector in India (22% of total).

The issue of energy conservation and efficiency

Table 1

Energy Efficiency Potential: Summary of Opportunities and Barriers

	(A) Estimated Share of Total Final Consumption	(B) Estimated Share of Total CO ₂ Emissions	(C) Total Energy Savings Possible	(D) Existing Market/Inst. Barriers	(E) Potential Energy Savings Not Likely to be Achieved
Residential	11.4%	11%	10-50%	Some/Many	Mixed
Space Heating and Conditioning					
Residential	3.4%	3.6%	Mixed	Some/Many	Mixed
Water Heating					
Residential Refrigeration	1.1%	2.1%	30-50%	Many	10-30%
Residential Lighting	0.6%	1.2%	over 50%	Many	30-50%
Commercial Space Heating and Conditioning	6.1%	6.8%	Mixed	Some/Many	Mixed
Commercial Lighting	1.5%	3.4%	10-30%	Some/Many	Mixed
Industrial Motors	4.5%	9.0%	10-30%	Few/Some	0-10%
Steel	4.1%	4.6%	15-25%	Few/Some	0-15%
Aluminum	8.4%	5.9%	10-25%	Few/Some	0-20%
Pulp and Paper	2.9%	1.2%	10-30%	Few/Some	0-10%
Cement	0.1%	0.9%	10-40%	Few/Some	0-10%
Passengers Cars	15.2%	13.7%	30-50%	Many	20-30%
Goods Vehicles	10.1%	9.1%	20-40%	Some	10-20%

How to read this table: For example, for lighting, over 50% per unit savings would result if the best available technology were used to replace the average lighting stock in use today over the next ten to twenty years. Some of these savings would take place under existing market and policy conditions. But due to the many market and institutional barriers, there would remain a 30-50% potential for savings that would not be achieved.

1. Based on a comparison of the average efficiency of existing capital stocks to the efficiency of the best available new technology. This estimate includes the savings likely to be achieved in response to current market forces and government policies as well as those potential savings (indicated in Column E) not likely to be achieved by current efforts.

2. Extent of existing market and institutional barriers to efficiency investments.

3. Potential savings (reductions per unit) not likely to be achieved in response to current market forces and government policies (part of total indicated in Column C).

4. Energy use only.

Source: IEA/OECD (1991), p. 16.

Table 2.

Regional potentials for reducing industrial carbon emissions by cost categories (in Mt carbon)

	Cost saving or at moderate cost	Cost (<100 \$/t C)	Cost (>100 \$/t C)	Sum
<i>Market economies</i>				
Efficiency improvement	15	45	84	144
Structural change/recycling	95	n.a.	25	120
Fuel substitution	6	n.a.	n.a.	>>6
Process technology change	0	2	98	100
<i>Reforming economies</i>				
Efficiency improvement	48	53	n.a.	>101
Structural change/recycling	185	50	n.a.	>215
Fuel substitution	10	n.a.	n.a.	>>10
Process technology change	0	10	46	56
<i>Developing countries</i>				
Efficiency improvement	12	41	n.a.	>63
Structural change/recycling	19	29	n.a.	>48
Fuel substitution	3	n.a.	n.a.	>>3
Process technology change	0	8	56	64
<i>World</i>				
Efficiency improvement	75	139	84	>298
Structural change/recycling	279	>79	>25	>383
Fuel substitution	19	n.a.	n.a.	>>19
Process technology change	0	20	200	220

*Total reduction potential could be higher because not all measures have been assessed.

n.a. = Not assessed.

Source: Grubler et al. (1993a), p.553.

in the developing countries differs in some respects from the issue in industrialized countries. First, often a substantial part of the demand for energy is met from renewable energy sources like biomass. This is likely to remain so in the short to the medium run; there are estimates to show that the scope for conservation for biomass is enormous in these countries. One reason is that cooking with traditional biomass fuels is very inefficient technically, although not necessarily from a socioeconomic perspective (US Congress, 1992). Second, energy efficiency in industrial activities generally showed little or no improvement (Imram and Barnes, 1990). Third, there are developing countries which have allocated a quarter to a third of public investment to generation of power, and even this is sometimes inadequate to meet the growing demand (World Bank, 1993). However, due to the present low level of energy efficiency in the developing countries and therefore large scope for improvement, the potentials for energy saving in the developing countries are considered somewhat similar in magnitude to those in industrialized countries at present, notwithstanding adverse factors such as the fast growth in commercial energy use and the increasing weight of the industrial sectors (Ewing, 1985; Levine et al., 1991; US Congress, 1992).

By contrast, energy conservation may be achieved somewhat easier in the industrialized countries insofar as less materials and energy consumption patterns are underway. Various indicators do seem to point into this direction.

Much of the discussion seems to increasingly focus on the issue to what extent improved energy efficiency and conservation serves the dual purpose of being now economically viable as well as saving energy and reducing CO₂ emissions (no regret). Optimism about the scope for no regret options generally is much greater among proponents of the bottom-up approach, than amongst those adhering to top-down methodologies.⁴

Various studies have been carried out focusing

on both the potentials for carbon emissions reduction, via energy efficiency improvement, and the net costs involved. As far as the industrial sector is involved, an overview is presented by Grubler et al. (1993a) in table 2, arguing that a potential reduction of 920 MtC (over 40% of current emissions) could be achieved, 372 MtC of which at net negative or modest positive costs (of which about two thirds in the countries in transition). These estimates disregard the potential for fuel switching and for decarbonizing the electricity supply, and assume an annuity rate of 10% throughout the life time of the investment.

The choice of a (financial) discount rate is an important factor in evaluating the cost-effective energy efficiency potential in a particular sector or region. Studies that have tried to assess the implicit consumer discount rates of household investments in energy efficiency reveal ranges varying (depending among others on income classes) from a few percentages only to well over 50%. Train (1985), in his survey, found ranges of: 10-32% for improvements of thermal integrity of buildings; 4.4-36% for space heating and fuel type; 3.2-29% for air conditioning; 39-100% for refrigerators and 18-67% for other home appliances.

So, it is clear that the scope for no regrets options is crucially dependent on the discount factor employed. If one would use for instance a market interest rate for assessing the feasibility of an energy efficiency improving investment or any other rate, e.g. based on normative considerations, whereas the actual investor/consumer applies a much higher rate, one will face the paradox that an option considered no regrets will not materialize, even if access to information, and the availability of human capacity and financial resources would not provide any serious bottlenecks. However, the practical situation especially at the grassroots level in developing countries and countries in transition is such that even the latter conditions are seldomly fulfilled.

For example, how to increase energy efficiency

in the consumption of wood fuels in the developing countries? Here, probably institutional measures and proper extension are quite important. Popularising energy-efficient cooking stoves among hundreds of thousands of households would necessitate efforts at many levels. Suitably designed credits, and if necessary subsidies or tax breaks may help in manufacturing the new stoves in large numbers, but dissemination may be difficult (Hurst, 1990). Non-government efforts in this area may go a long way in solving the problem (Asaduzzaman, 1994).

As a general remark with respect to the above it should be noticed that a high implicit discount rate does not mean that substantial energy efficiency improvements are not possible. Rather it suggests that significant policy intervention will be required to achieve such improvements. For example, in spite of a high implicit discount rate, the average energy efficiency of new refrigerators sold in the United States nearly tripled between 1972 and 1993. This large and steady improvement was due primarily to minimum efficiency standards adopted first at the state level and then at the national level (Geller and Nadel, 1994).

The choice of a discount rate can effect the overall magnitude of energy efficiency improvements that are economical. Meier (1991) argued that assuming an annual discount rate of 10%, more than a quarter of US electricity demand for refrigerators could be reduced by cost-efficient measures; using a 30% rate results in positive costs of all these measures. Similarly, COSEPUP (1991) shows how the percentage savings in electricity at the point where the costs of conserved electricity equals the typical operating costs for an existing US power plant, vary depending on the discount rate: at a 3% rate the electricity saving potential is almost 45%; at a 10% rate some 30%; and a 30% rate some 20%.

Notwithstanding the above, a host of studies has emerged suggesting a considerable scope for no regrets options, especially in the household and

tertiary sector: e.g. Springmann (1991), Mills et al. (1991), Rubin (1992), Jackson (1991), Blok et al. (1993), UNEP (1993 draft), Robinson et al. (1993 draft).

Finally and in addition to the potential of energy efficiency improvement options, there clearly is also considerable scope for conservation options even if their assessment often can only be somewhat qualitative and impressionistic. There seems to be considerable scope for energy conservation in the Western world by imposing stricter standards with respect to energy and materials use, and most of all alterations and adjustments in lifestyles.

4.2 Fossil Fuels Switch

According to most studies the present dominance of fossil fuels in global (primary and non-commercial) energy consumption (1990: 77%) will continue to exist in the next decades to come, e.g. varying between 76 and 66% in 2020 according to the recent, authoritative WEC scenarios⁷ (WEC Commission, 1993, p. 106) (table 3 next).

	1980		1990		in 2020					
	A	B	A	B	A	B	C	D	E	F
Coal	14	23	49	38	30	21				
Oil	10	28	46	45	38	29				
Natural Gas	0.4	1.7	3.8	3.6	3.0	2.5				
Nuclear	—	0.4	1.0	1.0	0.8	0.7				
Large Hydro	0.15	0.5	1.0	1.0	0.9	0.7				
"Traditional"	0.5	0.9	1.3	1.3	1.3	1.1				
"New" Renewables	—	0.2	0.8	0.8	0.8	1.3				
Total	33	8.6	17.2	16.0	13.4	11.3				

Table 3. Energy mix: annual past and future global fuel use (Gtoe).

Source: WEC Commission, 1993, p.106.

All the scenarios reflected in the table show: fossil energy to remain dominant; the share of natural gas, environmentally the least damaging of the fossil fuels, to increase from the present quarter to one third at most, the share of nuclear to remain modest; the relative potential of the presently modest "new" renewables to be not insignificant, as opposed to the limited size of the projected shifts for large hydro and "traditional" energy sources.

The remaining dominance of fossil fuels is due to the large resource base⁸, the strongly vested position in the current vintage of technologies and price distortions that externalize the environmental costs. Estimates point out that even total identified aggregated fossil fuel reserves will suffice to provide for current (1990) levels of energy consumption for the next 130 years.⁹ Obviously, this time span may become considerably shorter as energy use in the developing countries will increase rapidly.

Of the three fossil fuels, natural gas is least and coal is most carbon-intensive.¹⁰ Additional environmental advantages of natural gas are for instance minimal sulfur emissions and virtually no airborne particulates (World Resources 1994-95). Therefore, a switch from coal and/or oil to natural gas is to be seen as a response option with multiple benefits. Current estimates of the natural gas resource base, which will likely be revised upwards in the future, allow for a massive switch-over for the next century or so to come. If so, the entailed transition of current vintage of energy technology would as an additional beneficial side-effect pave the way for a broad diffusion of gas from biomass or coal gasification, or of H_2 , a considered potential (massive) renewable energy later in the next century.¹¹

Costs of this fuel stem from retrofitting or replacing the current vintage of energy technology and in some cases building additional transport grids to connect (remote) urban areas with gas fields. Estimates of the costs of switching even without extending the existing networks, vary to a large extent depending on the type of measure. Switching building electricity use from electric resistance heat to natural gas heating (improving overall efficiency by 60-70%) on the one hand would, according to Rubin et al. (1992), yield a net benefit of \$¹⁰⁰ 90/tCO₂, (assumption: 6% real discount rate). On the other hand, according to the same source, switching coal consumption in industrial plants to natural gas or oil where techni-

cally feasible is expected to involve net direct implementation costs of some \$¹⁰⁰ 60/tCO₂.

According to Van Ettinger et al. (1991, p. 129), the investment costs of exploration and extraction of a fuel switch scenario involving a natural gas supply growth rate of 3.3% per year during 1988-2005 (increasing from 64 to 112 EJ), and of the ensuing extension of the existing network into a global gas distribution system (1989 data from the Dutch Gas Union; average transport distance 2,500 km) would be in the order of \$70 billion gross per year, corresponding to \$70/tC on average.

However, two caveats should be mentioned. First, much of the attractiveness of natural gas as a less carbon-intensive fossil fuel is lost, if a sizeable fraction evaporates into the air by leakage during production and distribution. This is due to the substantially higher global warming potential of methane (CH₄): about 21 times that of CO₂.¹² Estimates of common current leakage rates range between 0.3 and 4% for distribution and between 0.13 to 6% for production (Simpson and Anastasi, 1993).¹³ The break-even point, that is the rate at which the reduced total warming potential is just offset by leakage of methane, occurs at 9%¹⁴ for switching from coal to gas and at 4% for switching from oil to gas (adopting a global warming potential index of 21). These figures point to the need of severely controlling leakage rates.¹⁵ Additional questions are, what happens to leakage rates in case of a large-scale fuel switch and whether leakage rates of newly built and/or additional grids, i.e. marginal leakages, can be reduced.

Second, the costs of the fuel switch option can also be approached on the basis of the opportunity cost concept. The point is now that precisely those countries that may in an absolute sense increasingly contribute to the global greenhouse problem, such as China and India, dispose of massive coal reserves. Consequently, the opportunity costs of fossil fuels switching may be considered large for these countries, especially if the environmental costs of coal are not taken into account.

4.3 Renewable Energy Technologies

Today many technologies have been developed to provide energy on a sustainable basis, in the sense that they harness energy resources that are practically unlimited and require relatively little additional energy input. Moreover, exploitation of renewable energy resources with appropriate technologies has the advantage of releasing relatively little (net) carbon.¹⁶ So, a switch from fossil fuels to renewables will result in reduced absolute greenhouse gas emissions.

However, renewable technologies are not always sustainable in the sense of socially and environmentally benign. Particularly in the case of large-scale applications in developing countries, notably of hydropower, and biomass, adverse effects may arise for the local population. Moreover, adverse environmental side-effects may occur, such as smog by the use of traditional biomass (fuelwood, dung, and crop residues), and acid rain and change in biological habitats and local climate.

The following classes of renewable energy resources are commonly distinguished: solar, wind, hydro, geothermal, ocean, and traditional and modern biomass.¹⁷ To understand the main factors underlying costs and potential of renewables as a group, a detailed treatment of their diversity is required.¹⁸ Most of them are variable in supply (exception: biomass) and some of them (especially traditional biomass, wind, solar) can easily be produced at a small scale and near the spot of consumption; especially the latter aspects determine the (potential) attractiveness of this option in remote and underdeveloped areas.

Further, large differences exist in technical and economical readiness: hydro, wind and traditional biomass are almost mature, whereas some ocean technologies are still in a demonstration stage, though this may in the shorter term be left to tidal and wave technologies. Solar, modern biomass and geothermal are in between, and photovoltaics will probably become competitive with fossil-fuel power plants within a decade or so (Mills et al.,

1991).

Energy technology	Mtoe	% of total
solar	12	0.8
wind	1	0.1
geothermal	12	0.8
modern biomass	121	7.8
ocean	0	0.0
small hydro	18	1.2
new renewables	164	10.5
traditional biomass ^a	930	59.6
large hydro	465	29.8
total	1559	(100)

Table 4. Breakdown of renewable energy technologies in 1990.

^a Includes fuel wood and dung

Source: WEC, 1993, p. 1-17.

Table 4 breaks down the various renewable energy technologies in 1990, and makes clear that traditional biomass and large hydro are the most prominent of renewable energy sources.

Some estimates of 'practicable'¹⁹ potentials (relative to current use) are given in table 5. It clearly shows, how small current use is when related to various estimates of 'practicable' potential, whatever discrepancies thereof may exist. Notable exceptions are (large) hydro and (traditional) biomass, that, according to the data presented, are exploited at about a quarter to half of probable capacity. Judging on these figures only, the scope for renewables is promising. However, a truly comprehensive assessment cannot do without a glance at the costs involved.

Table 6 gives a selective overview of cost estimates of renewable energy technologies. As usual, figures diverge widely. This is mainly due to 1) the calculation method used, and 2) the inherent peculiarities of the technology.

As for 1), the time horizon adopted, the level of discount rate chosen and the capacity and useful life time assumed are important factors. As for 2), costs are strongly influenced by site-specificity and (temporal) variability of supply as mentioned above, and by the form of final energy

Table 5. Current use and practicable potentials of renewable energy technologies (TWh_e/yr).

	solar	wind	hydro	geothermal	ocean	biomass
Current use ^a	54	3.2	2281.2 ^c	37-57	0.6	4713 ^d
Practicable potential estimate:						
Johansson et al. (1993) ¹			6000-9000	53-..		
Swisher et al. (1993) ²	1395	4931	7077	1499	247	8003
WEC (1993) ³	489-1592	20148	8295 ⁴	178-405	48-240	7031-7269

¹ in 2020² in 2030³ in 2020^a Source: Johansson et al. (1993), WEC (1993), Swisher et al. (1993).^b Includes 81.7 TWh/yr for small hydro.^c Includes 211-308 TWh/yr for small hydro.^d 4170 TWh/yr for traditional and 543 for modern biomass.

delivered.²⁰

Other aspects relevant for cost behaviour are learning effects, economies of scale, and the need for immediate storage or transport of the energy generated. The latter occurs not only because of (temporally) non-matching demand, such as in the case of solar and wind, but even more when sources and points of end-use are far apart. Preferably generated electricity should be fed into a linked distribution system of sufficient capacity to handle its intermittent supply.

Current prices of hydro, wind and some solar and biomass technologies as listed in table 6 are already competitive with conventional resources. Looking ahead, substantial cost reductions for virtually all major classes are to be expected within the next few decades.²¹ However, whether they will actually become competitive, is also related to: local conditions that shape a renewable's attractiveness, and complementarity between renewables.

In contrast to fossil fuels' mobility, renewable energy consumption currently seems to be more strongly bound to the production location. Whereas fossil fuels can be relatively easily stored or transported with the existing infrastructure, much of a similar exploitation of the new renewables would require new investment. The competition between renewables is generally more complex than that between fossil fuels. E.g. solar and geothermal energy can only be produced on the basis of complementarity by using temporal variation of supply.

Conversely, what often makes up the main part of a renewable's promise are its large potential and modest price on the spot relative to availability and prices of conventional resources. Moreover, by using local renewables countries could reduce dependence on imported fossil fuels and reduce foreign exchange constraints; in addition, in the case of biomass, local communities could significantly benefit from small-scale applications and their net positive side-effects. In a way parallel to energy efficiency measures, this could come to a

no regrets policy.

There is some reason to believe that a new generation of renewable energy technologies now under development could well become commercially viable in the near future. For example, a variety of promising photovoltaic demand side management technologies designed to shave commercial building demand during periods of utility system peak load is under active consideration in the USA and elsewhere and might become commercially feasible in the foreseeable future (Byrne, et al., 1994; Wenger et al. 1993).

The above discussion implies that the future role of renewables is hard to predict precisely. Though differences exist in optimism, renewables' share in the 2020 energy mix will according to various scenarios probably not exceed 25%.²² However, most studies agree that the new renewable mix will tend to be hybrid, exploiting each resource and backed up by fossil fuels which will remain dominant for the next decades to come.

4.4 Nuclear Energy²³

Nuclear energy now accounts for about 5% of all primary energy production or about 20% of the world's electricity generation. Its production, comparable to that based on renewables, causes overall relatively little CO₂.²⁴ Moreover, its technology has long passed the demonstration stage except for the still unresolved main issue of the storage of nuclear waste. In addition, further dissemination could be strongly prohibited by the lack of public acceptance due to major concerns about reactor safety, the risk of theft of nuclear technologies or materials, the proliferation of weapons-grade nuclear materials and the final storage of fission products.

Bearing these serious limitations in mind, nuclear energy (for comparison with gross costs, see also figure 2), if evaluated on the basis of the engineering efficiency approach, can most likely be competitively applied and in various countries is, albeit to a largely different degree (for an estimate

Table 6. Estimates of current¹ and future costs of renewable energy technologies (US\$0.01 per kWh).

Source	solar	wind	hydro	geothermal	ocean	biomass electric	fuel (\$/GJ)
IEA ²	0-14 ^a 7.6-41.9 (15-174) ^b 5.2-26 (22.6) ^c 5 (50) ^d (all 1984 Ec)	3.5-4.2 ^a (4.48-7.62) (20) ^e		(3.6-9.2)	5-20 ^a (0/kWh) (11.5-50) 6.7-8 ^c		7.58-12.80 (11.85-16.68) 12.70-20.85 ^c 15.64-23.70 ^c
Johansson et al. ³	4.5-11.7 (7.5-32.8) ^a 4.9-9.4 (8.5-28) ^b	3.13-4.46 (4.29-8.4)		3-12 ^a 0.15-2.5 ^c	(5-30) ^a 12-25 ^c 22-30 ^c		1.86-2.73 (2.73-3.86)
Swisher et al. ³	5-10 ^a (12) 4-8 ^a (25) 4-8 ^a (30)	3-6 (7)	5-10 (5)		8-10 ^a	5	6 (8) 7 (13) 10 (15) 1 ^c
WEC ⁴	no storage 0.4-2.5 (0.5-10) ^f 1-11 (1.2-28) ^g 4-14 (28-45) ^h	3-9 (5-10)		n.a.	(5-12) ^a (5-7) ^a (12) ^a (10-14) ^a	n.a.	n.a.

1. current costs in parentheses; 2. 1984; a. passive solar; b. active solar; c. solar thermal; d. solar thermal (low focus); e. solar thermal (point focus); f. solar thermal-electric; g. photovoltaic; h. small/medium wind energy conversion systems; i. large wind energy conversion systems; j. small hydro; k. electric; l. direct heat; m. tidal; n. wave; o. salt gradient; p. ocean thermal; q. ethanol from corn; r. ethanol from sugar; s. ethanol from wood; t. methanol from wood; u. methanol from heritage; v. biomass.

of the UK cost-effective potential, see Jackson, 1991). Because of the long design/construction time (10-15 years) and the enormous investment costs of nuclear power plants, the nuclear option is rather inflexible. According to Mills et al., 1991, p. 540 (see table 7), costs to produce electricity with nuclear energy (\$/kWh) which seem to have been rising and not falling (MacKerron, 1992), are still less than with many of the renewable options considered next.

However, if the nuclear option is assessed from the welfare economic point of view, the final assessment becomes much more uncertain because the lack of public acceptance and the various risks and uncertainties now also have to be taken into account explicitly. This not only holds in the industrialized countries, but probably even more so in the developing countries and the countries in transition. In addition, any future use of nuclear energy will, like any fuel switching to non-fossils, depend on the underlying cross price elasticities and energy price assumptions, inflation, public policy, and technological progress. Recognizing all this, the IEA projects the share of nuclear energy in total energy use by 2010 at 6.1%; the WEC C-scenario (see also note 7) projects the share of nuclear at 6.2% in 2020.

4.5 Capture And Disposal

CO₂ capture and disposal is understood as any sequence of processes in which carbon is recovered from an energy conversion process and disposed of at sites other than the atmosphere. It should be noted though, that disposal is ultimately limited, both for technical reasons, and because not all forms of disposal ensure a permanent prevention of carbon reentering atmosphere. However, assuming sufficient and feasible potential for disposal, the further development of these technologies combined with coal gasification is considered of significant intermediate potential, especially for coal-rich countries such as China. Indeed, should China actually consume 2 billion tons of coal per

year in the next century as some scenarios suggest, it might render almost useless the other efforts to reduce CO₂ emissions globally (Nakicenovic and Victor, 1993, p. 534; see in this respect also the outcomes of the OECD Model Comparison Project as discussed in chapter 8).

Since in general places of recovery do not coincide with places of disposal, transport of the recovered carbon is required as an additional process. In principle, carbon can be recovered from each fossil fuel conversion process. However, recovery is most attractive at energy intensive stationary point sources, such as steel manufacturers, fertilizer industry and power plants, since this is where carbon is most concentrated.²⁵ To date, most research effort was spent on power plants. For these, two types of recovering technologies exist:²⁶ separation of the CO₂ from the flue gases (scrubbing) with or without prior modifications in the energy conversion process. Technologies of the former type, which are now in experiment, are an Integrated Coal Gasifier Combined Cycle (ICG-CC), modification of the boiler and modification of the gas turbine.²⁷ Scrubbing encompasses chemical absorption, membrane separation and cold distillation. Of these, chemical absorption is most developed and membrane separation and cold distillation least.²⁸

Depending on the place of disposal, transport will take place onshore or offshore. Onshore, pipelines are most economical. Estimated costs vary between \$1-4/(CO₂ over 100 km, depending the flow rate (Hendriks, 1994). Offshore, tankers compete with pipelines. For larger distances, tanker transport is likely to be cheaper. Pipeline transport costs are more or less proportional with distance and decrease with increasing flow rate of the gas and lower ambient temperatures. Estimates of costs offshore therefore vary between somewhat more than 1/4 to 3 times the costs onshore (Hendriks, 1994; TNO, 1992).

After the carbon is recovered, it somehow has to be dealt with such that reentrance into the

Table 7.

Examples of avoided emissions and their costs: electricity.				
Electricity*	Measure Resource cost (\$/kWh)	Avoided emissions (g Carbon-eq./kWh)	(%)	Cost of avoided carbon-equivalent (CACeq) (\$/tonne)
Cost of avoided resource results: \$0.44/kWh				
End-use efficiency**				
Available technologies				
Lighting (incandescent → compact fluorescent)	-0.011	318	100	-171
Lighting (efficient fluorescent tube)	-0.007	318	100	-159
Lighting (lamps, ballasts, reflectors)	0.013	318	100	-96
Refrigerator-freezer, no CFCs	0.018	318	100	-79
Freezer, automatic defrost, no CFCs	0.022	318	100	-67
Heat pump water heaters	0.034	318	100	-30
Variable-speed motor drive	0.011	318	100	-102
US field data, multifamily, leaking retrofits	0.038	318	100	-19
Retrofits in 450 US commercial buildings	0.026	318	100	-54
No-cost or behavioural measures	0	318	100	-137
Electricity production† (basin costs)				
Available technologies				
Biomass steam-electric (woodchips)	0.041	318	100	-9
STIG (gasified coal)	0.041	9	3	-313
STIG (natural gas)	0.027	163	51	-103
Wind (1988)	0.054	318	100	33
Solar thermal electric (1988)	0.114	318	100	221
Solar photovoltaics (1988)	0.231	318	100	588
Nuclear	0.057	318	100	41
Emerging technologies				
ISTIG (gasified coal)	0.034	57	18	-176
ISTIG (natural gas)	0.024	187	59	-106
Chemically recuperated gas turbine	0.029	204	64	-73
Solar thermal electric				
(2000)	0.043	318	100	-1
(2010)	0.036	318	100	-24
(2020)	0.031	318	100	-40
Solar photovoltaics				
(2000)	0.072	318	100	89
(2010)	0.050	318	100	22
(2020)	0.036	318	100	-24
Wind				
(2000)	0.033	318	100	-33
(2010)	0.027	318	100	-51
Nuclear - industry target for USA	0.040	318	100	-11
Fuel choice (STIG technology in all cases)				
Avoided resource costs (gasified coal): \$0.071/kWh				
Gasified coal → natural gas (1990)	0.027	155	50	-91
Gasified coal → biomass (sugar) (→2000)	0.033	309	100	-25

Notes: * Unless noted, the annualized costs of efficiency and supply measures are calculated with a 6% real discount rate and no taxes. Costs for electric power plants are amortized over a 30-year period. Efficiencies based on higher heating value (HHV) are used throughout this analysis. The reference (avoided) technology is a coal (2 × 500 MW) steam-electric plant, 34.6% efficiency, \$1370/kW capital cost, and operations and maintenance (O&M) costs of \$0.89/kWh. For all power plant costs: 70% capacity factor, coal price \$1.79/GJ, natural gas price \$2.10/GJ. † Three lighting examples: The first two measures result in a net benefit because reduced labour costs exceed incremental capital costs. (7% real discount rate); Refrigerator and freezer without CFCs: assumes a blend of hydrochlorofluorocarbons (HCFC-22, HFC-152a, and HCFC-124) with 97% lower ozone-depleting potential than the CFC-12 refrigerant currently used. For foam insulation, today based on CFC-11 as a blowing agent, alternatives are based on HCFC-141b and HCFC-123 which in fact have higher insulating values than current foams (7% real discount rate). ‡ Variable-speed motor drive: ABB Corporate Research (personal communication, Lars Gertmar, 1988). Capital cost \$104/kW (750 kW motor). Assumes installation costs equal to 8% of capital cost; 15-year lifetime; 4 000 hours/year; 35% reduction in electricity requirement; Heat-pump water heater: adapted from Brown et al., assuming 2 000 kWh/year reduction in electricity required, 10-year life. § US field data, multi-family space heating: includes measured data from 42 actual projects in the USA. || STIG (Steam-injected gas turbine) for gasified coal: 2 × 50 MW steam-injected gas turbine (STIG), air-blown gasifier, hot-gas clean-up, 35.6% efficiency, \$1 300/kW capital cost and \$0.71/kWh O&M costs; STIG for natural gas: 4 × 51 MW, 40% efficiency, \$410/kW capital cost and \$0.29/kWh O&M costs; Chemically recuperated gas turbines: assumes 54% efficiency, \$500/kW capital cost, 70% capacity factor. ¶ O&M costs assumed same as for gas-fired STIG systems. Biomass-steam \$1 500/kW capital cost, \$0.08/kWh O&M, \$1.5/GJ fuel cost, wind, solar, thermal, and solar photovoltaics. †† These prices are based on the RD&D intensification scenarios developed by five US National Laboratories; Nuclear: see, *op cit*, Ref 7. ‡‡ ISTIG (intercooled STIG) coal: 110 MW, 42.1% efficiency, \$1 030/kW capital cost and \$0.60/kWh O&M costs; gas: 114 MW, 47% efficiency, \$400/kW capital cost and \$0.29/kWh O&M costs; Fuel choice: the coal base-case is gasified coal v natural gas. ‡‡‡ Gasified coal v biomass, 111 MW BIG/ISTIG system. ‡‡‡‡

atmosphere is prohibited or at least delayed as much as possible (not all applications ensure entire or long-term storage of the carbon).²⁰

Disposal can occur in two ways: either it is utilized in (long-lived) productive activities,²⁰ or it is stored underground, in aquifers (almost unlimited potential to store), or in the ocean.²¹ Especially in the latter cases environmental risks seem to be involved, however.

4.6 Enhancing Sinks: Forestry Options²²

Unlike removal options, in options enhancing sinks carbon is removed *after* dispersion in the atmosphere. Although much more carbon is stored in soils (some 700 GT C) than in forests (< 100 GT C) - which suggests significant attention for the range of measures to promote soil conservation, reduce carbon mobilization from soils to air, and increase soil storage of atmosphere carbon through the action of soil microorganisms - the main option to enhance carbon sinks - except for iron fertilization and weathering rocks both still in their experimental stage - relates to forestry measures. This is due to its large expected potential and modest costs, and because it seems to be one of the lowest risk options often with substantial positive side-effects both in the environmental and sometimes also in the socio-economic sphere.

Just as the potential for forestry measures in enhancing sinks is probably sizeable, so is the contribution of deforestation to greenhouse gas emissions. After fossil energy related activities, deforestation and other land use changes are the second largest source of carbon emissions: net annual flux of carbon to the atmosphere as a result of land-use changes and deforestation ranged between 0.6 and 2.8 GtC during the early and probably rest of the 1980s (compare the slightly less than 6 GtC global emissions from burning of fossil fuels, manufacture of cement, and flaring of natural gas).²³ The large amount of uncertainty that exist on net carbon release figures of deforestation and land use changes is due to: the extent of

the area deforested; the carbon content of biota and soils in the deforested land; and the dynamic release profile of biotic and soil carbon after disturbance.

The following subclasses of forestry measures are commonly distinguished: halting or slowing deforestation, reforestation, afforestation,²⁴ and sustainable forest exploitation cum sequestration of carbon in long-lived forest products. The first three measures intend to sequester carbon by increasing the standing inventory of biomass, or by preventing a decrease thereof. This comes to a once-for-all uptake of carbon. In contrast, the fourth measure aims at continuing to break the carbon cycle, thereby in principle enabling permanent application; this option becomes the more efficient if the timber is used to substitute for the more CO₂ emission intensive products, such as bricks, concrete, steel, and plastics.

However, in practice all forestry measures are ultimately limited: the first three by the amount of area available in competition with other potential land uses and the last one by demand for timber and other long-lived wood products growing saturated and by the eventual decay of the wood. Therefore forestry measures, like removal options, are to be seen as intermediate response policy. In this respect it is worth mentioning that trees grown on fairly short rotations (harvest at maximum Mean Annual Increment) are more effective (temporary) carbon sinks than trees which are allowed to mature in old-growth forests. This has large implications, especially for developing countries, where by far the largest demand for wood is for fuelwood and small construction poles which can be grown on short rotations.

In assessing the global potential of halting or slowing deforestation and of reforestation, there are three main fields of uncertainty: 1) the potential for slowing deforestation depends on resolving complex problems which are linked with the large-scale encroachment of human settlers into the (tropical) forests or policy distortions (e.g., below-

cost sales of timber on government lands) leading to deforestation in industrial countries; 2) the potential of the option depends on the amount of area globally available for some kind of forestry measure and 3) of the incremental (i.e. annual) and cumulative carbon uptake/ha²⁵ for the main forest species.²⁶

ad 1. In the literature there is near consensus that in developing countries most deforestation occurs because standing forests are converted to crop and pasture land. This occurs because those intruding the forests consider these to have lower economic value than crop and pasture land. The potential for slowing deforestation is therefore hard to estimate and require to: a) apply effective solutions to highly politicised problems such as inequitable land distribution and lack of secure land tenure; b) apply effective means of increasing the per hectare productivity of crop and livestock production. Solutions are partly technical but mostly economic in nature, including improved price structures for farmers (crop and livestock prices versus prices for inputs such as fertilizer) and better access to markets.

ad 2. Tropical deforestation rates vary widely among the various sources, partly due to different definitions of both tropical forests and deforestation (for a discussion, see Jepma, 1994). According to FAO (1991), annual tropical deforestation for the late 1980s amounted to some 17 million ha; other estimates vary between 3 to 20 million ha. Estimates of global annual biotic carbon fluxes from closed forests during the late 1980s show an equally large variety: ranging between 600 MtC (IPCC, 1992) and 2800 MtC (WRI, 1990) (for an overview see Grüber et al., 1993b, p. 503).

A similar discussion has arisen on the issue of the global land area that would be suitable and available for carbon sequestering plantations. According to Sedjo and Solomon (1989), annually 2.9 GtC of excess atmospheric carbon could be sequestered by approximately 465 million ha of (fast-

growing) plantation forests at a cost of about \$186-372 billion (without employing fast-growing species the area would be several times larger).

Clearly, a large potential exists in the tropics. A recent survey, carried out under the auspices of the Asian Development Bank in 8 Asian countries (Pakistan, India, Sri Lanka, Bangladesh, Indonesia, Malaysia, Vietnam, and the Philippines) clearly indicates not only that climate change is likely to have large and generally adverse impacts on forests and forest ecosystems in the Asia-Pacific region, but also that "forest conservation and afforestation can often be judged to be cost-effective and excellent opportunities for limiting net greenhouse emissions" (Qureshi and Sherer, 1994). However, it should be emphasized once again that much of the land availability will depend on the perceptions of the local population with respect to the most appropriate land use.

Keeping the above in mind, one can compare the above findings with the estimate of Grüber et al. (1993b, p. 510), showing that currently globally 265 million ha would be available and suitable for forest plantations and 85 million ha for agroforestry. Other sources (Winjum et al., 1992, and Centeno, 1992) suggest significantly larger (some 400-1200 million ha) areas, however. These figures are in sharp contrast with the potential in the OECD countries, amounting 15-50 (in future) mln. ha in the EU, mainly due to redundancy of farm lands, and 30-60 mln. ha in the US. Carbon sequestered in global annual wood production is currently estimated at some 1 GtC (TNO, 1992, p. 110). This gives some indication of the potential of carbon sequestration through wood products, depending on the price, product life time and the trend in timber demand (commonly projected to rise). Some authors argue that a considerably higher demand for wood could be achieved if it is used to produce electricity (and liquid fuels such as methanol), thereby replacing fossil fuel CO₂ emissions with a system in which net emissions are zero, provided the wood is grown on a sustainable

basis (for a feasibility study, see BTG, 1994).

ad 3. Only rough estimates exist for the carbon content of biomass and soils in disturbed areas. Estimates of average annual carbon uptake vary considerably, depending among others on plantation age (for a correlation, see Cannell, 1982), timber species, soil/climate conditions, and management practices (see also Houghton, 1991). However, most estimates are in the likely range of 1-8 tC/ha/yr. Cumulative carbon uptake would as a maximum be somewhere between 100 and 150 tC/ha for the main forest types (note that the vegetation and soils of undisturbed forests can hold 20-100 times more carbon than agricultural systems).

4.6.1 Costs

Mitigation policies using forests are generally considered relatively cost-effective especially if applied in developing countries. An early US high cost estimate of Nordhaus (1990) of \$100/tC now seems to have ignored changes in soil carbon through tree planting as well as the rapid growth that could be achieved in young forests. Richards et al. (1993) estimated that the overall costs of stabilizing US carbon emissions could be reduced by as much as 80% by forestry options.

The major part of the studies, dealing with the costs of 1) afforestation or 2) halting or slowing deforestation option, take the engineering-efficiency approach rather than the welfare economic approach. With respect to 1) afforestation the assumption is commonly made that the forests are not harvested but are left alone to mature (the so-called carbon cemetery forests). The emphasis therefore is on the assessment of the costs of afforestation (plantations), maintenance and protection, and of land requirement; however, sometimes land required for establishing carbon plantations is even considered free, therefore implying zero opportunity costs (e.g. Winjum et al. 1992).

One generally recognizes that 2) halting or slowing deforestation probably belongs to the category

of both the most urgent and cost-effective options (Grübler et al., 1993b, p. 499). This impression is reinforced by the fact, that experience with the closest alternative, reforestation, has so far produced mixed results. On the one hand some success stories can be told about reforestation projects in Sweden, Finland and parts of Canada. On the other hand, however, large losses occurred in Angola, Nigeria, Morocco, and several other countries, whereas in China the rate of survival of reforestation efforts is estimated to be not higher than 20% (Nakicenovic and John, 1991).

There are, as it seems, two crucial factors determining the feasibility of the afforestation option in actual practice. First, it matters a great deal if the forest can be harvested (sustainably) and forest products can be sold at commercial rates, or instead should be left alone. Second, much depends on the acceptance of the newly planted forests by the local population, e.g. because they derive an economic benefit from it.

If for instance the forest can be harvested through the exploitation of timber and non-timber products, and if in addition carbon sequestration credit can be given to trees which are harvested, then net costs of afforestation could easily become negative. In that case afforestation would become a no-regrets option and initiatives could possibly except for the problem of the pay back period be left to the market. The problem clearly is, that not all externalities can be incorporated in the prices of the timber and non-timber products (think of environmental benefits from the trees on the one hand, and productive losses due to trees such as shading of or water competition with adjacent field crops on the other hand).

However, even if afforestation cum sustainable exploitation offers a net positive return, many other factors may still form an obstacle. Actual experience has made abundantly clear that, even if environmental quality and economic productivity in a certain area are both low, those who use the land may still be unwilling to convert it to forest.

Some even argue that, for at least a decade social, political, and infrastructural barriers will keep plausible reforestation rates very modest (Trexler, 1991). Indeed, "tropical forestry programs undertaken with global climate change mitigation in mind will need to be integrated into the social, environmental, and economic contexts and needs of the countries (and local communities, ed.) in which they are undertaken. Failure to understand this has brought about the failure of many tropical forestry efforts intended to solve fuelwood and other problems. The same could easily occur with forestry efforts intended to mitigate global climate change" (Brown et al., 1993).

Estimates on the cost-effectiveness of forestry measures in the engineering efficiency approach are subject to uncertainties about availability of land area, carbon uptake per ha, and costs of establishment and maintenance per ha. In addition, figures diverge depending on the methodology adopted. Here, two points should be discussed: 1) derivation of point estimates or of a cost function, and 2) forestry cost function methodology.

ad 1. To date most effort was spent on deriving point estimates from average costs. Some selected cases are given in table 8 and 9. Note that the estimates generally assume 'tree cemeteries'. Tables 8 and 9 show relatively low carbon sequestering costs through tree planting, in many cases under \$10/tC and rarely over \$30/tC. Other studies with similar results stressing various aspects of the problem include Trexler et al. (1989), Swisher (1991), Winjum and Lewis (1993) and Faeth et al. (1993). For a detailed assessment see Turner et al. (1993).

Source	Tropical Agroforest - Plantation	Temperate Plantation	Boreal Plantation - Protection
Andrianto (1993)	3-5	3-6	0-2
Dixon et al. (1993)	4-16	6-60	2-50
Krakunas and Dixon (1993)		1-3	1-4
Houghton et al. (1991)	3-12	4-37	1-3

Source: Adapted from Dixon et al. (1993)

Table 8. Costs of Sequestering Carbon through forest projects: some selected cases (\$/tC).

Source: Adapted from Dixon et al. (1993).

Forest Type/ Practices	Median \$/tC	Median \$/ha
Boreal:		
Natural Regeneration	5 (4-11)	93 (83-126)
Reforestation	8 (3-27)	324 (127-455)
Temperate:		
Natural Regeneration	1 (<1-1)	9 (9-100)
Afforestation	2 (<1-5)	259 (41-444)
Reforestation	6 (3-29)	357 (257-911)
Tropical:		
Natural Regeneration	1 (<1-2)	178 (106-238)
Agroforestry	5 (2-11)	454 (255-699)
Reforestation	7 (3-26)	450 (303-1183)

Interquartile ranges (middle 50% of observations) in parentheses

Table 9. Establishment costs of cost-efficient forestry practices.

Source: Drawn from Turner et al. (1993).

Though these point estimates may give a satisfactorily accurate description of cost-effectiveness for small areas and single plantation programs, they are bound to lack validity in the case of large areas. From a global perspective, the costs in terms of economic welfare are likely to rise with the scale of the effort. Four forces underlie this cost pattern:

- diminishing growth rates as less suitable or less well-managed land is forested, resulting in a lower carbon uptake per ha;
- increasing public resistance and social and

legal objections of the local population against interference with land use plans.

c. rising establishment costs due to higher opportunity costs as plantation establishment moves from fallow land to land suitable for alternative uses;³⁷

d. no or negligible economies of scale in operating and maintenance costs;

All but d) tend to enhance marginal costs; the potential of d) to offset the trend is generally absent. Hence, marginal costs will generally increase as more area is being forested. Exceptions to this rule might only occur if the amount of land needed for agriculture shows a declining trend. Clearly this is almost nowhere the case in developing countries and countries in transition, but it might hold for parts of the Western world. Only recently a number of somewhat more sophisticated studies have begun to appear, that do take increasing marginal costs explicitly into account.³⁸ This way also better justice is done to the welfare economic point of view by explicitly recognizing that an expansion of the area forested most likely will increasingly interfere with the expanding domestic request for agricultural land. Table 10 sketches this feature.

apparent that only for low levels of sequestering effort do figures correspond roughly. For higher levels, divergence rapidly grows wider. Therefore, the conclusion seems justified, that point estimates though valid for small areas, seriously fail to describe actual costs for larger areas.

ad 2. Recently, a number of forestry studies have begun to appear employing a somewhat more sophisticated methodology than before. These include Moulton and Richards (1990), Adams et al. (1993) and Parks and Hardie (1992). These studies have refined the approach of estimating the cost of establishing carbon sequestering tree plantations in three ways. First, they estimated a cost function, not a point. Second, they refined the tree plantation establishing cost estimate, recognizing differences associated with location and site considerations. Third, they built discounting procedures into the methodology, a common practice in the assessment of other options, but virtually ignored until recently with respect to this option. Keeping all this in mind, it is clear that both the methodology and the empirical estimates of the various studies are still amenable to further revision. It is probably an accurate generalization to state that the newer research is tending to find a somewhat steeper increase in costs than did the earlier studies, with the costs per tC roughly doubling, from about \$30 to \$60/tC, for large annual uptakes.

Finally, it is increasingly recognized that there are probably limits to the extent to which the global system can maintain forest stocks: it may be most useful to view tree planting as a measure to buy time. Richards (1993) has pointed out that the expected life of carbon sinks may be limited and therefore asked the question of how transitory sinks are to be valued, if at all.

In sum, although the methodology and empirical estimates have come a long way in the past five years, there are still issues that have not yet been addressed and/or completely resolved.

Table 10. Estimates of cost of carbon sequestered by tree planting; some comparative results for the US.

When comparing tables 8 and 9 with table 10, it is

Study	Total Carbon Sequestered (million tons per year)			
	140	280	420	700
	\$/ton			
Moulton/Richards (1990)	\$16.57	20.69	23.24	34.73
Adams et al. (1993)	18.50	25.11	37.21	95.06
Parks/Hardie (1992)	175.00	n.a.	n.a.	n.a.

Source: Moulton and Richards (1990), appendix table 1A; Adams et al. (1993) TABLE 1, page 79; Parks and Hardie (1992), Figure 2, p. 40.

4.7 Methane

After CO₂, methane (CH₄) most likely accounts for the largest anthropogenic contribution (about 18%) to greenhouse warming, although there is still considerable uncertainty about methane emissions.³⁹ Major sources of anthropogenic methane are: losses from the production and distribution of natural gas, releases from coal mining, from ruminant animals and from paddy rice production. For natural gas in distribution most of the losses occur from leaks in the pipework. The remaining losses stem from routine maintenance, pressure release valves and non-efficient end-use applications. In production losses are due to leakage at wellheads and gas treatment plants, venting and incomplete flaring operations and exploration and drilling activities.

Data available for 1984 on the fraction of vented and incompletely flared gas released during production of natural gas reveal wide discrepancies between the various regions: 1% in North America, 2% in Europe and CIS, 11% in Asia and Australia, 18% in Central and South America, 40% in Africa and 61% in the Middle East (!) (Fung et al., 1991).

The information currently available about methane leakage in distribution is also rather scanty. According to some authors, methane releases from gas production and transportation in the CIS and Eastern Europe may well be by far the largest sources of emissions, accounting for perhaps 50% of total global emissions (Ebert et al., 1993). Others, however, suggest that much of these losses may be explained by 'errors' in accounting. For example, in Bangladesh in the 1980s a rapidly increasing share of total gas was unaccounted for, that had risen from about 1% in 1981 to 10% by 1990. A report on these losses identified as causes of the increasing loss besides leakage: inaccurate meter reading, excessive use in unmetered connections and unauthorized gas connections.⁴⁰

According to Van Amstel et al. (1993), currently available techniques allow for a 70% reduction of

methane emissions from coal mining (particularly gassy mines). Future techniques may increase the figure up to 90%. For oil and natural gas many techniques are available as well.

Rubin et al. (1992) estimate the costs: of eliminating US paddy rice production at about \$0.5/-tCO₂; and of reducing US ruminant animal production by 25% at \$2/tCO₂ (for a crude overview of the technological options for reducing methane emissions from different source sectors and their capital needs, see also Van Amstel et al., 1993, p. 28).

5. Adaptation Options

There are no comprehensive surveys of the various adaptation options and their costs, probably because adaptation covers such a broad range of potential action and also because of the large uncertainties surrounding these options. Therefore, no more than fragmentary information can be provided.⁴¹

When talking about adaptation, a few questions have to be born in mind: 1) what impacts to adapt to; 2) how to adapt; and 3) when to adapt. In this section only the first two questions will be considered; likewise, no attention will be given to the aspect of insurance, which could be viewed as an adaptation option in its own right (see in this respect also chapter 6). The question of when to adapt is one of implementing no regrets adaption options now (e.g., developing drought-resistant cultivars and techniques) and of weighing the implementation of mitigation options now against adaptation options in the future. In the literature hardly any attention has been paid to any possible trade-off between both types of options. The section concludes with some remarks on modelling adaptation.

5.1 Adaptation to what?

Climate change may cause accelerated sea level rise, possibly attended with floods or hurricanes, changes in regional temperature, an increase in

TABLE 11. Agricultural Yield Changes 2xCO₂ (percent of Gross Agricultural Product)¹

region/scenario ^a	model ^b	UKMO			GISS			GFDL			avg.	avg.	diff.
		1	2	3	1	2	3	1	2	3	2+3 ^d	1 ^c	avg. ^f
OECD-A		-20.0	-5.0	-5.0	-5.0	+10.0	+10.0	-5.0	+10.0	+10.0	+5.00	-10.00	-15.00
OECD-E		+5.0	+5.0	+5.0	+10.0	+10.0	+10.0	-5.0	-5.0	-5.0	+3.33	+3.33	0.00
OECD-P		+7.5	+7.5	+7.5	+7.5	+7.5	+7.5	+7.5	+7.5	+7.5	+7.50	+7.50	0.00
CEB&SU		-7.5	-7.5	-7.5	+22.5	+22.5	+22.5	+7.5	+7.5	+7.5	+7.50	+7.50	0.00
M-E		-22.5	-22.5	-7.5	-7.5	-7.5	-7.5	-7.5	-7.5	-7.5	-5.00	-12.50	-7.50
L-A		-22.5	-22.5	-8.5	-15.0	-15.0	-1.0	-10.0	-10.0	+4.0	-8.83	-15.83	-7.00
S&SEA		-20.0	-20.0	-10.0	-10.0	-10.0	0.0	-10.0	-10.0	0.0	-8.83	-13.33	-4.50
CPA		-7.5	+7.5	+7.5	+7.5	+22.5	+22.5	+7.5	+22.5	+22.5	+17.50	+2.50	-15.00
AFR		-20.0	-20.0	-20.0	-7.5	-7.5	+7.5	-15.0	-15.0	0.0	-6.67	-14.17	-7.50

Notes: ^a After Rosenzweig et al. (1993); cf. also Fischer et al. (1993), Rosenzweig and Parry (1994) and Reilly (1994).
^b The climate change scenarios used are the equilibrium 2xCO₂ experiments according to the General Circulation Models of the United Kingdom Meteorological Office, the Goddard Institute for Space Studies and Geophysical Fluid Dynamics Laboratory.
^c The scenarios concern no adaptation (1), minor shifts (2) and major shifts (3) in behaviour.
^d The average of adaptation scenarios 1 and 2 over the three models.
^e The average of the no adaptation scenario over the three models.
^f The difference between the averages described under notes c and f.

Source: Tol (1994), p.5

1 storminess and changes in the run off of river
2 water due to changing precipitation (in terms of
3 mean value and variability). Research on the likely
4 impacts of climate change differs considerably as
5 to the assumptions of scenario building: IPCC
6 (1994) works with one meter sea level rise in 100
7 years, whereas others work with a scenario of 50
8 cm. In addition, the appropriate or adequate
9 response options to be called for differ significantly
10 for all these impacts.

11 Global research on sea level rise is increasingly
12 being carried out (Tol, 1994; Nordhaus, 1993;
13 Cline, 1992a; Frankhauser, 1992, 1993, 1994a and
14 1994b). The World Coast Conference 1993 (IPCC,
15 1994) has pointed to the need to integrate
16 responses to long-term threats such as climate
17 change and associated sea level rise with existing
18 planning and management efforts so as to arrive at
19 Integrated Coastal Zone Management. On the
20 impacts of changes in river discharges, only some
21 scattered information is available. As an example,
22 the discharge of the river Rhine in the Netherlands
23 is predicted to fall by 10 to 15 percent due to an
24 assumed temperature increase of 4°C in the Alpine
25 part of the basin (Kwadijk, 1991 as cited in Pen-
26 ning-Rowell and Fordham, 1994, p.26). However,
27 little research has yet been carried out to combine
28 the effects of changes in precipitation with the
29 effects of temperature rise.

30 A major conclusion in IPCC (1994) is that it is
31 very difficult to differentiate between sea level rise
32 and non-climate related factors, such as subsidence
33 and excessive groundwater abstraction, which may
34 be equally important determinants in relative sea
35 level rise.

36 Finally, effects on agriculture may be caused by
37 regional changes in temperature and by sea level
38 rise. A sea level rise of one meter would affect the
39 supply of rice of more than 200 million people in
40 Asia (IPCC, 1994). Changes in temperature have
41 mixed regional effects (Tol, 1994 based on Rosenz-
42 weig et al., 1993). See table 11.

5.2 How to adapt

Adaptation to sea level rise generally will take
the form of a) retreat, b) accommodation, or c)
protection.

a) Retreat will cause loss of dry land and loss of
wetlands. IPCC (1994) computes that a one meter
sea level rise could threaten 170,000 km² (or 56%)
of global coastal wetlands. Loss of dry land means
losses in agriculture, in forestry, in species and in
assets and implies migration of people. Attempts
to estimate these losses can be found in Ayres and
Walter (1991), Rijsbergen (1991), Frankhauser
(1994a), Cline (1992a and 1992b), Suliman (1990),
Nordhaus (1991b, 1993) and Tol (1994). In some
of these sources, estimates have been made of the
land protection costs insofar as land loss is pre-
vented on economic grounds by coastal infrastruc-
ture etc. An overview of both types of costs (on an
annual basis) is given in table 12.

Annual Costs of Sea Level Rise					
region	Wetlands (mln \$)	Drylands (mln \$)	Protection (mln \$)	Total (mln \$)	Total (% GDP)
OECD-A	5,000	2,000	1,500	8,500	0.15
OECD-E	4,000	500	1,700	6,200	0.14
OECD-P	4,500	4,000	1,800	10,300	0.45
USSR&EE	1,250	1,250	500	3,000	0.07
M-E	0	0	0	0	0
L-A	1,500	500	1,000	3,000	0.35
S&SEA	1,500	1,000	2,000	4,500	0.65
CPA	500	0	500	1,000	0.29
AFR	500	500	500	1,500	0.43

1 All estimates 2502 Source: Tol (1994, p.50).

Table 12. Annual costs of sea level rise.

Not all estimates include the side-effects of
resettling people that used to live on the lost land.
These costs involve the costs of taking up refugees
on the one hand, and of (the hardship of) people
leaving on the other hand. By combining various
sources of information, Tol estimated the global
annual costs of relocating due to sea level rise at
some \$14 billion. These costs vary between 0.01-
0.03% of GDP for the OECD and the countries in
transition, and some 0.3-0.8% for the developing

regions (Tol, 1993, p.52).

b) Accommodation to sea level rise means not only to adapt existing structures to higher sea level but also, e.g., to eliminate subsidence in industrialized countries for building new structures along sea shores and to prevent developers from dynamiting coral reefs to provide souvenirs for tourist. In the state of transition it may involve that countries have to deal with inundation, causing loss of lives, damage to assets, to agriculture and to the environment (Penning-Rowell and Fordham, 1994).

Adaptation to changing river water discharges has the same pattern as adaptation to sea level rise: retreat, accommodation or protection. No global costs are available. For a European example see Penning-Rowell and Fordham (1994).

c) Protection cost estimates against sea level rise differ somewhat: Tol (1994), assuming a 0.5 meter rise, estimates global coastal defence on an annual basis to be \$¹⁹⁹⁰ 9.5 billion; IPCC (1994), assuming a one meter rise, computes costs to be \$¹⁹⁹⁰ 10.0 billion per year; whereas Ayres and Walter (1991, as cited in Winpenny, 1994) derive a figure of \$¹⁹⁹⁰ 50-100 billion.

Protection costs for an increased intensity of storms are not available on a global scale. For the Netherlands protection costs are based on a sea level rise of 60 cm (IPCC, 1994).

Adaptation to changing temperatures mainly involves improving infrastructure and adaption of agriculture and fisheries. Improving infrastructure concerns irrigation/water storage systems, including (small) dams, drainage/sewer systems, dikes and locks, as well as urban building and construction.

In agriculture various types of technical responses are available: change in crop variety; in irrigation, fertilizer and drainage; in crop management; and in farming strategies. Some salt-tolerant crops, to give an example, can be very successfully grown along the shore line of coastal deserts when

irrigated with ocean water. Global estimates for adaptation in agriculture, including shifts per region, are presented in table 11.

Given our still limited understanding of climate change, extending the range of policy options rather than refining technical responses seems to be the most logical. Special attention deserve:

i) capacity building in both industrialized and developing countries, to educate people in the former about the effects of their activities on carbon-trapping biota and people in the latter about responses to effects of natural climatic variability and of potential future climate changes.

ii) changes in land use allocation including developing potential of tropical (plant) species. Since most of the world's plant food comes from only 20 species, the potential of the vast majority of plant species is still to be developed;

iii) food security policies and reduction of post-harvest losses. Post-harvest losses - due to deficient systems of storage and transport - amount in many developing countries to 50% or more, so that a major scope for improvement does seem to exist;

iv) conversion to 'controlled environment agriculture'. Massive introduction of integrated 'controlled environment agriculture' in developing countries, at \$250 per capita as a 'ball park estimate', would require an investment of several hundreds of billion of dollars, or some tens of billions of dollars per annum if introduced over some decades;

v) aquaculture. Climate change affects ocean circulation in the upper layers, upwelling and ice extent, all of which affect marine biological production and hence marine fisheries. One way to adapt is to intensify efforts to develop aquaculture. Integrating aquaculture with 'controlled environment agriculture' has a great potential: recently, dramatic advances in marine biotechnology have been made. The almost sterile, nutrient rich bottom water from Ocean Thermal Energy Conver-

sion (OTEC) systems promises much as culture medium for kelp, abalone, oysters, and a range of fish species.

As a final remark, it should be mentioned that for marginal groups the risks of damages due to climate change will become larger the more unequal the land distribution system is. Changes in land tenure may therefore, as a side-effect, reduce these risks and can be viewed as an indirect adaptation option in itself.

5.3 Modeling Adaptation

Modeling of adaptation to climate change has been done for sea level rise; storminess; and changes in river discharges. A methodology to assess damages can be found in Howe et al. (1991) and in Green et al. (1994). Penning-Rowell and Fordham (1994) present a general methodology for adaptation. Models for flood hazard assessment and management can be found in Klaus et al. (1994). For river zone management, including the institutional setting, Correia et al. (1994) present a framework for analysis.

Two important problems can be mentioned in modeling adaptation. First, the general greenhouse assessment problematic, i.e. the handling of time, uncertainty and discount rate. Second, and specific for adaptation, the valuation of intangibles like wetlands and species is a major problem: a valuation in \$/person costs for threatened species is incomparable with one in \$/km investment costs for coastal protection.

6. An Integrating Approach

A major part of the literature on the response options focuses on the various technologies and their cost-effectiveness within a specific option. Options are then not assessed on the basis of mutual comparison. The main explanation why the 'partial' approach dominates, is probably the limited availability of reliable and accepted data about the options' costs and benefits.

Nevertheless, a truly generic assessment would

require an integrating framework that allows a simultaneous evaluation of the various technologies. If emission reduction targets are to be achieved in an optimal way also in terms of flexibility and spreading of risks, a full picture of all the alternatives should be available. The need for such an integrating approach is reinforced by the fact that evidence suggests that many of the options' cost functions show internal economies of scale (for some evidence with respect to forestry options see e.g. Moulton and Richards (1990), Adams et al. (1993), Parks and Hardie (1992), and Qureshi and Sherer (1994); with respect to energy technologies, see e.g. Kram (1994b), and Southern Centre/Risø (1993); for some broader analysis, see e.g. TNO (1992)). For the implication is that the most efficient option after reaching a certain scale of application, will become more costly than another option and so on.

The need for an integrating approach is further reinforced by the evidence that cost functions per option also differ depending on where the option is being applied. The underlying rationale is the same as why production costs of the same goods and services may differ among the various regions of the world: there are differences between the various regions in supply conditions, levels of technology, infrastructure, etc. Evidence suggests that even within a relative homogeneous area, such as the European Union, marginal emission reduction cost curves differ significantly (COHERENCE, 1991); a fortiori, one can hypothesize that some options can also be significantly more cost-effective if elsewhere applied means in countries in transition or in developing countries (McKinsey & Company, 1989).

A number of studies have been carried out in the tradition of the integrating approach, some of which in the sphere of a 'top-down' approach, aiming at completeness and based on generalized estimates of options' cost functions (McKinsey & Company, 1989; Nordhaus, 1991a; Jepma and Lee, 1994), others more in the 'bottom-up' tradi-

tion, commonly pursuing a greater level of detail (Jackson, 1991; Rubin, 1992; Mills et al., 1991; Kram, 1994b).⁴²

The 'top-down' studies show, that the differences between the various options cost functions for the various regions provide a strong case for jointly implementing the various options, if the ultimate target in terms of CO₂ reduction is to be achieved with the least cost (see also FCCC, Article 4.2.B.). This is irrespective of what parties will take the main responsibility for financing the options.

A general remark is in order here. Often the various sources are not completely clear as to the degree to which opportunity costs, social and institutional barriers and other environmental side-effects have been included in the cost functions employed. As was explained in section 3, cost functions may differ depending on whether they have been designed according to the engineering efficiency approach or the welfare economic approach. This will obviously have a strong impact on integrating assessment. Welfare economic considerations may cause the various options' cost curves to become more or less steep or to shift up or downwards relative to what would otherwise have been the case. In so far as one may assume that welfare considerations all in all will cause various options' cost functions especially of countries in transition and developing countries to shift upward and show steeper slopes than if designed from the engineering efficiency tradition, this may easily reduce the anticipated scope for joint action.

In addition, the global costs of achieving the generally acknowledged long-term emission reduction targets - commonly estimated at several hundreds of billions of dollars per annum - turn out to be rather sensitive to the degree to which one assumes scope for no regrets, especially in the energy conservation and efficiency improvement and in fossil fuels switch.

These studies also indicate that in the optimal case serious attention is paid to applying all

options at the same time and in the various regions albeit to a different degree; the largest potential in overall emission reduction at current cost estimates seems to be in forestry (especially in developing countries), energy conservation and efficiency improvement (especially in OECD and Eastern Europe), and albeit to lesser extent, renewable energy (especially in developing countries) and fuel switch (especially in Eastern Europe, that is if methane leakages can be limited). Needless to say that the optimal mix may easily change due to the ongoing processes of technological progress.

To illustrate, the results of an optimization procedure (LP) applied to cost functions of the various options per region featuring stepwise increasing marginal costs, and based on a combination of various sources (McKinsey & Company, 1989; Jackson, 1991; Mills et al., 1991; and Rubin et al., 1992), have been represented in table 13 (Jepma and Lee, 1994). The table shows the optimal mix of options both in terms of type of options and regions of application if an emission reduction target of -2.4 GtC is to be achieved. (Between brackets the outcomes if marginal costs of the renewable option are assumed 50% of those in the data base, and if marginal costs of the forestry option are doubled compared to the data base, respectively. Obviously, various other sensitivity tests, e.g. on the impact of changing lifestyles, could be carried out.)

A detailed integrating response study in the bottom-up tradition is Kram (1994b). Here an overall assessment is made on the basis of long-term bottom-up country models (MARKAL) for nine Western countries, with more than seventy types of technologies (more than 30 supply technologies and more than 40 end use technologies), which are then integrated. A range of targets for CO₂ emission reductions by 2020 was tested to determine the mix of energy technologies that would produce the reductions at least total energy system cost. The results revealed considerable diversity among these countries in their optimal path, in terms of mix of

energy technologies toward CO₂ emission reduction and in the cost and amount of reductions that could be achieved. This diversity turned out to depend on the various countries future energy needs, existing energy system, natural resources, technology options, and energy policies especially with regard to hydro-electric and nuclear power.

Secondly, the marginal costs of CO₂ reduction during 1990-2020 were calculated for the various countries (see figure 3). The results clearly show that the marginal costs vary greatly among the countries according to their circumstances. If one accepts that the most efficient allocation of emission reductions would be at the point of equal marginal costs, this provides another argument why options should be implemented jointly, irrespective of the issue how the financial burden is shared among the countries.

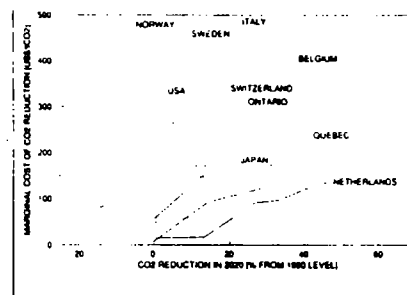


Figure 3. Marginal costs of CO₂ emission reduction for a number of OECD countries.

Source: Kram, 1994a, p. XIV.

7. Regional Differences and International Cooperation

Though the industrialized countries constitute only 25% of the world's population, they account for 72% of the current global energy-related carbon emissions, whereas most of the historical cumulative carbon emissions, i.e. some 80-85% are also due to them (Fujii, 1990). Clearly, this advocates for industrialized countries to assume their historic

responsibility, which has been translated into the concept of 'common but differentiated responsibilities' mentioned in FCCC, Article 3.1 and elaborated in Principle 7 of the Rio Declaration: "... The developed countries acknowledge the responsibility that they bear in the international pursuit of sustainable development in view of the pressures their societies place on the global environment and of the technologies and financial resources they command."

In Table 14 the 1990 situation of the main regions of the world is compared with respect to their economic development in general and their energy use in particular. This comparison highlights the following striking differences between and within regions, and may serve to clarify why the involvement of the developing countries in the greenhouse policy formulation and implementation is imperative:

- The GNP per capita varies from \$440 for Asia to \$17,473 for the West; the ratio is 1:40. The differences can also be large within regions: sub-Saharan Africa has a per capita GDP of \$322 as against \$1,507 for North and South Africa together (1:5).

- The relative use of traditional energy (wood-fuel, crop residues, and animal dung) varies from 1% for the East to 37% for Africa, within Africa this use amounts to 5% for North plus South and 61% for sub-Saharan Africa (1:12).

- The relative use of fossil fuels varies from 57% of total energy use for Africa to 98% for the Middle East; within Africa it amounts to 30% for sub-Saharan Africa and 92% for North plus South-Africa (1:3).

- The relative use of nuclear plus renewables varies from 1% for the Middle East to 22% for Latin America. Within Africa it amounts to 3% for North plus South and 9% for sub-Saharan Africa.

- The share of the main energy source varies from 36% for the East (natural gas) to 64% for the Middle East (oil). For Africa this source is traditional, for Asia coal, and for the West and

Table 14.

Comparison of the 1990 development and energy situations in the main (sub-)regions.													
Region	Tr (%)	Fossil Fuels %					AI (%)	ΣEner (Mtoe)	Popul (million)	GNP (billion US\$)	GNP (\$ per capita)	Toe per capita	Toe per thousand US\$
		Co	Oil	NG	Σ F								
West	1	22	41	19	82	16	4 296	849	14 840	17 473	5 06	0.29	
North America	2	22	38	24	83	15	2 289	276	5 738	20 809	8.30	0.40	
Western Europe	1	22	43	16	80	19	1 456	430	5 901	13 726	3.39	0.25	
JANZ	1	21	51	12	84	16	551	144	3 202	22 279	3.83	0.17	
East	1	25	29	36	91	8	1 745	414	3 047	7 367	4.22	0.57	
Eastern Europe ex-USSR	1	46	25	19	90	9	352	125	388	3 101	2.81	0.91	
	1	20	31	40	91	8	1 393	289	2 660	9 215	4.83	0.52	
North	1	23	38	24	85	14	6 040	1 263	17 888	14 163	4.78	0.34	
Africa	37	21	27	9	57	6	360	642	385	600	0.56	0.93	
North and South Africa sub-Sahara	5	na	na	na	92	3	154	150	227	1 507	1.02	0.68	
	61	na	na	na	30	9	206	492	158	322	0.42	1.30	
Asia	15	49	25	4	78	7	1 475	2 810	1 237	440	0.53	1.19	
China	6	72	15	2	89	5	718	1 139	393	345	0.63	1.83	
India	25	41	23	4	68	7	253	853	287	337	0.30	0.88	
Other	23	19	39	8	66	11	504	817	557	681	0.62	0.90	
Latin America	15	4	45	14	63	22	556	448	842	1 880	1.24	0.66	
Brazil	30	5	34	2	41	29	185	150	375	2 495	1.23	0.49	
Mexico	5	5	49	22	75	20	142	89	170	1 920	1.60	0.83	
Other	9	4	51	20	74	17	228	209	297	1 421	1.09	0.77	
Middle East	1	1	64	32	98	1	233	129	370	2 860	1.81	0.63	
South	17	31	33	10	74	10	2 624	4 029	2 835	704	0.65	0.93	
World	6	25	36	20	81	13	8 664	5 292	20 723	3 916	1.64	0.42	

Sources: BP Statistical Review, 1992 and World Resources 1992-93.

* Tr = traditional (woodfuel, crop residues and animal dung); Co = coal; Oi = Oil; NG = natural gas; ΣF = total fossils; AI = alternatives (nuclear, hydro, wind, geothermal, etc.) (all % of total energy); ΣEner = total energy; (M)toe = (million) tons of oil equivalent; popul = population; GNP = gross national product in 1989.

^b Western Europe = OECD Europe (includes Turkey); Eastern Europe = non-OECD Europe (includes Cyprus, Gibraltar and Malta); JANZ = Japan, Australia and New Zealand.

Source: Van Ettinger (1994), p.12.

Table 13. Base case simulation
Level of emission reduction (Mt/C)

Option	OECD	E-Eur	ROW	Total
1. energy cons. & eff. improvement	250 (250;250)	250 (250;250)	100 (100;100)	600 (600;600)
2. fuel switch	50 (50;50)	50 (50;50)	50 (50;50)	150 (150;150)
3. removal & disposal	100 (100;150)	50 (50;100)	0 (0;50)	150 (150;300)
4. nuclear energy	50 (50;50)	50 (50;50)	0 (0;50)	100 (100;150)
5. renewable energy	50 (100;50)	50 (100;100)	100 (150;150)	200 (350;300)
6. forestry	250 (250;250)	250 (250;250)	700 (550;400)	1200 (1050;900)
Total	750 (800;800)	700 (750;800)	950 (850;800)	2400 (2400;2400)

Between brackets: figures for 50% reduction in marginal costs of renewables over all intervals, and for a doubling of marginal costs of forestry over all intervals respectively.

Marginal costs in optimum: \$50/tC.

Source: Japma and Lee (1994).

Latin America oil.

- In terms of energy use per capita, the regions vary from 0.53 for Asia to 5.06 toe for the West or by 1:10. Between Western subregions it still varies from 3.39 for Western Europe to 8.30 toe for Northern America.

- The energy intensity (in toe/\$1000 GNP) varies from 0.29 for the West to 1.19 for Asia (1:4). Between Western subregions it varies from 0.17 for Japan/Australia/New Zealand to 0.4 for Northern America. However, energy intensity in toe/\$1000 GNP forms an unreliable yardstick for comparisons between regions, especially between North and South because of differences between nominal GNP and real GDP in purchasing power parities (PPP). If the energy intensity data in the table were expressed in toe/\$1000 PPP (correction based on UNDP Human Development Report, 1993 data), the energy intensity of the South would become 0.35 but that of the North would remain 0.34. However, this would still ignore the relatively higher energy content of Southern imports and lower energy contents of its exports. If these two factors are taken into account, Southern energy intensity would be higher than that in toe/\$1000 PPP but probably lower than that in nominal terms (Van Ettinger, 1994, p. 118, note 9).

Most scenarios suggest that during the next decades the growth in carbon emissions will increasingly take place in the developing countries. According to the data summarized in chapter 10 of this report, the mean world annual growth rate of CO₂ emissions for over twenty scenarios is 1.56%, the corresponding mean rate for China is 2.83%, for Eastern Europe and ex-USSR 0.76%, and for Africa 3.85%. Consequently the share of developing countries in global CO₂ emissions is projected to 46% according to ECS'92 (compare OECD 34% and countries in transition 20%); however, according to the various WEC scenarios the developing countries' share in 2020 would be much larger, over 60%. In any case, it seems most likely

that the developing countries as a group will start to become the major CO₂ emittant within a few decades. This picture is reinforced if the emissions of CH₄ from wetland rice cultivation and from enteric fermentation are also taken into account.

At the same time it is clear that, although the scope for effectively applying policy options in the developing countries seems to be significant (for a recent evaluation of various technical options at the country level, see UNEP 1994), so are the obstacles to be encountered. Indeed, the availability of technical options for higher energy efficiency, to give just an example, does not guarantee their adoption on a large scale. There may need to be significant stimulus to achieve widespread efficiency improvements, particularly in markets characterized by high implicit discount rates. But a combination of education, financial incentives, and minimum efficiency standards can effectively transform energy use markets so that large energy savings and emissions reductions are achieved along with net economic savings (Geller and Nadel, 1994).

The literature on adoption and diffusion of technology clearly indicates that while profitability is probably the most straightforward determinant of the adoption of a new idea, technology, or equipment, various other factors may also be important. A review of recent research of diffusion of energy technologies in developing countries shows that there are many financial, institutional and other factors which influence the successful adoption of these technologies (Barnett, 1990; Ghai, 1994). Often the initial awareness about such benefits and new opportunities may be contingent upon such factors as, say, winning over women to introduce more energy efficient cooking stoves. To give another example, research into drought-tolerant crops have had limited diffusion success in Africa due to social resistance.

Moreover, one necessary ingredient for adaptation of technology, namely a pool of local skills to draw upon, may be lacking or be inadequate in

many cases so that even proven technologies may spread rather slowly in these countries. For all these reasons an adequate and timely process of energy efficiency institution building seems imperative, especially in developing countries; there is evidence that the existence of such separate institutions has for instance helped Indonesia, South Korea and Thailand make greater headway in the scope and coverage of energy efficiency policies and programmes (Byrne et al., 1991).

1 The 'engineering efficiency' approach determines the financial costs of various options in terms of
2 CO₂ emission reduction/absorption; in the 'welfare economics' approach the broadly defined costs and
3 benefits of options are determined. These two approaches will be further discussed in section 3.

4 2. For an example on energy conservation, see e.g. Rubin (1992). Here 25% of employer-provided
5 parking places and tax remaining places are eliminated to reduce solo commuting by 15 to 20% in the
6 US. Net costs are estimated to be - \$22/IC (i.e. savings).

7 3. It may seem, that the above categories are not strictly mutually exclusive, that is, measures are
8 conceivable that can be classified in more than one category. An example would be the plantation of
9 forests or biomass, that are used for energy purposes. These measures seem to fall both in category (5)
0 renewable energy and in (6) enhancing carbon sinks. However, this is not the case. The measures are an
1 example of how easily markedly different processes that underlie the measures can be confused.

2 In the case of forests, broadly three types of measures are conceivable in order to fix carbon: 1) to
3 afforest new lands to let the forest simply mature; 2) to plant forest and sequester the timber derived
4 from it; and 3) to use the wood for energy purposes on a sustainable basis, and thereby avoiding the
5 alternative use of fossil fuels. In the following 1) and 2) are discussed in section 4.6 forestry options,
6 whereas 3) belongs to the renewable/biomass category. With respect to 3), it should be born in mind
7 that sometimes a significant amount of additional energy may be required to turn the biomass into
8 energy. This is for instance the case for the production of ethanol from corn, where additional energy
9 requirements are of the order of the energy content of the produced ethanol itself (!) (Swisher et al.
0 1993, p. 442).

1 Another example would be to classify an Integrated Gasification Combined Cycle (IGCC) or the
2 hydrocarb process both in category (1) energy saving and efficiency and in (3) clean fossil technologies.
3 In the present paper both are considered primarily clean technologies and changing the energy conversion
4 process to the extent, that it violates the definition for the energy saving and efficiency category.
5 However, ultimately no clear distinction can be made as modifications in the energy conversion process
6 become minor (due to further technological progress).

7 4. While increasing the probability of a no regrets outcome has obvious advantages, there may also be
8 drawbacks of a distributional nature. See, for example, Byrne et al. (1994).

9 5. For instance, a set of three studies for Poland, Hungary, and the former USSR indicate that a
0 combination of energy efficiency improvements, fuel substitution and structural change (Chandler, 1990),
1 could reduce carbon emissions by 40-60% from base case projected levels by 2030: Poland, from 260
2 MMT in 2030 to 117 MMT (Sitnicki et al, 1990); and the former USSR, -40% (Makarov and Bashmakov,
3 1990).

4 6. For a more detailed discussion on top-down versus bottom-up modelling, reference is made to chapter
5 6 and 7.

6 7. The WEC distinguishes four scenarios for the energy mix in 2020: scenario A assumes high annual
7 world economic growth (esp. in developing countries), high annual energy intensity reduction and very
8 high total energy demand; scenario B1 assumes moderate annual world economic growth rates, moderate
9 annual energy intensity reduction and high possible total energy demand; scenario B, the reference
0 scenario, assumes high annual energy intensity reduction; scenario C assumes moderate annual economic
1 growth, very high energy intensity reductions and relatively low total energy demand in 2020.

2 8. Here a set of definitions is used of Rogner et al. (1993), to distinguish between different levels of
3 geological certainty and economical and technical feasibility. The *resource base* is defined to consist of
4 (proven) *reserves* and *resources*. Reserves are those occurrences that are identified, measured and known
5 to be economically and technically recoverable at current prices and using current technologies.
6 Resources comprise the remainder of occurrences with less certain geological and economic characteristics.
7 Additional quantities with unknown certainty of occurrence or with unknown or no economic
8 significance at present are referred to simply as *occurrences*.

1 9. Total global energy consumption amounted 10 TWyr in 1990, whereas identified fossil energy reserves
2 are estimated at 1,280 TWyr (Rogner et al. 1993, p. 463). Obviously, the use of an aggregate figure for
3 fossil fuels (which is mostly coal reserves) should not obscure the fact that the corresponding time span
4 for the individual fossil fuels differs widely. The ratio of proven Reserves to annual Production (R/P) is
5 estimated at about 55 years for natural gas, at about 45 years for oil, and at about 235 years for coal.

6 10. IPCC carbon emission rates are: 13.8, 18.7 and 26.6 kg of carbon per GJ for natural gas, crude oil
7 and coal respectively (Source: Inaba, 1990, pp. 40-45.)

8 11. This is, because type of transport and combustion technologies are roughly the same for natural gas
9 and hydrogen (H₂).

10 12. Adopting a 100-year time horizon.

11 13. This would imply 3-41% (for distribution) and 1-63% of the carbon reduction of a 100% coal to natural
12 gas fuel switch is offset by the detrimental effects of leakage.

13 14. $BEP = A / ((MER \times GWP) + A)$, with BEP = break-even point, $A = (26.6 - 13.8) \times 3.67$, MER = mass:energy
14 ratio for methane = 22 Tg CH₄/EJ, GWP = global warming potential index of methane = 21, mass ratio of
15 CO₂:C = 3.67, and assuming a zero-leakage rate of methane in coal production; for other figures see note
16 7. Similarly, a 100% oil-to-gas switch shows a break-even point at about 4% leakage.

17 15. See e.g. Jackson (1991) for an analysis of cost-effectiveness in the UK, explicitly incorporating CH₄-
18 leakage.

19 16. In this respect, electricity and hydrogen appear as rather ideal intermittent energy carriers from a
20 technological point of view.

21 17. See e.g. IPCC (1991), Johansson et al. (1993), WEC Commission (1993) or WEC (1994). With
22 respect to the classification of renewables as commonly used, it should be noted that classifying
23 geothermal as a renewable resource is technically not correct as the Earth's core will slowly but surely
24 cool down.

25 18. Solar can broadly be subdivided in solar thermal, solar architecture, solar thermal-electric,
26 photovoltaic systems and thermochemical and photochemical systems. Wind and hydro are relatively
27 homogeneous energy technologies, the largest differences stemming from scale of operation. Here,
28 distinction is made between small/medium scale and large scale conversion systems. In contrast, biomass
29 appears to be the most complex of all technologies. A wide range of conversion technologies exist,
30 depending on the type of feedstock used and the form of energy output required. Geothermal consists of
31 hydrothermal, hot dry rock, geopressed and magma resources technologies. Current ocean technologies
32 encompass tidal, wave, biomass and salt and thermal gradient technologies.

33 19. Different approaches exist to get hold of the concept of 'practicable', i.e. realizable, potential. Most
34 common dimensions of distinction are physical, technical and economical, the ensuing potentials each
35 being a subset of the earlier mentioned one. The physical potential would denote the maximum potential
36 that is constrained by geological and meteorological factors only. Technical potential would refer to that
37 part of physical potential that can be exploited given the state of technology at hand. Finally, the
38 remainder of technical potential after excluding what is not deemed feasible due to prevailing economical
39 constraints (such as a prohibitive level of costs, institutional constraints in the energy markets, etc.) would
40 pass for economical potential. Notice that, for the present purpose, the former of the three can be
41 considered constant in time, whereas the others prevail only at a certain moment.

42 Practicable potential now would be defined as somewhere between technical and economical potential.
43 This is, because the two do not hold independently, but are interlinked in time: e.g. technical potential is
44 enlarged by investments that stimulate technological progress. Conversely, the impact of improvements
45 of, say, silicon films in photovoltaic systems on the price of solar energy is obvious.

20. E.g. wind energy costs depend heavily on wind speed and solar energy costs on solar irradiance, features that are not equally favourable throughout countries (/locations) and seasons (/hours of the day).

21. It is not possible to tell cost developments for individual subclasses of technologies from the enlisted figures, as they are aggregated into ranges of similar technologies. The same holds for disparities stemming from differences of sites. It should be realized, that this significantly hampers a direct comparison. However, a greater sense of detail was avoided for the purpose of clarity.

22. Estimates are 21.3 to 29.6% in 2020 by WEC (1993b), 15% (6% of which hydro) in 2020 by Gröbler et al. (1993) and close to 43% in 2025 by Johansson et al. (1993). According to Gröbler et al. (1993) the latter estimate is most likely too high. It would imply an unprecedented rate of change of technology and infrastructure. For comparison, it took about 80 years for the market share of oil to grow to 40% of global primary energy supply (1) (Gröbler et al. 1993, p. 580). In the past the mean duration for replacing most technological systems was about 30 to 40 years.

23. For an extensive discussion on the nuclear option, see WG IIa, Second Assessment Report.

24. Only relatively minor fossil fuel inputs are used that support the overall functioning of the breed reactor.

25. Recovery of carbon at power plants has the advantage of removing carbon from energy before it is distributed to highly dispersed end-users.

26. As the use of coal and natural gas is predominant in power plants, virtually no technologies are based on oil.

27. In an ICGCC coal is converted prior to combustion. After some intermediate steps, CO₂ and H₂ are obtained. The former can be extracted by absorption at a 98% rate and the latter can either be used directly in the power plant to generate electricity, or as a carbon-lean fuel to be distributed to end-user sectors, like households, industry or transport. Modifying a conventional gas or coal fired boiler comes to changing the oxidant from air into pure oxygen. The gasturbine of an ICGCC or a STEG can be modified by changing the combustion medium into a O₂/CO₂ medium.

28. Cost information suggests absorption and oxyfuel combustion to be most attractive. It appears that absorption is cheaper for natural gas based flue gases than for conventional coal based ones. An ICGCC is promising, though it is not clear yet whether it will replace proven conventional pulverised coal-fired installations.

29. In enhanced oil recovery, part of the injected CO₂ reenters the atmosphere, and in food packaging CO₂ is released within days or weeks. Obviously these applications, though perhaps commercially interesting, are of no significant long-term interest from an abatement point of view.

30. Applications of carbon (dioxide) storage exist in food industry, chemical manufacturing, metal processing and enhanced oil recovery, the latter having the highest potential. In enhanced oil recovery carbon dioxide is pumped into the production well to be used as a miscible flooding. This enhances oil recovery rates.

31. The aggregate potential of the other applications is limited to several hundreds of MtC per year. Storage capacity of the ocean is very uncertain, as it already contains nearly 40,000 GtC as (dissolved) CO₂ (compare with some 750 GtC in the atmosphere) and for environmental reasons. What is more, most of the injected carbon will come out after 50 to several hundreds of years, depending on the depth and way of injection.

32. Here, forestry measures are understood to be distinct from biomass as a renewable energy resource. Forests or biomass could be classified as a renewable energy resource, if harnessed for energy purposes and harvested in such a way, that supply is practically unlimited and no additional energy is required. This means that the plantation is rotated after harvest and net energy inputs for the energy extraction and conversion process are negative, or gross energy inputs are easily paid out of the extracted energy.

Inherently, net carbon emissions (/removal) will be zero for such applications of forests or biomass, since the carbon emitted by combustion is exactly offset by the carbon removed in the next generation of plantations. Only if the forest/biomass energy substitutes for fossil energy, net carbon emissions are reduced.

33. Gröbler et al., 1993, p. 499; see also Houghton, 1990.

34. Afforestation is defined to apply for lands which have not been covered by forests for the last 50 years. In contrast, reforestation applies for lands that have been denuded no longer than 50 years ago.

35. Besides carbon stored in the forest wood itself, soil carbon and carbon in other biomass growing in the forest are included.

36. Cumulative uptake refers to the total amount of carbon stored after a certain period, usually after the forest has reached maturity and no (net) carbon is absorbed anymore, i.e. incremental uptake is nihil. Annual uptake is usually described by one figure only, this being an average annual uptake rate. However, for plantations to be logged before maturity, it should be noted that the absorption rate is dependent on the age of the forest. In contrast to widespread belief, annual uptake is in general not greatest in the first years, but only after the forest has reached an intermediate age. More precisely, accumulated uptake is an S-shaped growth function of time (Nilsson, 1982; Cooper, 1983).

37. Opportunity costs for land would in theory largely be reflected in land market rents.

38. See e.g. Moulton and Richards (1990), Adams et al. (1992) and Parks and Hardie (1992).

39. Known emissions of methane are in the range of 331-850 Tg/yr while the total size of the known sinks ranges between 463-602 Tg/yr (Watson et al., 1992).

40. Task Force Report on Energy, 1991, p. 40.

41. For an overview of the costs of greenhouse damages, see also chapter 3 of this report.

42. Note that the distinction between bottom-up/top-down employed here does not coincide with a similar distinction elsewhere in the literature, where top-down modelling is associated with macro-economic modelling techniques assuming fixed behavioural patterns, and bottom-up modelling with identifying the (technical) opportunities presented by a changeable world.

References

- Abdel-Khalek, G., 1988. Income and Price Elasticities of Energy Consumption in Egypt: A time series Analysis. *Energy Economics*, 1, ...
- Adams, R.M., D.M. Adams, C.C. Chang, B.A. McCarl, and J.M. Callaway, 1993. Sequestering carbon on agricultural land: A preliminary analysis of social cost and impacts on timber markets, *Contemporary Policy Issues*, XI:...
- Amstel, A.R. van, R.J. Swart, M.S. Krol, J.P. Beck, A.F. Bouwman, and K.W. van der Hoek, 1993. Methane, the other greenhouse gas, research and policy in the Netherlands, National Institute of Public Health and Environmental Protection (RIVM), Bilthoven, The Netherlands.
- Asaduzzaman, M., 1994. Energy savings potentials, issues and constraints, Paper presented at the international conference on Joint Implementation, Groningen, 1-3 June 1994. C.J. Jepma (ed.), 1995, *The Feasibility of Joint Implementation*, Kluwer Academic Publishers, Dordrecht, forthcoming.
- Ayres, R.U. and J. Walter, 1991. The Greenhouse Effect: Damages, Costs and Abatement. *Environmental and Resource Economics*, 1, 237-270.
- Baldwin, S.F., 1986. Biomass Stoves: Engineering Design, Development, and Dissemination, VITA, Arlington, VA, USA.
- Barnett, A., 1990. The Diffusion of Energy Technology in the Rural Areas of Developing Countries: A Synthesis of Recent Experience, in: *World Development*, Vol. 18, No. 4.
- Blok, K., 1989. C. Hendriks, W.C. Turkenburg, The Role of Carbon Dioxide Removal in the Reduction of the Greenhouse Effect. *Energy Technologies for Reducing Emissions of Greenhouse Gases - Proceedings of an Experts' Seminar*, 2, 135-156, IEA/OECD, Paris.
- Blok, K., J. Farla, C. Hendriks, and W. Turkenburg, 1991. Carbon Dioxide Removal: A Review, Paper presented at the International Symposium on Environmentally Sound Energy Technologies and their Transfer to Developing Countries and European Economies in Transition (ESETT'91), October 1991, ENI - San Donata Milanese, Italy.
- Blok, K., E. Worrell, R. Culenae, W. Turkenburg, 1993. The cost-effectiveness of CO₂ emission reduction achieved by energy conservation. *Energy Policy*, June 1993, 656-667.
- Biomass Technology Group (BTG), 1994. Potential woodfuel production in developing countries for power generation in the Netherlands, University of Twente, Enschede, The Netherlands.
- Cannell, M., 1982. World Forest Biomass and Primary Production Data, Academic Press.
- Chandler, W.U. 1990: Carbon Emissions Control Strategies, World Wildlife Fund, Washington, DC.
- Cline, W.R., 1992a. The Economics of Global Warming, Institute for International Economics, Washington, DC.
- Cline, W.R., 1992b. Global Warming - The Benefits of Emission Abatement, OECD, Paris.
- Committee on Science, Engineering and Public Policy (COSEPUP), 1991. Policy Implications of Greenhouse Warming: Report of the Mitigation Panel, U.S. National Academy of Sciences, U.S. National Academy of Engineering and Institute of Medicine, U.S. National Academy Press, Washington, DC, USA.
- Cooper, C.F., 1983. Carbon storage in managed forests, *Canadian Journal of Forestry Research*, 13, 155-166.
- Correia, F.N., M. da Graça Saraiva, J. Rocha, M. Fordham, F. Bernardo, I. Ramos, Z. Marques and L. Soczka, 1994. The planning of flood alleviation measures: Interface with the public. *Floods across Europe: Flood hazard assessment, modelling and management*, Penning-Rowell, E.C. and M.H. Fordham, 1994, Middlesex University Press, London.
- DeCicco, J. and M. Rossi, 1993. An Updated Assessment of the Near-Term Potential for Improving Automotive Fuel Economy. *American Council for an Energy-Efficient Economy*, Washington, DC.
- Dixon, R.K., K.J. Andrasko, F.A. Sussman, M.A. Livinson, M.C. Trexler, and T.S. Vinson, 1993. Forest sector carbon offset projects: Near-term opportunities to mitigate greenhouse gas emissions. *Water, Air, and Soil Pollution*, 70, 561-577.
- Dronkers, J., R. Boeye and R. Misdorp, 1990. Socio-economic, legal, institutional, cultural and environmental aspects of measures for the adaptation of coastal zones at risk to sea level rise. *Changing climate and the coast, vol. 1: Adaptive responses and their economic, environmental, and institutional implications*, J.G. Titus (ed.), US, EPA, 1990.
- Ebert, C., D. Picard, P. Pope, and A. Rosland, 1993. Methane emissions from oil and natural gas systems, A methodology to Estimate National Emissions.
- Economic and Social Commission for Asia and the Pacific (ESCAP), 1991. Energy Policy Implications of the Climatic Effects of Fossil Fuel Use in the Asia-Pacific Region, Bangkok.
- Eitinger, J. van, T.H. Jansen, and C.J. Jepma, 1991. Climate, Environment and Development, in: *Sustainable Development, The European Journal of Development Research*, Vol. 3, No. 1, June 1991.
- Eitinger, J. van, 1994. Sustainable use of energy, A normative energy scenario: 1990-2050. *Energy Policy*, February 1994, 111-118.
- Ewing, A.J., 1985. Energy Efficiency in the Pulp and Paper Industry with Emphasis on Developing Countries, World Bank Technical Paper No. 34, Washington, DC.
- Faeth, P., C. Cort and R. Livernash, 1993. Evaluating the carbon sequestration benefits of sustainable forest projects in developing countries. *World Resources Institute Report*, Washington, DC.
- Frankhauser, S., 1992. Global warming damage costs: Some monetary estimates, CSERGE Working Paper GEC 92-29, London and Norwich.
- Frankhauser, S., 1993. The economic costs of global warming: Some monetary estimates. *Costs, impacts and benefits of CO₂ mitigation*, Kaya, Y., Nakicenovic, W.D. Nordhaus and F.L. Toth (eds.), IASA, 1993, Laxenburg.
- Frankhauser, S., 1994a. Global warming damage costs: Some monetary estimates (revised version), CSERGE, London and Norwich.
- Frankhauser, S., 1994b. The economic costs of global warming damage: A survey, CSERGE, London and Norwich.
- Fujii, Y., 1990. Assessment of CO₂ emission Reduction Technologies and Building of a Global Energy Balance Model, Kaya Laboratory, Department of Electrical Engineering, University of Tokyo, Japan.
- Fung, I., J. John, J. Lerner, E. Matthews, M. Prather, L.P. Steele, and P.J. Fraser, 1991. Three-dimensional model synthesis of the global methane cycle. *Journal of Geophysical Research*, Vol. 96, 13033-13065.
- Geller, H.S., and D. Zylbersztajn, 1991. Energy Intensity Trends in Brazil. *Annual Review of Energy and Environment* 16:179-203, Annual Reviews Inc., Palo Alto, CA, USA.
- Geller, H.S., 1994. Review of Long Term Energy Efficiency Potential Throughout the World. *American Council for an Energy Efficient Economy*, Washington, DC.
- Geller, H. and S. Nadel, 1994. Market Transformation Strategies to Promote End-Use Efficiency. *Annual Review of Energy and Environment* 19: 301-46, Annual Reviews Inc., Palo Alto, CA, USA.
- Ghai, D., 1994. Environment, Livelihood and Empowerment, *Development and Change*, Vol. 25, No. 1, Januari, pp. 1-11.
- Go'demberg, J., T.B. Johansson, A.K.N. Reddy, and R.H. Williams, 1988. *Energy for a Sustainable World*, Wiley Eastern Limited, New Delhi, India.
- Green, C.H., A. van der Veen, E. Wierstra and E.C. Penning-Rowell, 1994. Vulnerability refined: Analysing full flood impacts. *Floods across Europe: Flood hazard assessment, modelling and management*, Penning-Rowell, E.C. and M.H. Fordham, 1994, Middlesex University Press, London.
- Grübler, A., S. Messner, L. Schrattenholzer, A. Schäfer, Emission Reduction at the Global Level, 1993a. *Energy - The International Journal*, Special Issue, Long Term Strategies for Mitigating Global Warming: Towards New Earth, Nakicenovic, N., (editor), Laxenburg, IASA, March 1993.
- Grübler, A., S. Nilsson, and N. Nakicenovic, 1993b. Enhancing carbon sinks. *Energy - The International Journal*, Special Issue, Long Term Strategies for Mitigating Global Warming: Towards New Earth, Nakicenovic, N., (editor), Laxenburg, IASA, March 1993.
- Gupta, S. and N. Khanna, 1991. India country paper. *Collaborative Study on Strategies to Limit CO₂ Emissions in Asia and Brazil*, P. Ghosh, A. Achanta, P. Bhandari, M. Damodaran, and N. Khanna (eds.), Asian Energy Institute, New Delhi, India.
- Guzman, O., A. Yunez-Naude and M.S. Wionczek, 1987. Energy Efficiency and Conservation in Mexico, Westview Press, Boulder and London.
- Hendriks, C.A., 1994. New Absorption Technologies, Internal draft, not to be quoted.
- Houghton, R.A., 1990. The future role of tropical forests in affecting the carbon dioxide concentration of the atmosphere. *Ambio*, Vol. 18, 204-9.
- Houghton, R.A., 1991. Tropical deforestation and atmospheric carbon dioxide. *Climatic Change*, 19, 99-118.
- Howe, C.H., H.C. Cochrane, J.E. Bunin and R.W. King, 1991. Natural Hazard Damage handbook, University of Colorado.
- Huang, Jin-ping, 1993. Industry energy use and structural change: A case study of the People's Republic of China. *Energy Economics*, April 1993.
- Hurst, C., 1990. Establishing New Markets for Mature Energy Equipment in Developing Countries: Experience With Windmills, Hydropowered Mills and Solar Water Heaters, *World Development*, Vol. 18, No. 4.
- IEA/OECD, 1987. Renewable Sources of Energy, Paris.
- IEA/OECD, 1991. Energy efficiency and the environment, IEA/OECD Paris.
- Intergovernmental Panel on Climate Change (IPCC), 1991. Climate Change. The IPCC Response Strategies, Island Press, Washington, DC, USA.
- Intergovernmental Panel on Climate Change (IPCC),

1992. 1992 IPCC Supplement, February, Geneva, Switzerland.
- Intergovernmental Panel on Climate Change (IPCC), 1994. Preparing to meet the coastal challenges of the 21st Century, Conference report: World Coast Conference 1993.
- Jackson, T., 1991. Least-cost Greenhouse Planning: Supply Curves for Global Warming Abatement. *Energy Policy*, Vol. 19, No. 1, Jan/Feb 1991, 35-46.
- Jepma, C.J., 1994 (forthcoming). Deforestation in the Tropics: a socio-economic approach, Earthscan, London.
- Jepma, C.J. and C.W. Lee, 1994. Carbon dioxide emissions: a cost-effective approach, Draft paper presented at the Groninger Conference on Joint Implementation, Groningen, The Netherlands.
- Johansson, T.B., H. Kelly, A. Reddy, R.H. Williams, L. Burnham (executive editor), 1993. Renewable energy: sources for fuels and electricity, Island Press, Washington, DC, Covelo, California.
- Kaya, Y., Y. Fujii, R. Matsushashi, K. Yamaji, Y. Shindo, H. Saiki, I. Furugaki, and O. Kobayashi, 1991. Assessment of the Technological Options for Mitigating Global Warming, Paper presented at the IPCC EIS Group Meeting, 6-7 August 1991, Geneva, Switzerland.
- Klaus, J., W. Pflüger, R. Schmidtke, H. Wind and C.H. Green, 1994. Models for flood hazard assessment and management. *Floods across Europe: Flood hazard assessment, modelling and management*, Penning-Rowell, E.C. and M.H. Fordham, 1994, Middlesex University Press, London.
- Kram, T., 1994a. Boundaries of future carbon dioxide emission reduction in nine industrial countries (Executive summary), Energy Technology Systems Analysis Programme, Annex IV: Greenhouse Gases and National Energy Options, Netherlands Energy Research Foundation ECN/International Energy Agency.
- Kram, T., 1994b. National Energy Options for Reducing CO₂ Emissions, Volume I: The International Connection, A report of the Energy Technology Systems Analysis Programme / Annex IV (1990-1993): Greenhouse Gases and National Energy Options, Netherlands Energy Research Foundation ECN/International Energy Agency.
- Kwadijk, J.C.J., 1991. Sensitivity of the river Rhine discharge to environmental change: a first tentative assessment. *Earth Surface Process and Landforms*, 16, 627-37.
- Ledbetter, M. and M. Ross, 1989. Supply Curves of Conserved Energy for Automobiles, American Council for an Energy Efficient Economy, Washington, DC, USA.
- Levine, M.D. et al., 1991. Energy Efficiency, Developing Nations, and Eastern Europe, U.S. Working Group on Global Efficiency, Washington, DC, USA.
- Li, J., R.M. Shreshtha and W.K. Foell, 1990. Structural change and energy use: The case of the manufacturing sector in Taiwan. *Energy Economics*, April 1990.
- MacKerron, G., 1992. Nuclear costs, Why do they keep rising?. *Energy Policy*, July 1992: pp. 641-652.
- Makarov, A.A. and I. Bashmakov, 1990. The Soviet Union. *Carbon Emissions Control Strategies*, W.U. Chandler, World Wildlife Fund, Washington, DC.
- Mathur, A., 1991. Energy and CO₂ Scenarios Developed Within Asian Energy Institute's Collaborative Study, Paper presented at the Workshop on CO₂ Reduction and Removal: Measures for the Next Century, 19-21 March 1991, International Institute for Applied Systems Analysis, Laxenburg, Austria.
- Matsuo, N., 1991. Japan country paper. *Collaborative Study on Strategies to Limit CO₂ Emissions in Asia and Brazil*, Asian Energy Institute (AEI), AEI, New Delhi, India.
- McKinsey & Company, 1989. Protecting the Global Environment, Findings and Conclusions, Appendices, Ministerial conference on atmospheric pollution and climate change, Noordwijk 1989.
- Meier, A., 1991. Supply Curves of Conserved Energy. *Proceedings of the IEA International Conference on Technology Responses to Global Environmental Challenges: Energy Collaboration for the 21st Century*, 6-8 November 1991, Vol. 1, Inter Group Corporation, Kyoto, Japan.
- Mills, E., D. Wilson, T.B. Johansson, 1991. Getting started, No-regrets strategies for reducing greenhouse gas emissions. *Energy Policy*, July/Aug 1991, 526-542.
- Mongia, N., R. Bharia, J. Sathaye and P. Mongia, 1991. Costs of reducing CO₂ emissions from India. *Energy Policy*, 19(10):978-986.
- Moulton, R.J., K.R. Richards, 1990. Costs of sequestering carbon through tree planting and forest management in the United States, USDA Forest Service General Technical Report WO-58, Washington, DC.
- Nakicenovic, N. and A. John, 1991. CO₂ reduction and removal measures for the next century. *Energy - The International Journal*, Vol. 16, No. 11/12, pp. 1347-77.
- Nakicenovic, N. and A. Grübler, 1993. Energy Conversion, Conservation and Efficiency. *Energy - The International Journal*, Special Issue, Long Term Strategies for Mitigating Global Warming: Towards New Earth, Nakicenovic, N., (editor), Laxenburg, IIASA, March 1993.
- Nakicenovic, N. and D. Victor, 1993. Technology Transfer to Developing Countries. *Energy - The International Journal*, Special Issue, Long Term Strategies for Mitigating Global Warming: Towards New Earth, Nakicenovic, N., (editor), Laxenburg, IIASA, March 1993.
- Nakicenovic, N., D. Victor, A. Grübler, and L. Schrautholzer, 1993. Introduction. *Energy - The International Journal*, Special Issue, Long Term Strategies for Mitigating Global Warming: Towards New Earth, Nakicenovic, N., (editor), Laxenburg, IIASA, March 1993.
- Niksson, N.-E., 1982. An alley model for forest resources planning. *Statistics in Theory and Practice*, Essays in honour of Bertil Malm, B. Ranney (ed.), Section of Forest Biometry, Swedish University of Agricultural Sciences, Umea, Sweden.
- Nordhaus, W.D., 1990. An intertemporal general-equilibrium model of economic growth and climate change. *Proceedings of the Workshop on Economic/Energy/Environmental Modeling for Climate Analysis*, D.O. Wood, Y. Kaya (eds.), Oct 22-23, 1990, MIT Center for Energy Policy Research, pp. 415-433.
- Nordhaus, W.D., 1991a. The cost of slowing climate change: a survey. *The energy journal*, 12(1):37-65.
- Nordhaus, W.D., 1991b. To slow or not to slow: The economics of the greenhouse effect. *The energy journal*, July 1991, 101:920-37.
- Norhaus, W.D., 1993. Managing the global commons: The economics of climate change, The MIT Press.
- Office of Technology Assessment (OTA), 1991. Changing by Degrees: Steps to Reduce Greenhouse Gases, OTA-O-842, Congress of the United States, U.S. Government Printing Office, Washington, DC, USA.
- Ogawa, Y., 1992. Analysis of Factors Affecting Carbon Dioxide Emissions due to Past Energy Consumption around the World. *Green House Research Initiatives in the ESCAP Region: Energy*, ESCAP, Bangkok.
- Parikh, J. and S. Gokarn, 1993. Climate change and India's energy policy options: New perspectives on sectoral CO₂ emissions and incremental costs. *Global Environmental Change*, September 1993.
- Park, Se-Hark, 1992. Decomposition of the Industrial Energy Consumption: An Alternative Method. *Energy Economics*, 14(4), October 1992.
- Parks, P.J. and I.W. Hardie, 1992. Least-cost forest carbon reserves: Cost-effective subsidies to convert marginal agricultural land to forest, Washington, DC.
- Penning-Rowell, E.C., B. Peerbolte, F.N. Correia, M. Fordham, C.H. Green, W. Pflüger, J. Rocha, M. Saraiva, R. Schmidtke, J. Torterotot and A. van der Veen, 1992. Flood vulnerability analysis in climate change: toward a European methodology. *Floods and flood management*, A.J. Saul (ed.), Dordrecht, Kluwer.
- Penning-Rowell, E.C. and M.H. Fordham, 1994. Floods across Europe: Flood hazard assessment, modelling and management, Middlesex University Press, London.
- Qureshi, A., and S. Sherer, 1994. Climate Change in Asia: Forestry and Land Use, Asian Development Bank's Regional Study on Global Environment Issues, 1994.
- Reijntjes, C. et al., 1992. Farming for the Future: An Introduction to Low-external-input and sustainable development, McMillan, London.
- Richards, K.M., 1993. Valuation of temporary and future greenhouse gas reductions, presented at Western Economic Association Annual Meeting, Lake Tahoe NV.
- Richards, K.R., R. Moulton, and R.A. Birdsey, 1993. Costs of creating carbon sinks in the U.S. *Energy Conservation and Management*, forthcoming.
- Rijsbergen, F., 1991. Potential Costs of Adapting to Sea Level Rise in OECD Countries. *Responding to Climate Change: Selected Economic Issues*, OECD, Paris.
- Robinson, J., M. Fraser, E. Haites, D. Harvey, M. Jaccard, A. Reinsch, and R. Torrie, 1993. Canadian Options for Greenhouse Gas Emission Reduction (COGGER), Final Report of the COGGER Panel to the Canadian Global Change Program and the Canadian Climate Program Board, Bill Andrews, Sustainable Development Research Institute, UBC, Draft, July 30.
- Rogner, H., N. Nakicenovic, A. Grübler, 1993. Second- and Third-Generation Energy Technologies. *Energy - The International Journal*, Special Issue, Long Term Strategies for Mitigating Global Warming: Towards New Earth, Nakicenovic, N., (editor), Laxenburg, IIASA, March 1993.
- Rosenzweig, C., M.L. Parry, G. Fischer and K. Froberg, 1993. Climate change and world food supply, Environmental Change Unit Research, 3, University of Oxford, Oxford.
- Rubio, E.S. et al., 1992. Realistic Mitigation Options for Global Warming. *Science*, July, 257:148-149, 261-266, American Association for the Advancement of Science, 77.
- Schipper, L., R.B. Howarth and H. Geller, 1990. United States Energy Use from 1973 to 1987: The Impacts of Improved Efficiency. *Annual Review of Energy*, 15:455-504.
- Sedjo, R.A. and A.M. Solomon, 1989. Climate and forests. *Greenhouse Warming: Abatement and Adaptation*, N.J. Rosenberg, W.E. Easterling III, P.R. Crosson, and J. Darmstadter (eds.), Resources for the Future, Washington, DC, USA.
- Simpson, V.J. and C. Anastasi, 1993. Communication, Future emissions of CH₄ from the natural gas and coal industries. *Energy Policy*, August 1993, pp. 827-30.
- Sitnicki, S. et al., 1990. ..., Poland. *Carbon Emissions Control Strategies*, W.U. Chandler, World Wildlife Fund, Washington, DC.
- Southern Centre/Risø, 1993. UNEP Greenhouse Gas

- Abatement Costing Studies, Zimbabwe Country Study, Phase Two, Southern Centre for Energy and the Environment, Risø National Laboratory Systems Analysis Department.
- Springmann, F., 1991. Analysis of the Ecological Impact of Demonstration Projects in the Field of Rational Use of Energy: Development of Evaluation Criteria, Study on behalf of the Commission of the European Communities, Directorate General for Energy (DG XVII), Regio-Tec GmbH, Starnberg, Germany.
- Suliman, M., 1990. Introduction: Africa in the IPCC report. *Greenhouse Effect and its Impact on Africa*, M. Suliman (ed.), Institute for African Alternatives, London.
- Swisher, J.N., 1991. Cost and performance of CO₂ storage in forestry projects. *Biomass and Energy*, 1(6):....
- Swisher, J., D. Wilson and L. Schratzenholzer, 1993. Renewable Energy Potentials. *Energy - The International Journal*, Special Issue, Long Term Strategies for Mitigating Global Warming: Towards New Earth, Nakicenovic, N., (editor), Laxenburg, IIASA, March 1993.
- Task Force on Energy, 1991. Report for the Bangladesh Government, Vol. 3, University Press Limited, Dhaka.
- TNO, 1992. Confining and abating CO₂ from fossil fuel burning - a feasible option?, Rapport voor de EG, TNO, Apeldoorn.
- Tol, R.S.J., 1993. The Climate Fund, Survey of Literature on Costs and Benefits, Institute for Environmental Studies (IVM), Free University Amsterdam.
- Tol, R.S.J., 1994. The Climate Fund: Optimal greenhouse gas emission abatement, Institute for environmental studies, W-94-08, Vrije Universiteit Amsterdam.
- Train, K., 1985. Discount rates in consumers' energy-related decisions: a review of the literature. *Energy*, 16(12):1243-1253.
- Trexler, M.C., P.E. Faeth and J.M. Kramer, 1989. Forestry as a response to global warming: An analysis of the Guatemala agroforestry and carbon sequestration project, World Resource Institute, Washington, DC.
- Trexler, M.C., 1991. Estimating Tropical Biomass Futures: A Tentative Scenario, Proceedings of the Technical Workshop to Explore Options for Global Forestry Management, 24-29 April 1991, Bangkok, Thailand, International Institute for Environment and Development, UK.
- Turner, D.P., J.J. Lee, G.J. Koperper and J.R. Barker (editors), 1993. The forest sector carbon budget of the United States: Carbon pools and flux under alternative policy options, US EPA, ERL, Corvallis, OR.
- UNEP, 1993. UNEP Greenhouse Gas Abatement Costing Studies, Analysis of Abatement Costing Issues and Preparation of a Methodology to Undertake National Greenhouse Gas Abatement Costing Studies, Phase Two Report, Draft 25 November 1993.
- UNEP, 1994. UNEP Greenhouse Gas Abatement Costing Studies. Part 1: Main Report, and Part 2: Country Summaries, UNEP Collaborating Centre on Energy and Environment, Risø National Laboratory, Denmark, May.
- U.S. Congress, 1992. Office of Technology Assessment (OTA), Fuelling Development: Energy Technologies in Developing Countries, OTA-E-516, U.S. Government Printing Office, Washington D.C., April, 1992.
- Viner, D., and M. Hulme, 1994. The Climate Impacts LINK Project, Providing climate change scenarios for impacts assessments in the UK, Norwich, UK.
- Watson, R.T., L.G. Motra Filho, E. Samhuesa, and A. Janetos, 1992. Sources and Sinks. *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment*, J.T. Houghton, B.A. Callander, and S.K. Varney (eds.), Cambridge University Press, 25-46.
- Winjum, J.K., R.K. Dixon and P.E. Schroeder, 1992. Estimation of the Global Potential of Forest and Agroforest Management Practices to Sequester Carbon. *Water, Air, and Soil Pollution* 62:2131-227.
- Winjum, J.K., and D.K. Lewis, 1993. Forest management and the economics of carbon storage: The nonfinancial component, Research paper, USEPA, Environmental Research Laboratory.
- Winpenny, J.T., 1994. The relevance of global climatic effects to project appraisal. *The economics of project appraisal and the environment*, J. Weiss, Edward Elgar, Aldershot.
- World Bank, 1993. Energy Efficiency and Conservation in the Developing World, A World Bank Policy Paper, Washington, DC.
- World Energy Council (WEC) Commission, 1993a. Energy for Tomorrow's World - the Realities, the Real Options and the Agenda for Achievement, World Energy Council, Kogan Page, London/St. Martin's Press, New York.
- World Energy Council, 1993b. Renewable Energy Resources: Opportunities and Constraints 1990-2020, London.
- World Energy Council, 1994. New Renewable Energy Resources: A Guide to the Future, Kogan Page Ltd., London.
- World Resources Institute, 1990. World Resources 1990-91, A Guide to the Global Environment. WRI, Oxford University Press, New York, USA.
- World Resources Institute, 1994. Oxford University Press, Oxford, p. 173.
- Yamaji, K., Matsushashi, R., Nagata, Y., and Kaya, Y., 1991. An Integrated Systems for CO₂/Energy/GNP Analysis: Case Studies on Economic Measures for CO₂ Reduction in Japan, Paper presented at the Workshop on CO₂ Reduction and Removal: Measures for the Next Century, 19-21 March 1991, International Institute for Applied Systems Analysis, Laxenburg, Austria.

CHAPTER 8 **EVALUATING THE COSTS OF MITIGATION OF** **GREENHOUSE GAS EMISSIONS BY SOURCES AND** **REMOVALS BY SINKS**

Report of Writing Team 6/7:
Costs of Mitigation of Greenhouse Gas Emissions

Convening Author : J. C. Hourcade

Principal Lead Authors : R. Richels, J. Robinson

Lead Authors : W. Chandler, D. Finon, M. Grubb, K. Halsnaes, K. Hogan,
M. Jaccard, D. Jorgenson, F. Krause, E. D. Montgomery, E. La Rovere, P. Nastari,
K. Richards, D. Siniscalco, P.R. Shukla, P. Sturm, J. Weyant

Contributors : C. Carraro, O. Davidson, A. Kolesov, R. Shackleton, Y. Sokona,
C. Stokes, A. Tudini, P.J. Wilcoxon

October, 1994

CONTENTS

0.	Introduction	3
1.	Costs: Definitions and Determinants	5
1.1	How Is Cost Measured?	5
1.2	Taxonomy of Emission Reduction Cost Concepts	5
1.2.1	Gross Costs, Net Costs and the Overall Cost-Benefit Balance of Mitigation Strategies	7
1.3	Key Factors Affecting the Magnitude of Costs: Costs as a Function of Baselines and Policy Strategies	9
2.	Patterns of Development and Technological Change	13
2.1	Links Between Development Patterns, Technical Change and Emission Reduction Costs	13
2.1.1	The Importance of the Socio-Economic Assumptions Underlying Scenarios	13
2.1.2	Current and Future Socio-Economic Development Patterns	17
2.1.2.1	Material and Energy Content of Development in Industrialized Countries	17
2.1.2.2	Links Among Energy, Transport and Urban Planning	18
2.1.2.3	Land Use and Human Settlements	19
2.1.2.4	Development Patterns in the Third World	19
2.2	Modeling Development Paths and Mitigation Costs	21
2.2.1	Prediction and Simulation: The Need for Multiple Baselines	21
2.2.2	Economic Modeling and Development Trends: Some Limits	24
2.3	Multiple Baselines, Uncertainty, and Long-Term Mitigation Costs	25
2.3.1	Multiple Baselines and the Non-Comparability of Cost Assessments ..	26
2.3.2	Mitigation and Prevention: An Uncertain Baseline	27
3.	Modeling Technology Dynamics, Consumption Behaviours and Economic Feedbacks of Climate Policies	29
3.0	General Methodological Considerations	29
3.1	Critical Dimensions of a Typology of Existing Models	30
3.1.1	Diversity of Models, Diversity of Purposes	30
3.1.2	Two Different Representations of Technology: The Meaning of the "Aggregation Gap"	31
3.1.3	Representing How do Market Mechanisms Operate with Regard to innovation and Technology Adoption?	33
3.1.4	Behaviors Over the Short Term or the Long Term, Two Different Questions Addressed	35
3.2	Lessons from Modelling Energy-Related GHG Emissions	36
3.2.1	The Structure of Existing Models	36
3.2.2	The Role of some Key Features of Modelling Techniques	39
3.2.3	The Role of Key Input Assumptions	41
3.2.4	The Top-Down Down versus Bottom-Up Modelling Controversy	43

0. Introduction

Although most of the available literature on the costs of GHG emission reduction has been written in the period since 1988, interest in this issue began more than a decade earlier with Nordhaus¹ whose contribution was followed by around a dozen pioneering studies. The picture has evolved since then, but it retains two features from this earlier period:

- First, the focus is on CO₂ emissions and the other GHGs are either ignored or treated separately in an ad hoc manner. This is not only due to the importance of CO₂ emissions relative to those of other GHGs, but also to the existence of a strong tradition in long-term energy modeling and energy forecasting, which made possible analysis of the CO₂ emissions associated with energy production and use. Because of the long lead-times required for planning of energy supply systems, and the instability of energy markets (oils shocks, influence of geopolitical considerations, etc.), energy analysts had by the mid-1970s started to develop long-term energy demand and supply models. These models could be used to analyze the CO₂ emissions associated with the energy system simply by adding emission coefficients to the models. Such a modeling capability was not available with respect to other GHGs.
- Second, the structure of the debate was determined very early by the wide range of numerical results about the potential for, and costs of, emission reduction: some studies argued that emission reduction policies were likely to entail very substantial costs,² others that the costs would be relatively small,³ and still others that these costs might in fact be negative and bring an overall benefit.⁴

This debate became more heated, and the demand for this type of studies accelerated, after the drafting of the UN Framework Convention on Climate Change in 1992. At this time, the climate issue appeared on the international negotiation agenda and countries and international organizations became interested in obtaining information on the economic impacts of climate policies.

The resultant controversies about the overall costs of GHG emission reduction strategies made it clear that statesmen, policy makers, journalists and the public stand in an ambiguous posture in the face of figures coming from economic modeling exercises. On the one hand they expect a clearcut answer about for example the effectiveness of a carbon tax to curb GHG emissions, and the economic consequences of this tax, preferably in the form of an aggregated figure such as a loss of GDP. On the other hand, they are very skeptical about the results of such analyses, and above all about the capacity of economic models to provide reliable predictions and cost estimates.⁵

¹ Nordhaus, W.D., (1977), "Strategies of the Control of Carbon Dioxide". Cowles Found. Discuss. Paper, n° 443, Yale University, New Haven, Conn.; Nordhaus, W.D., (1979), "The Efficient Use of Energy Resources". New Haven, Conn: Yale Univ. Press.

² Nordhaus (1977, 1979), Manne (1984)

³ Edmonds, J.A., Reilly, J. (1983) "A global energy - economic model of carbon dioxide release". *Energy Economics*, vol. 5, n° 2, april.

⁴ Lovins, A.B. (1977) *Soft Energy Paths: Towards a Durable Pace*. Harmondsworth, Penguin Book. For a discussion of the wide range of views on future energy demand in the early 1980s, see Caputo, R. "Worlds in Collision", *Futures*, 16, 1984, pp. 233-59, and M. Thompson, "Among the Energy Tribes: A Cultural Framework for the Analysis and Design of Energy Policy", *Policy Sciences*, 17: 321-39.

⁵ For discussion of the sometimes vexed relationship between energy modellers and energy policy-makers, see Robinson, John, "Of Maps and Territories: On the Use and Abuse of Models in Support of Policy-Making", *Policy Sciences*

Much of this skepticism stems from the well-documented failure of energy forecasters in the past to provide reliable predictions of future energy demand after the oil shock disturbances beginning in the early 1970s,⁶ as well as the more general problems of errors in economic forecasting even over short time horizons.⁷ Part, however, stems from misunderstandings about what economic and energy models are able to capture and about how to use their results. There is a gap between the answers expected by policy makers and the type of information economic models can supply. As discussed below, the lessons of modelling analysis are rather complex and cannot easily be translated into clearcut policies.

Another difficulty stems from the fact that, in the first phase, many agencies have employed models that were not initially designed to shed light on the cost of emissions reductions. Examples would be models with energy sectors so aggregated that it was impossible to describe a substitution between fossil and non fossil energies, or the use of short term models to simulate medium term impacts. Some of these models are no longer in use; others have evolved through several versions, further complicating the picture. The result of such factors is that part of the apparent diversity of results is simply due to the development of research itself.

These circumstances have created an opportunity for misusing models and their results in public debates. To help avoid either uncritical acceptance or total distrust of current analyses of emission reduction costs, this chapter will present a discussion of the critical determinants likely to influence the overall cost of climate policies and of the main methodologies employed to account for them. The purpose is not to have a detailed comparative analysis of the models, this would be of interest only for the specialists, but to concentrate on all the possible sources of misunderstanding and misinterpretations of the results presented in section 8 so as to facilitate the explanation of their policy implications. We will examine successively:

- the various concepts of costs used in the literature (section 7.1);
- the relationships between (i) economic cost assessments and (ii) assumptions about development patterns and technical change which (explicitly or implicitly) underlie any economic scenario used to assess emission reduction costs (section 7.2),
- the main methodological approaches for costing assessments, the key assumptions likely to determine the numerical results, and the lessons derived from modelling debates in the energy field and in the forestry sector (section 7.3).

⁶ See, for example, the various national case studies in Baumgartner, T. and A. Midttun, eds. *The Politics of Energy Forecasting* (New York: Oxford University Press, 1987).

⁷ See, for example, Ascher, W. *Forecasting - An Appraisal for Policy-Makers and Planners*. (Baltimore: Johns Hopkins University Press, 1978).

1. Costs: definitions and determinants:

1.1 How Is Cost Measured?

It is important to begin with a clear definition of costs that can be found in literature because many misunderstandings stem from using very different costs concepts when presenting and comparing the results of existing studies. There are two crucial elements in the definition: how costs are measured and whether costs are reported on a gross basis or net of some of the ancillary benefits of policies to reduce emissions.

1.2 Taxonomy of Emission Reduction Cost Concepts

In any economic analysis, the cost of emission reduction is calculated as a difference in costs (defined in monetary units) between a reference situation and a new one characterized by lower emissions. Beyond this common feature however the concept of cost is not unique, meaning that the measurement criteria chosen to represent costs will depend on the level and the purpose of the measurement.

First, before comparing any result, a due attention must be given to the way reduction targets are set because this affects their meaning. Some models calculate reduction from a benchmark date t_0 ; this is the case for most of the US studies in the energy field and for the studies carried out in the other OECD studies about how to stabilize GHGs emissions up to the next decade. Others (systematically in developing countries and very often in long term studies in Europe) set the target in terms of percent reduction from an emission level at a given date in $t+n$.

Second, to understand many critical debates about the costs of climate policies, it is necessary to distinguish four types of cost concepts used in costing analysis:

1. the direct costs of specific technical measures to reduce emissions, for example the cost of switching from coal to gas in electric production, of improving the thermal efficiency of existing homes, or of planting trees in reforestation programs. Costs are normally reported in present value terms and represent the life-cycle cost of the technique used or of the project (up front cost of the measures considered plus annual energy and operating cost, all reduced to a net present value or levelized costs). They depend upon both technico-economic data and a given interest rate and can be used to construct technology cost curves of the kind described in Figure 1.1. They can be calculated in the absence of any global scenario but, as such, they do not provide an economically meaningful cost assessment unless they are fed into coherent technical and economic frameworks. They are the only source of information available for abatement measure in activity fields for which no comprehensive sectoral model has been so far developed.

2. economic costs for a given sector: Here sectoral models are used to integrate sets of measure in consistent pictures of a given sector, and to compare the relative costs of different scenarios. These sectoral scenarios take some macro-economic indicators such as the overall rate of growth as input parameters. They provide what is referred to as "partial equilibrium" analysis in the sense that these sectoral models do not capture the feedback effects between the behaviour of a sector and that of the overall economy. To date, most sectoral analyses of emission reduction costs have used energy sector models and forestry models. Other sectoral models, such as transportation or

Figure 1.1 Sample technology cost curves

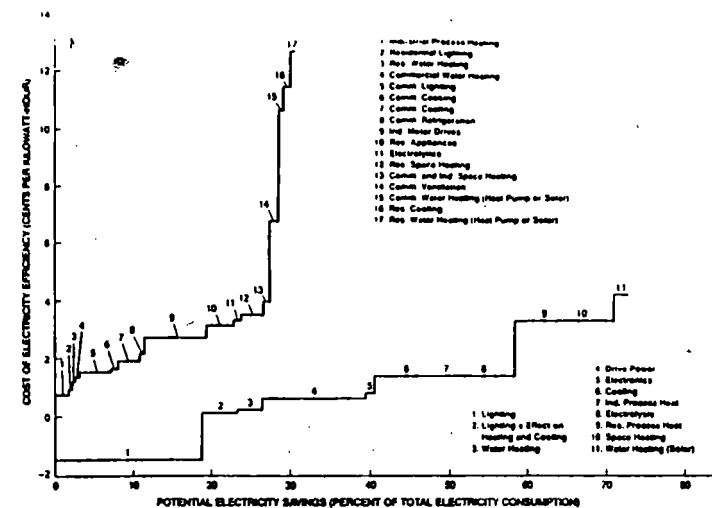


Figure 1. Discrete energy-efficient technology cost curves for the United States. The figure shows two estimates of the potential savings of electricity (as percentage of system demand) available by using various more efficient technologies, in order of increasing cost per unit saved. These costs compare with typical US electricity prices of 6-8 cents per kWh; all costs below this thus involve net economic savings for the user at the discount rates employed for the analysis. The upper curve is an estimate by the US Electric Power Research Institute; the lower curve is by the Rocky Mountain Institute of Amory Lovins et al. Source: Scientific American, September 1990.

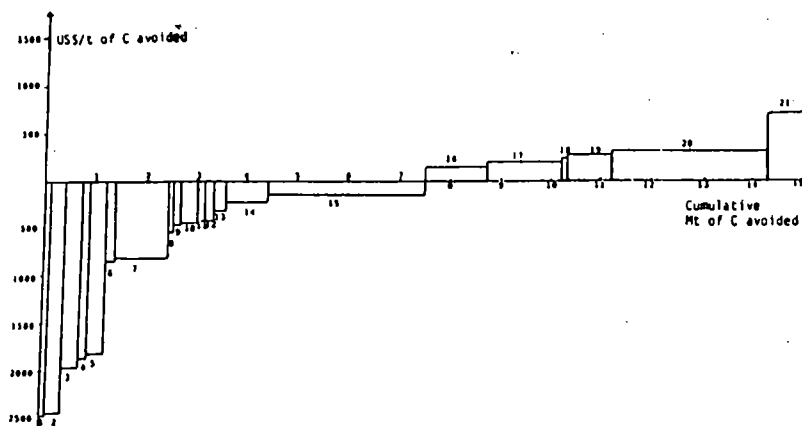


Figure 2. Discrete CO₂ abatement technology cost curve, Brazil. Cumulative amount of C avoided by the year 2000 for several technological improvements. 1—Incandescent (incand) and efficient (eff) — incand, standard (std) — commercial sector, 2—Fluorescent (fluor) — std — incand, std — commercial sector, 3—Fluor eff — fluor std — commercial sector, 4—Compact fluor — incand, std — commercial sector, 5—Incand eff — incand, std — residential sector, 6—Fluor eff — fluor std — industrial sector, 7—Fluor std — incand, std — residential sector, 8—Improved electric, oven—industrial sector, 9—High eff motors—industrial sector, 10—Horsepower measures—industrial sector, 11—Variable speed motors—industrial sector, 12—Better electrolytic processes—industrial sector, 13—Improved air conditioners—residential sector, 14—Compact fluor — incand, std — residential sector, 15—More eff vehicles—transport sector, 16—More efficient refrigerators—residential sector, 17—Alternative fuel alcohol—transport sector, 18—More eff. public illumination—public sector, 19—Highway improvements—transport sector, 20—Solar water heating—residential sector, 21—Ethanol engine—transport sector.

agriculture models, exist but that they have not yet been used so extensively for analysis of GHG emission reduction.

3. macroeconomic costs measure the impact of a given strategy on the level of the gross domestic product (GDP). These aggregate indices measure the monetary value added of goods and services produced in single year and provides an index of the scale of human activities that pass through markets plus, by convention, the imputed value of some nonmarket activities (such as the value of services provided by public administration). At this level of cost analysis one tries to account for the interrelationships between a specific sector and the overall economy. This requires the use of either pure macroeconomic models or modelling frameworks coupling sectoral models and macro-economic models in order to capture the changes throughout an economy caused by policies in a given sector (what is commonly labelled the general equilibrium effects who are to be distinguished from the partial equilibrium).

4. welfare costs GNP variations do not provide direct measures of human welfare. There are many reasons for this: first a climate policy may change the composition of GDP in direction of higher investments and lower consumption, second human welfare does not increase linearly with consumption, third it does not account for the relationship between distribution of income and overall welfare, finally spending money on disaster relief or environmental rehabilitation enhances economic growth without increasing welfare prevailing before this environmental disaster;

The four types of costs outlined here represent increasing levels of generality as one moves from direct financial costs to welfare costs. However, the different levels of cost cannot be aggregated or correlated in any systematic way. For example, ranking efficient technologies in terms of their individual price on the marketplace is not the way these technologies will be actually adopted and combined in a economically consistent productive system; a given energy efficiency improvement may not be rationally selected if this improvement occurs in a period of time where the electric supply is in excess. Similarly, a sectoral optimization of a very capital intensive sector may not give results consistent with some form of overall macroeconomic optimum; the amount of money spent in optimized energy supply or transportation systems may prevent investing in other sectors such as education and health without resorting to increased foreign debt or internal interest rates. On the other hand, aggregate macroeconomic analysis of costs may not capture important changes to the extent that these changes remain below the level of "noise" of analysis and are not captured by historical variation in the aggregate variables. This typically occurs with respect to the agricultural sector, which represents a small part of overall GDP but often plays a decisive role in the social and spatial equilibrium of a society.

Despite the intrinsic difficulties of solving the problem of the consistency between sectoral modelling and macroeconomic modelling, and despite the methodological problems discussed in sections 2 and 3 below, progress has been made in incorporating successively broader concepts of costs in GHG emission reduction studies, and in accounting for the possibility of significant technological and behavioural change.

One of these difficulties has to be nevertheless underlined. It lies in the fact that, in a number of developing countries and Central and Eastern European countries, the level of government intervention or market distortion (who exists also in OECD countries) may interfere very drastically in the absolute and relative prices of goods and services. This results in distortions between observed market prices of technologies and their "shadow prices" assessed "at factor

costs" who would reflect the actual balance between human capabilities, technical potentials, natural resources scarcity and final needs within a given economy. To use market prices is relevant for assessing the likelihood of the adoption of some technical alternatives at constant⁸ institutional context; but, if these costs are interpreted as capturing the overall social costs of a given measure they hide some intrinsic costs of goods and services and create the basic conditions for misleading measurements.

More empirically and theoretically difficult is passing from GDP costs to welfare costs. First the precise meaning of a very specific welfare measures frequently found in economic literature as to be explained. This is the variation of consumer surplus based on estimates of how consumers will adjust their purchases in response to changing prices. We will not enter here a rather sophisticated discussion on the 'dynamic equivalent variation' welfare measure used in some general equilibrium models or on the possible use of a social welfare function, which puts different weights on the welfare of different groups of population and makes the measurement of cost sensitive to issues of how wealth is distributed. Suffices it to say that, in most of empirical models welfare cost measures are made on the basis of variations of the consumption of marketed goods around an equilibrium to assess the impacts of variations in tax policies, all the rest being given (see box n° 1). These results cannot be directly translated into practical terms first because they generally do not account for the dynamic effects of important policy measures on technology and consumer preferences, second because they depend on market product calculations and do not account for the goods and services produced by non-market and informal economies.

In fact much work remains to be done in attempting to incorporate broader conceptions of human welfare (such as those that are suggested in the United Nations Development Program's Human Development Index) and none of the models reported hereafter accounted for this type of index variations who are not so far rooted in totally consistent theoretical frameworks despite their heuristic interest. The consequence is cost figures provided following the practice of current economic modelling must be strictly interpreted as estimates of losses (or gains) in the overall activity level of an economy, not as estimates of impacts on overall welfare.

The interest of the GDP variation measure is nevertheless very high; the only one precaution to take before drawing policy-relevant conclusions is to recall the utmost importance to examining other indicators (unemployment, distribution of income, security and political stability).

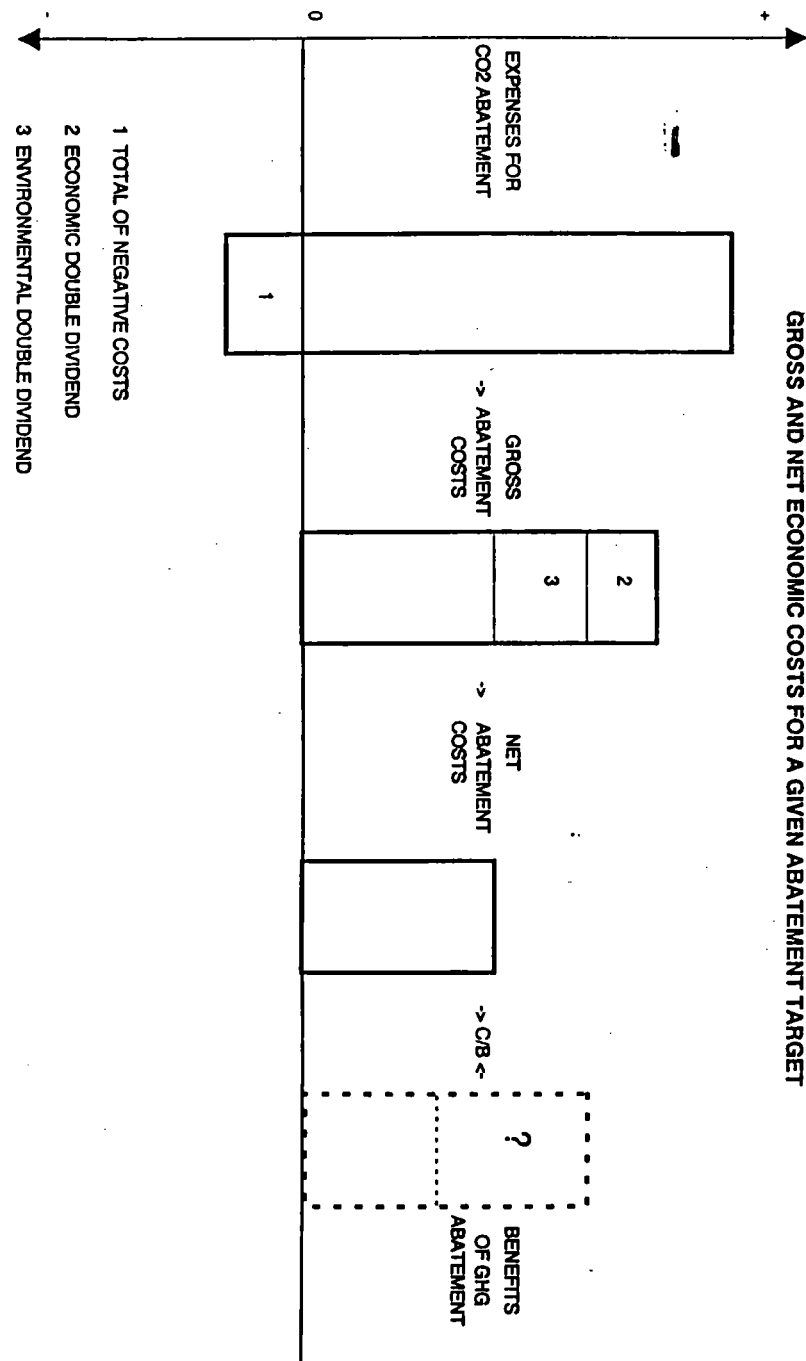
1.2.1 Gross Costs, Net Costs and the Overall Cost-Benefit Balance of Mitigation Strategies

In assessing the costs of emission reduction, it is first important to make a distinction between what economists call the gross costs and the net costs of emission reduction strategies. The two are different to the extent that there are possible positive side-effects of emission reduction strategies that would offset some of the gross costs. These positive side-effects can be divided into three categories:

- the "negative cost potential" namely emission reductions caused by technologies whose costs are lower than the technologies currently in use. As discussed further in

⁸ Early works in this area is summarized in Little and Mirrlees (1974) or Squire and Van der Tak (1975) (for a more recent methodological surveys see Gittinger (1982)). A good illustration of the interest of making a distinction between market prices and factor costs is given in the debates around the biomass ethanol program in Brazil where the cost of ethanol is far lower if one utilizes some form of social costs (Nastari P. 1991).

Figure 1.0



section 3, this issue is controversial since it implies there are cost-effective emission reduction strategies which are not now in use and which will not be adopted in the absence of new policies. Such measures would have a negative net cost, and obviously lower the gross cost of GHGs abatement for a given target.

- an "economic double dividend", such as the possible positive effects on growth or employment of the recycling of carbon tax revenues or of the technological externalities (i.e. side-effects) associated with fostering research and development programs;

- an "environmental double dividend", namely the synergy between GHG emission reduction strategies and the mitigation of other environmental nuisances such as SO₂ emissions, urban congestion or land degradation, such that GHG emission reduction also contributes to reducing these other problems.

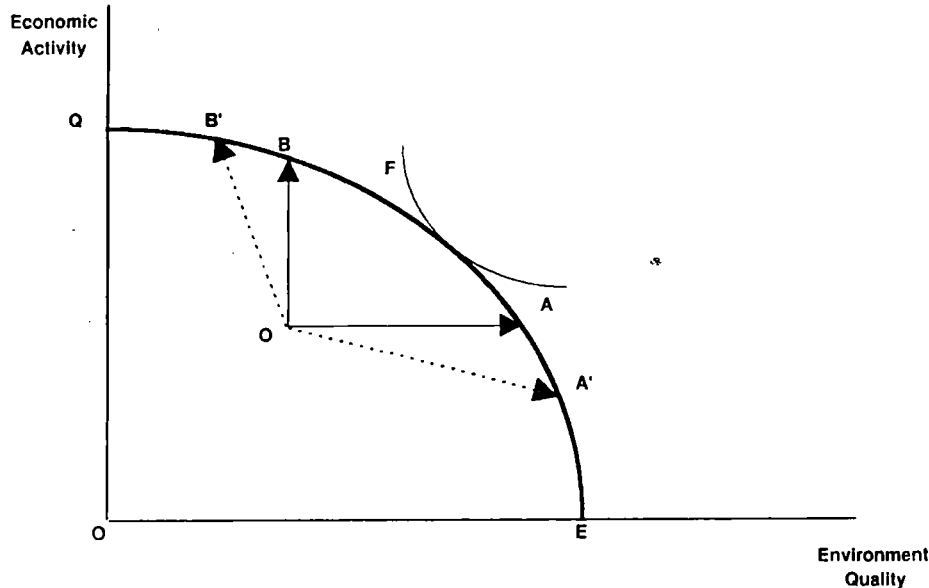
The existence of such positive side-effects within a suite of emission reduction measures would result in lowering the gross cost of the full set of emission reduction measures. To the extent that such positive side-effects may totally offset the gross costs of a specific emission strategy, then they represent what has been called a "no regrets potential": measures that are worth undertaking whether or not there are climate-related reasons for doing so⁹. However, as discussed below, there is much controversy about the existence and magnitude of these positive side-effects. The point here is simply that, from the point of view of GHG emission reduction policy, what matters are the net costs of emission reduction strategies, that is gross costs minus any positive side-effects.

Many current economic models account for the first and/or the second category of positive side-effects; very few account for positive environmental externalities. This however is mainly due to practical reasons and one can expect quick improvement in this direction in the rather near future. In the meantime, it is useful to remember that the studies discussed in this chapter do not include this category of secondary benefit.

To avoid any possible misunderstandings, it must be emphasized that the double dividend positive side effects described here are not the same as, and should not be mistaken for, the benefits of emission reduction policies (or costs of climate change) which are discussed in section 7 above. Instead, these positive side-effects represent items which lower the total cost of emission reduction policies and it is the resulting net cost figure (gross cost minus positive side-effects) which is to be compared with the benefits of emission reduction policies (whether these benefits are accounted for in terms of explicit monetary values or purely normative emission reduction targets). Figure 1.3 aims at clarifying the differences between gross costs and net costs and explains some possible theoretical confusions.

⁹ Most discussions of the issue of "no regrets" potential have centred around the first category of positive side-effects described here: whether there exist "negative cost" measures such as some types of energy efficiency programs. This "no regret" concept has to be clearly distinguished from the idea of "free-lunch"; to mobilize these potential requires indeed a specific effort who may not be regretted from the collective optimum perspective but some specific policy measures could hurt the interests of some or other category of agent. Conversely this concept is not meant to imply that undertaking all such measures will guarantee no regrets with regard to the effects of climate change, if these effects ultimately are proven to be very significant.

Figure 1.3
Relationship Between Economic Activity
and Emission Reduction



1.3 Key Factors Affecting the Magnitude of Costs: Costs as a Function of Baselines and Policy Strategies:

The above taxonomy suggests that assessing the costs of GHG emission reduction strategies is not equivalent to adding up the observable and tangible costs of individual measures or policies. The cost of emission reduction is always a net incremental cost (or a marginal cost) relative to a given scenario—usually called a baseline scenario. This means that the calculation of these net costs is determined in large part by both the assumptions underlying such baseline scenarios, and the assumptions about emission reduction policies.

1.3.1. Baselines and magnitude of the "no-regret" potentials

The most sensitive issue in the debates about how to interpret the results of the models is the way assumptions about the existence and the size of potentials for so-called "no-regret strategies" are conveyed in specific modelling frameworks and baseline scenarios.

The discussion of "no regrets" potential triggered a sensitive policy debate who can be summarized rather simply, though rather abstractly, in graphical form. (See Figure 1.3). To begin, we represent the whole economy as producing two sets of goods and services: (i) a composite good Q, namely an aggregate of all existing goods and services, and (ii) a given level of environmental quality E, represented in this case by a certain amount of emissions reductions. Given such an assumption, then it is possible to construct a curve $F(Q,E)$, called a theoretical production frontier by economists, which represents the trade-off between economic activity (Q) and emission reduction (E). For a given economy at a given time, each point on this curve shows the maximum size of the economy for each level of emission reduction; put another way, it shows the maximum emission reduction for each level of economic activity. If the economy is at a size and level of emission reduction that is below and to the left of this curve (e.g. point O in Figure 1.2), it is possible for that economy to move upwards (e.g. from O to B), producing more goods without increased emissions, or to move rightwards (e.g. from O to A), reducing emissions without reducing the size of the economy, or somewhere in between, increasing both economic activity and emissions reduction.

From the point of view of cost analysis, a key consideration is what is assumed about the location of the reference or baseline scenario with respect to this curve. If the baseline scenario assumes the economy to be located somewhere on the production frontier (curve F), it is clear that there is a direct trade-off between economic activity and the level of emissions. In effect, all increases in emission reduction (moving down the surface of the curve to the right) will decrease economic activity (i.e. increase costs). That is, there is no "no regrets" potential: moving up to the left on the curve will increase economic activity but also increase emissions. In such a context, an appropriate policy mix can minimize the net cost of lower emissions but can never offset it totally¹⁰. Conversely, in a baseline scenario who describes an economy below the production frontier represented by curve F, no-regret strategies are possible. Under these conditions, emissions can be reduced without reducing the size of the economy (i.e. without increasing overall costs) and, possibly can enhance economic activity¹¹.

¹⁰ Goulder, L.H. (1994) "Environmental Taxation and the Double Dividend: A Reader's Guide". 50th congress of the International Institute of Public Finance, Session 1 "Green Taxes and the Rest of the Tax System", Harvard University, 22-25 August 1994, 35 p.

¹¹ Of course it would also be possible to move from O to a point above and to the left of point B (increasing economic growth and also increasing emissions); this means that the economic surplus gained thanks to the removal of inefficiencies is devoted to improving environmental quality only if there is a collective preference and political will to do so. It could also be possible to move to a point below and to the right of A (reducing

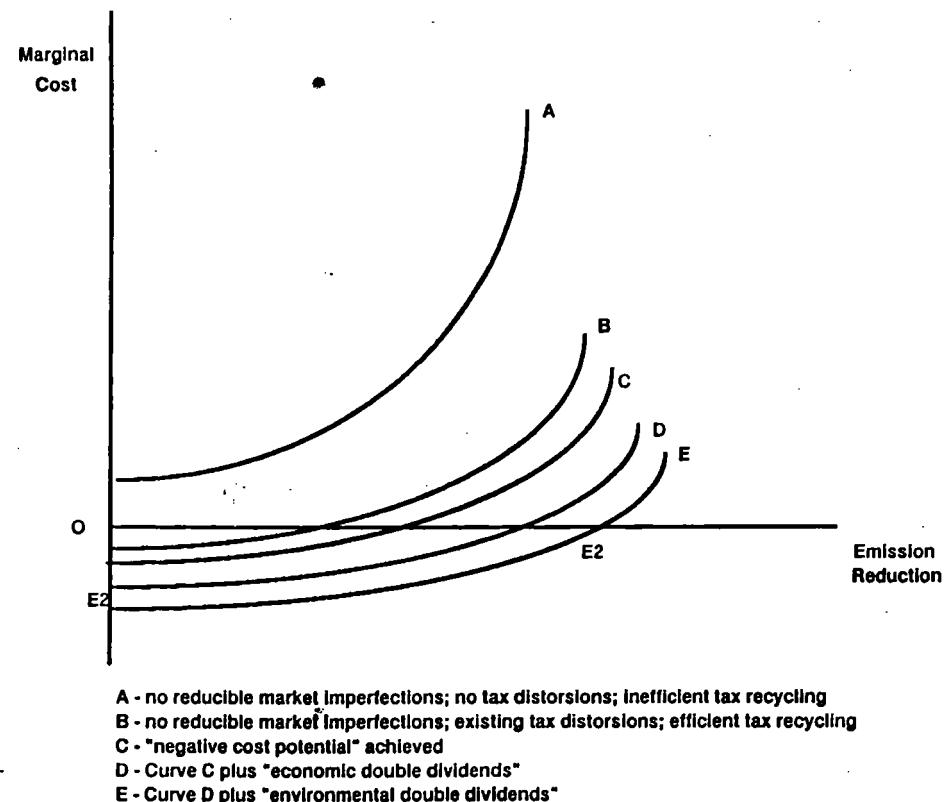
The critical question is then whether the reference or baseline scenario to which emission reduction scenarios are compared is on this frontier or not. Assuming "no regrets" potential exists implicitly suggest that any baseline scenario is below the frontier and that appropriate policies would move the economy up towards that frontier. The counterargument is that, if such a potential had existed, it would already have been adopted by the marketplace at least as long as there is no huge institutional failures preventing market forces to operate. That is why many analysts therefore assume that any cost-effective emissions reduction is already embodied in any baseline scenario and locate this baseline on the frontier. In this sense the economic debate is as much about the location and characteristics of the baseline scenarios as it is about the nature and costs of specific emission reduction measures.

In fact, the existence of a "no regrets" potential implies (i) that markets and institutions do not behave perfectly because of market failures (lack of information, distorted price signals, lack of competition, etc.); (ii) that it is possible to identify policies that have the ability to correct these market and institutional failures; and (iii) that a policy decision is made to eliminate selectively those failures which give rise to increased GHG emissions (since there may exist other market failures whose removal might increase GHG emissions).

In other words, the existence of market and institutional failures that give rise to a "no regrets" potential is a necessary but not sufficient condition of the development of strategies to realize that potential. The latter depends on the existence of significant political desire to realize the potential. In practice, such as in many fields of public policy-making countries will consider climate policies in a multiobjective decision-making; GHG emission reduction policies are likely to be a by-product or joint product of policies developed in part for other reasons and models could not but confront this issue which, as it will be seen later complicate the comparison of the results.

Figure 1.4 illustrates different views about the relation between cost and emission reduction in the case of a carbon tax. Each curve in Figure 1.3 shows how marginal costs would increase for higher levels of emission reduction, given different underlying assumptions about offsetting policies. Curves A and B assume that there exist no reducible market imperfections; thus there are no emission reduction measures below the x-axis (i.e. with negative net costs). Curve A shows higher costs than B since it assumes that any carbon tax revenues are spent on economically inefficient projects (that increase total costs), while curve B assumes efficient recycling of tax revenues. Curves C, D and E all start below the x-axis: they all assume that there exist market failures in the energy, transportation or agricultural systems that can be corrected by emission reduction policies at negative cost. Curve C includes only the "negative cost potential" described in section 1.1 above; curve D includes also "economic double dividends" gained by using carbon tax revenues to replace highly distorting taxes elsewhere in the economy; curve E includes also the "environmental double dividend" represented by the other environmental benefits induced by GHG emission reduction. The room for no regret policies is obviously represented by the area OE_1E_2 .

Figure 1.4
Alternative Views on Costs of Emission Reduction



both emissions and economic activity) if the surplus is devoted to very high investments with a low return and a very low efficiency in terms of environmental quality improvement. This could occur in the case of misallocation of efforts for a given level of concern for environmental quality.

1.3.2. Targets setting – Level and Timing

As stated in section 1, the growth rate of CO₂ emissions is determined by the growth rate in GDP, the ratio between GDP and the required level end-use services (energy, transport, food) and the level of GHG emission per unit of each of these services.

When targets are set for levels of emissions calculated from a given benchmark year t_0 , the level of baseline emissions is critical because higher rates of economic growth makes any given target more costly to achieve by increasing the gap between baseline and target emissions. This tendency is obviously less strong if the baseline incorporates a tendential decoupling between economic growth and emissions and assumes many flexibilities in the system (high responsiveness of consumption to price and non price signals, availability of low carbon intensive techniques).

With emissions growing over time, a target of constant emissions implies that larger emission reductions are required in every future time period, requiring recourse to more and more expensive measures. But conversely, if a model embeds optimistic assumptions about the long run this tendency may be counterbalanced and the costs about the short term higher than over the long run.

For given assumptions about technical progress the time profile of the abatement may then be a key factor of differences of the numerical results. In discussing these timing issues, a key distinction is between the transition period and the backstop period.

The transition period comes first, and is characterized by an existing capital stock and limited technological options for replacing existing techniques with carbon-free techniques. The backstop period is entered after sufficient time elapses to allow the entire capital stock to be replaced and for carbon-free backstop technologies to become available, i.e., technologies available for widespread adoption at constant cost at the end of the economic life of existing equipments.

One of the most important determinant of costs during the transition period is then the turnover of the capital stock. Over the backstop period the cost of carbon-free technologies place a limit on how great the costs of reducing carbon emissions can be. Successful R&D that accelerates the availability carbon-free technologies can reduce costs in the backstop period.

1.3.3 Policy Instruments

What policy instruments are used to trigger modifications in consumption behaviours and technical adoption behaviours and how they are accounted for in the models can also affect their outcome. The types of policy instruments that have been studied in detail are energy taxes on the one hand and a collection of regulatory programs, efficiency standards, incentives, and information programs to bring about adoption of specific technical measures to reduce energy use.

In the technico-economic models capturing technical costs of a technology or of a sector the difference is important between models depending upon the way they account for the possibilities, the pace and the costs of removing market imperfections, and on the efficiency of regulatory programs or of R&D programs.

So far the focus of macroeconomic models was placed on carbon or energy taxes, when the focus of new generations of sectoral technico-economic analysis was placed on the impact of other type of incentive instruments. Critical differences in the outcome of the models come from the way the revenue of a carbon tax are recycled in an economy. In the earlier periods, some simulations were made assuming no recycling which comes to assimilating a carbon tax to an external shock such as an oil shock and places an upper bound to the macroeconomic costs. In a second step, most of the models represented the recycling in the form of a lump-sum, namely without modifying the rest of fiscal structure; this makes the comparison easier but does not describes the recycling technique who has the highest probabilities to be actually implemented. In a third step, models tried to exemplify the others ways of recycling a tax by changing the level of payroll taxes, income taxes, corporate taxes or simply by reducing public deficits. This overcomplicates comparisons because the outcome depends on the ways the existing distortions of fiscal structures (or subsidies) are accounted for in the baseline; but this is more meaningful from a policy-making viewpoint and, as it will be demonstrated later, is a major determinant of differences in the existing studies.

1.3.4. international dimension of climate policies;

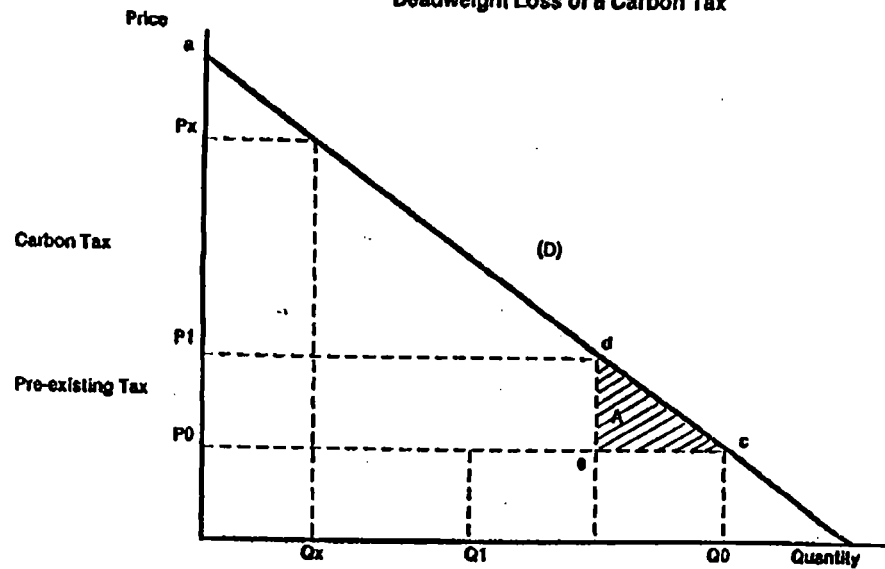
The last parameter determining the cost figures provided by the model is the scenario assumption on the international context of climate policy.

On the one hand, unilateral reduction of GHGs may negatively affect the competitiveness of national industries and create a "leakage" of GHG emissions from one country to another. This "leakage" occurs if emission reduction policies in a given country cause firms to relocate their polluting plants and production processes to countries in which no such policies exist, or if firms in countries with no emission reduction policies gain a comparative advantage due to lower costs, thus increasing their output and thereby their emissions relative to countries with emission reduction policies.

On the other hand, international coordination of emission reduction policies may not only avoid these outcomes but may result in lowering the total global cost of reducing emissions. Assuming that emission reduction costs vary among countries, then the costs of a given level of global emission reduction would be lower if international coordination results in the most cost-effective emission reduction policies being adopted first, than if each country simply reduced emission by an equal amount.¹² Even if a growing theoretical literature is currently devoted to this issue, it has been addressed only in a few empirical modelling works to date. Most analyses have assumed either that national policies are adopted unilaterally or that the effects of national emission reduction policies are neutral with respect to international competition (i.e. that all countries take the same action or that the effects of emission reduction policies on international competitiveness are small). So far no model is available to account for the gains to be expected from international cooperation in R&D and technologies diffusion.

¹² To give a simple example, if there were two countries in the world and the cost of emission reduction was always twice as expensive in country A as in B, then it would be cheaper to use up all the reduction potential in country B before reducing emissions in A.

Chart 22
Deadweight Loss of a Carbon Tax



2. Patterns of Development and Technological Change

For any country, both the level of GHG emissions and the costs of emission reduction of those emissions depends on a series of factors, including the range of technologies used and the underlying technological and socio-economic conditions that give rise to final demands for land, energy services or transportation. Most model explore options and alternatives, and possible future economic conditions, based upon particular assumptions about the nature of technological change and long-term development paths. This section of the chapter will explore this latter question in more detail because these assumptions are very often only implicit and because current modelling methodologies and current data do not enable modellers to treat explicitly some of critical parameters.

2.1. Links Between Development Patterns, Technical Change and Emission Reduction Costs

2.1.1 The Importance of the Socio-Economic Assumptions Underlying Scenarios

Much of the discussion about the costs of GHG emission reduction--and indeed about energy issues in general--naturally focuses on economic concepts and variables such as income, prices, growth in GDP, and others. We therefore begin with a rather trite observation: damages to environment are not caused by a given amount of dollars, yen, pounds, deutchmarks or francs, but by the material content of the consumption or production activities which are the counterparts of these monetary values. To put it in another way, GHG emissions over the long run depend not only on the rate of economic growth but also on the structure and physical content of this growth.

It is well known that countries with rather similar development levels may have very different energy consumption per capita ratio, or very different transportation requirements. Some of these disparities are obviously due to natural and geographical characteristics (temperature, population density, etc.), but many of them stem from differences between the development patterns of these countries. Comparative studies aiming at explaining these differences¹³ suggest the importance of five factors that will influence the amount of GHG emissions, given a certain overall rate of economic growth:

- *technological patterns* in sectors such as energy, transport, building, agriculture and forestry. As discussed below, these patterns encompass individual technological choices and options but also include overall technological systems with their internal consistency and dynamics;

- *consumption patterns*: For a given per capita income, parameters such as housing patterns, leisure styles or the durability and the rate of obsolescence of consumption goods will have a critical influence on long run emission profiles; beyond the technical content of these patterns they are related to education, distribution of income and the degree of dualism in an economy.

¹³ Martin, J.M., (1992) *Economie et politique de l'énergie*. Paris, Armand Collin, coll. Cursus Economic, 192 p.; Darmstadter, J., Dunkerely, J., Alterman, J. (1977), *How industrial societies use energy*, Johns Hopkins University Press, Baltimore

1 - *geographical distribution* of activities, which encompasses both the distribution of
 2 human settlements in a given territory and the nature of urban form within a given settlement.
 3 The impact of this parameter is twofold: first on the evolution of land uses, and second on
 4 mobility needs and transportation requirements;

5
 6 - *structural changes* in the production system and in particular the role of high or low
 7 energy intensive industries and services. The energy content of industries such as steel, non
 8 ferrous metals, heavy chemistry or paper and pulp is between four and six times the energy
 9 content of the other industries. At the other end of the spectrum, a simple phone call on a
 10 given commodity futures market can generate substantial gains and e-mail connections sensibly
 11 increased the efficiency of researchers for insignificant energy contents. A shift in the relative
 12 size of primary production and service industries in an economy may or may not affect the
 13 overall level of economic activity but will have significant implications for energy use.

14
 15 - *trade patterns*: it is generally admitted that removing tariff and non-tariff trade
 16 barriers enhances overall economic efficiencies. But, because historical experience
 17 demonstrates that some form of protectionism was necessary to many countries at the early
 18 stages of industrialisation, and because of the transition problems for removing these barriers
 19 (risks of social and economic disruptions) complete free trade will be implemented only
 20 gradually after the Uruguay Round. World apparently moves towards the creation of
 21 commercial blocks (European Union, NAFTA, Mercosul). The future of these evolutions is
 22 very hard to predict and will alter significantly the access to the best available technologies, the
 23 capacity of developing countries to generate high enough internal capital accumulation to
 24 finance infrastructures and education, the location of industrial activities and the future of land
 25 uses because of the impact on agricultural markets.

26
 27 Of course, these factors are not ignored by current economic models. They are in some way
 28 captured by changes in economic parameters such as the structure of household expenses
 29 devoted to heating, transportation or food, the share of each activity in the total value added,
 30 the share of energy costs and transportation costs in the production function of industrial
 31 sectors, the import-export elasticities. This type of treatment is convenient for addressing the
 32 questions traditionally posed by policy makers since the beginning of economic modeling just
 33 before the second world war: to provide information on the consequences of economic policies
 34 (of a monetary devaluation, of a fiscal policy, of an incentive to final demand through public
 35 investment programs etc.) over the short term (1 to 3 years), or to develop consistent medium
 36 term (4 to 10) economic scenarios to frame sectoral planning and policy (mainly in energy and
 37 transportation). For these time horizons and objectives it is logical to assume continuation of
 38 historical trends in the main characteristics of development patterns and the speed and
 39 direction of the transformation of these characteristics.

40
 41 For the longer term periods under consideration in greenhouse debates these assumptions
 42 cannot be easily maintained, and economic parameters can not easily be viewed as the sole
 43 command variables used to predict the future of our production and consumption systems. For
 44 example, a given amount of value added produced by the steel or chemical industries may
 45 correspond to very different levels of material production (and thus energy demand) depending
 46 upon the level of sophistication of the final product; in the same way, the differences in
 47 household budgets devoted to transportation may not fully express the differences in mobility
 48 and transportation patterns prevailing between towns with or without public rail transport
 49 system, or between car uses in towns with very different levels of congestion.

1 More fundamentally, the dynamics of long-term technological development cannot be fully
 2 captured by changes in the capital output ratio (the aggregate amount of economic capital used
 3 per unit of output) and by the impact of the rate of investment on overall productivity. These
 4 parameters are of course important but the outcome in terms of GHG emissions will also
 5 depend upon dynamic linkages between technology, consumption patterns (mainly as regard to
 6 energy requirements), transportation and urban infrastructure, urban planning or rural-urban
 7 distribution of population. We will come back later to the attempts of existing models to take
 8 these parameters into account but the lack of knowledge available about their dynamic linkages
 9 and about their interactions with economic policies and economic signals over the long run
 10 must be underlined at this stage, together with the intrinsic difficulty of predicting innovations
 11 and transformations of lifestyles over the long run. While many fields of social science address
 12 these issues, such information is not typically available in a form easy to process in a numerical
 13 model.

14
 15 In principle, alternative configurations of the factors determining development patterns could
 16 be formally combined to give internally consistent scenarios characterized by various physical
 17 and technical characteristics and economic equilibria for a given rate of economic growth. But
 18 this does not mean that all of these possible scenarios are viable and that it is possible to
 19 achieve a transition towards these long term pictures without entailing high social and
 20 economic costs. What matters here is that these underlying technological and consumption
 21 pattern factors are critical not only for the definition of the baseline scenarios but also for the
 22 assessment of actual emission reduction costs for a given emission reduction policy or
 23 objective.

24
 25 As explained earlier, the emission reduction costs attached to each possible baseline scenario
 26 depend not only on the absolute level of the required emission reduction and on the array of
 27 available technologies (energy efficiency, fuel switching, biomass planting, modal choices in
 28 transport) but also on the timing of this emission reduction¹⁴. In this connection, three groups
 29 of partly related factors become very important:

30
 31 - *the flexibility (conversely inertia) of consumption patterns* underlying the activity of
 32 GHG-emitting sectors such as energy, transport or cement. This flexibility parameter
 33 determines the speed of adaptation to a given economic or non economic signal and
 34 encompasses two aspects. The first one is the rate of renewal of existing end-use equipment,
 35 which is likely to be an important factor in the case of buildings, which have longer lifetimes
 36 than most capital stock. A more critical inflexibility stems from the systemic linkages between
 37 consumption patterns, technology and the spatial distribution of activities. To take an extreme
 38 illustration, it would be far more costly to move away from oil-based automobile fuels in big
 39 conurbations where urban structure makes the use of cars almost compulsory than in a town of
 40 about 40 000 inhabitants where it would be easier to satisfy a significant proportion of intra-
 41 urban personal transportation with electric buses and bicycles. Similar considerations apply
 42 with respect to the energy supply system, in which the flexibility of policy response is
 43 associated with the size and lead times associated with new energy supply technologies. For

¹⁴ Grubb, M., Ha Duong, M., Chapuis, T. (1994) "Optimising Climate Change Abatement Responses on Inertia and Induced Technology Development", in Integrative Assessment of Mitigation Impacts and Adaptation to Climate Change, Nakicenovic, N., Nordhaus, W.D., Richels, R., (eds) pp. 513-534; Hourcade, J.C., Chapuis, T. (1993) "No regret potentials and technical innovation: a viability approach to integrative assessment of climate policies" pp. 535-558 Integrative Assessment of Mitigation Impacts and Adaptation to Climate Change, IIASA, 13-15 October 1993; Manne, A., Richels, G.R., (1992) *Buying Greenhouse Insurance. The Economic Costs of Carbon Dioxide Emission Limits*. Cambridge, The MIT Press.

example, such considerations have prompted the development of methods in the electric power industry whereby such flexibility can be incorporated into electric power planning.¹⁵

- *behavioral characteristics* which determine technical change and the evolution of life styles; this point will be elaborated further as regard to technical adoption mechanisms. As regard to consumption patterns, the roots of inertia are not only technical; anthropology and social psychology demonstrate how far they are embedded in cultures, habits and, more generally, how individual consumption behaviors are shaped by social determinants hard to change overnight¹⁶.

- *interactive effects* due to the feedbacks between the use of certain options and the rest of the economy. Some sectors have a pervasive effect on the rest of the economy and drastic adaptations would trigger strong structural shocks on the entire productive system.

As a whole, the critical role of these factors comes from the fact that, the bigger the inertia of the production and consumption systems, the more the emission reduction costs will be determined by the timing of the required emission reduction. This is easy to understand as far as the adoption of new technologies is concerned: to accelerate the replacement of old equipment could be a major source of the costs of emission reduction. But this inertia also determines the magnitude of the loss of consumer welfare associated with emission reduction. If the range of available alternatives is restricted by the material and spatial features of one's living conditions, the consumer will tend suffer from welfare losses during the transition period towards less GHGs emitting consumption and production systems.

A special case for inertia in development patterns occurs when such inertia creates irreversible processes of technological change. To a large extent such irreversibilities emerge out of the factors traditionally discussed in the literature on technical innovation: learning curves, economies of scale, increasing informational returns, positive network externalities, barriers to entry, etc. Irreversibility occurs when these factors combine such that a particular trajectory of technological change and development is created, which effectively makes impossible alternative choices that were available earlier. This gives rise to a time dependence of technical choices and the occurrence of "lock-in" effects¹⁷. Beyond such a bifurcation point, market forces will reinforce the first choice in a self-fulfilling process. To give a single example, given the high research and development costs involved in a new automobile engine, it is unlikely that equivalent R, D and D risks will be incurred on electric cars, 2l/100 km gasoline engines or biofuel engines. As with gasoline engines in the early days of the automobile, choice of a particular technology will essentially prevent the development of alternatives.

More generally, beyond technical considerations themselves, the self reinforcing loops among technical choices, consumer demand and the geographical distribution of activities and human settlements explain the fact that particular sets of technological and behavioural options can be clustered into consistent packages which, at least for a rather long period of time, creates foreclosures of options in technology and innovations. These clusters are rather systematic in industries relying on network structures, such as energy, transportation or telecommunications because of the characteristics of their production function (e.g. discontinuities, economies of

¹⁵ Northwest Power Planning Council. 1991. "1991 Northwest Conservation and Electric Power Plan", Volume II, Portland, Oregon

¹⁶ Robinson, 1991, Stern and Aronson

¹⁷ Arthur, W.B. (1988), "Self-reinforcing mechanisms in economics". In : P.W. Anderson, K.J. Arrow, D. Pines (eds.) *The Economy as an Evolving Complex System*. Redwood City, Addison-Wesley, pp. 9-31

scale), the need for technical harmonization across the network, and their dynamic interactions with markets. This is particularly clear for transportation systems because of their linkages with urban and spatial dynamics. For example, trends observed in Western Europe over the past several decades could be expected to lead to a doubling of road freight on highways during the following 15 years under the influence of the Single European Market. However, if Austria and Switzerland maintain their policy of limiting international truck freight transport across their country for reasons of security, congestion and local environment, Europe will create over the next several decades two very different transport systems (combined rail-road versus road dominant) and will certainly have gone beyond a bifurcation point¹⁸. A similar choice is to be faced in the near future in many of large developing countries with far more dramatic consequences, as decisions are made how to expand road, rail and air networks to respond to large increases in the demand for personal mobility and freight transport.

2.1.2 Current and Future Socio-Economic Development Patterns

Six factors are likely to give rise to different development path underlying different baseline emission levels and different cost curves for emission reduction or adaptation. We will describe briefly their nature so that to point out to what extent that such factors are amenable or not to conscious control or choice. The critical issue is that many of the decisions apt to control the long term paths will usually be taken for reasons that have nothing to do with energy policy or climate change issues and very often taken "in passing" without explicit public policy.

2.1.2.1. Material and energy content of development in industrialized countries

An important determinant of GHG emissions in any economy is the raw material intensity of that economy: the amount of matter and energy used per unit of economic activity. Broadly speaking, for any given level of economic activity, the lower the raw material intensity, the lower the GHG emissions. Over the past several decades, the raw material intensity of industrialized countries has dropped significantly.¹⁹ An important question is whether such reductions in industrialized economies simply reflect the shifting of energy and matter intensive activities to other countries, in which case the net effect may be to hold constant or even increase global raw material intensities, or whether there is a net reduction in the energy and matter intensive activities themselves.²⁰

Some of the major socio-economic factors that will effect the future raw materials intensity of industrialized economies are:

- structural shifts in the economy towards services;
- increases in the "information-intensity" of industrial processes, goods and services²¹;
- the effects of telecommunications on travel and transportation energy use²²;

¹⁸ Hourcade, J.C., 1992. "Modelling Long Run Scenarios: Some Methodological Lessons from a Prospective Study on a Low CO2 Intensive Country", *Energy Policy*, November.

¹⁹ Bernardini, O. and R. Galli, "Dematerialization: Long-Term Trends in the Intensity of Use of Material and Energy", *Futures*, May, 1993, pp. 431-448; Williams, R., "Materials, Affluence and Energy Use", *Annual Review of Energy*, Vol 12, 1987, pp. 99-144.

²⁰ *Energy Environment and Sustainable Development: Challenges for the 21st Century*. 16th Annual International Conference of the International Association for Energy Economics, Nusa Dua - Bali, Indonesia, 27-29 July, 1993

²¹ Chen, X. 1994. "Substitutions of Information for Energy", *Energy Policy*, January, 15-27.

²² Selvanathan, E. and Selvanathan, S., 1994. "The Demand for Transport and Communications in the United Kingdom and Australia", *Transportation Research B*, Vol 28B, No. 1, 1-9.

1 - saturation in the consumption of some goods and services, and the emergence of new goods
2 and services.

3
4 Clearly quite different configurations of these factors are possible, resulting in potentially large
5 differences in raw materials intensities, independent of the size of the economy. It is also clear
6 that emission reduction costs per unit of economic activity (e.g. dollars per unit GDP) will
7 depend on both the mix and level of such intensities and will necessarily vary among economies
8 with different structures.

9 10 2.1.2.2. *Links among energy, transport and urban planning*

11
12 Transportation energy use accounts for a significant proportion of GHG emissions²³ and its
13 growth rate is higher than the one of other categories of energy demand. More critically it is
14 the only one energy use not drastically decoupled from economic growth after the oil shocks.
15 This does not demonstrate that prices effects are nul in this sector but that they play on the
16 long term together with other structural determinants which difficults shifting trends in this
17 sector. The size and type of those emissions are indeed a function of the demand for
18 transportation services (i.e. the amount of travel), the mode chosen (auto, air, bus, rail), the
19 efficiency of the vehicles and the types of fuel used. The first two of these, in turn, are greatly
20 influenced by, and influence, the size and configuration of cities and towns²⁴. Important factors
21 are:

- 22 - the location of housing relative to jobs, schools and retail outlets;
- 23 - the distribution of retail trade and industrial activities within the region;
- 24 - the road and rail network within and among different cities and towns;
- 25 - the investment in, and choice of, public transit systems

26
27 Beyond these specific urban planning issues are a whole set of questions related to the
28 development of new transportation systems and technologies.²⁵ The growth in personal
29 mobility in industrialized countries over the past several centuries has been closely correlated
30 with technological advances in the types of vehicles used, the availability of fuels, and the
31 transportation infrastructure created. In turn, such factors interact in complex ways with urban
32 form and development, and directly affect both the prospects for, and the costs of, GHG
33 emission reduction. For example, the level of future automobile emissions will depend in part
34 on the degree of saturation of automobile densities in urban areas, due to the availability of
35 effective air and high speed ground transportation alternatives²⁶. For example, most of the
36 increase in atmospheric pollution verified in the metropolitan area of Sao Paulo, has been
37 associated to a reduction in the average vehicle speed from 28 kilometers per hour during the
38 eighties to 20-24 km/h in 1993²⁷.

23 In 1989, the range for Europe and North America was 20-35% (World Resources Institute. 1993. *World Resources, 1992-3*, New York: Oxford University Press.

24 Newsman, P., Kenworthy, J. 1989. *Cities and Automobile Dependence: An International Sourcebook*, Borrickfield, USA: Gower Technical;

25 Ross, M., 1989. "Energy and Transportations in the United States", *Annual Review of Energy*, Vol 14, pp. 131-171.

26 Grübler, A., Nakicenovic, N., Schäfer, A., 1993. "Dynamics of Transport and Energy Systems", International Institute for Applied Systems Analysis, Report RR-93-19, December.

27 CETESB, Companhia de Saneamento Basico do Estado de Sao Paulo "Relatorio de Qualidade do Ar em Sao Paulo" Secretaria de Saneamento e do Meio Ambiente do Estado de Sao Paulo, Sao Paulo, Maio 1994.

1 Clearly, quite different configurations of these factors can be envisaged and transportation is
2 typically a field in which bifurcations towards contrasted paths may occur in any region of the
3 world and these alternatives would have major impacts on emission reduction options and
4 costs. As explained earlier the costs of transportation sector emission reduction for a
5 population dependent largely upon automobile transport in highly dispersed suburban
6 developments would be very different than for a population located at the core of dense urban
7 agglomerations with a well-developed urban transit infrastructure. Since towns and cities take
8 shape, and change, over periods measured in decades and centuries the full effect of alternative
9 transportation developments will be manifest only in the relatively long-term and a high
10 uncertainty stems from the long run impact of short term decisions (or non-decisions).

11 12 2.1.2.3. *Land use and human settlements*

13
14 This issue concerns all the regions of the world but its numerical impact is more impressive in
15 developing countries. Land use and human settlement pattern changes derived from
16 agricultural and forestry activities as well as rural-rural and rural-urban migrations are among
17 the main sources of GHG emissions in these countries. In many African countries urban
18 population growth accelerates rural deforestation due to a rapid increase in charcoal
19 consumption in the cities, which requires approximately double the amount of wood to be
20 harvested per meal cooked, compared to the rural cookstoves using fuelwood directly.
21 Deforestation in the Amazon region is a complex phenomenon mainly caused by the expansion
22 of the road network, logging and cattle raising activities, agricultural production and
23 population growth fostered by rural-rural migrations due to the absence of guaranteed access
24 to land (agrarian reform) in other regions.

25
26 These examples show that emission reduction cost estimates that don't take account of such
27 institutional factors can be very misleading. Hidden costs can be very important when one
28 considers the institutional capacity building needed, on the one hand, to prevent the harvesting
29 of a very low cost natural resource such as a native forest, and, on the other, to enforce instead
30 environmental protection, reforestation and forest management practices. Moreover, even
31 macroeconomic cost assessments don't tell the whole story: for instance, the whole GDP loss
32 resulting from completely halting the development of Amazon region would be very low
33 compared with overall Brazilian economic output, but this scenario is clearly inconceivable for
34 social, political and cultural reasons. Deep structural changes in these underlying factors will
35 often be required in order to make emission reduction strategies feasible.

36
37 In this field it is even more important than elsewhere to look at the "emission reduction
38 component" of more general development strategies instead of considering GHG emission
39 reduction measures on their own. Emission reduction costs are only one part of a larger set of
40 factors in such cases. For example, a first step towards increasing the relevance of a carbon
41 sequestration objective might be to link it with the preservation of biodiversity. This could
42 increase its political and social relevance, though it would make the task of quantifying
43 economic costs and benefits much more difficult.

44 45 2.1.2.4. *Development patterns in the Third World*

46
47 The importance of development pattern assumptions for the assessment of emission reduction
48 costs is of particular importance in the case of developing countries. As a major part of the
49 needed infrastructure to meet development needs is still to be built, the spectrum of future
50 options is considerably wider than in industrialized countries. The traditional approach of using
51 "business as usual" assumptions as the baseline is then particularly problematical.

Nor can one assume that developing countries will automatically follow the past development paths of industrialized countries. The significant transformations recently evident in the international economy and energy markets highlight the dangers of such an assumption. In this respect, we need to consider the structure of GDP in developing countries and how that structure might evolve given such global transformations. A crucial question regards the developing countries' share of the world production of highly energy- and pollution-intensive goods, such as steel and aluminum. For example, as the recent shift of heavy industries from the North towards developing countries begins to slow, economic output may increasingly come from services and other less energy intensive activities.

Moreover, technological choices in both the production and consumption sectors can substantially change critical parameters such as energy demand/GDP elasticities. Many extrapolation scenarios have been indeed written in the past ignoring that experience demonstrates that new countries entering in the path to development have been generally lower energy profiles than in the countries having developed sooner. This does not mean that the energy/GDP ratio will not increase in many of these countries and that increases in consumer purchasing power in many developing countries will not drive up energy demand growth rates. This means that these countries are not bound to pass by the same levels of energy intensity that countries such as United-Kingdom and USA in the past; they are not bound for example to adopt the same model of energy wasteful refrigerators that still are in operation in developed countries or to fail to include up-to-date technological improvements in factories, many of which will improve energy efficiency. More generally a growing interest in the preservation of cultural diversity might also favour in less energy intensive housing, transportation, leisure and consumption patterns, less resources consuming per capita than it is currently the case in the developed countries. One among other possible examples is related to avoiding low urban population densities that are coupled with long daily trips to work and large shopping centers by car.

Finally, the spatial distribution of the population and economic activities is still not settled, offering formally the possibility of adopting urban/regional planning and industrial policies directed towards rural development and strengthening the role of small and medium cities, thus reducing the extent of rural exodus and the degree of demographic concentration in large cities. But, given current heavy trends towards huge conurbations, it is uncertain that it is still possible to shift them over the next century; anyway we are faced here to a large socio-economic inertia that can be overcome only gradually through steady long term policies. This is not an argument for discarding the importance of spatial parameters. The difficulty to shift current trends must be indeed weighed by their impact on some sectoral dynamics. For example more decentralized development patterns than typical of industrialized countries, could facilitate tapping large amount of natural resources available in developing countries through the use of modern technology (biotechnology, solar energy, wind and small scale hydro power). In the same ways it could change the needs for transportation and ease forest valorisation.

These examples show that developing countries might be in position to adopt anticipative strategies directed to avoid in the long-term some of the problems faced today by industrial societies. For example, in industrialized countries, energy demand/GDP elasticities first increased with successive stages of industrialization (with an acceleration during the fifties and sixties), but have sharply decreased since then, due to a number of different factors: relative growth of services in the share of GDP, technical progress induced by higher oil prices and

energy conservation efforts, etc.²⁸ Developing countries could follow a path leapfrogging these intermediate stages and leading directly to less energy intensive development patterns, thus avoiding a large increase in energy/GDP intensities in the short and medium terms (the so-called "tunnel effect").²⁹

Such possibilities for alternative development patterns highlight the technical feasibility of low carbon futures in the South compatible with national objectives. But, in the opposite direction, past and present experience suggest that these countries might not be in position to switch towards low GHGs emitting profiles. The recent experience of economic stagnation or recession in a substantial set of developing countries, demonstrates for example that the access to superior technologies may be limited by the increase of the share of second hand equipments or the import of obsolete technics and products. Along the same line the prevailing endebtmnt of many countries could prohibit the adoption of interurban transportation infrastructures or of urban infrastructure necessary to reach balanced human settlement patterns. As a whole, barriers to a more sustainable development in the South can hardly be underestimated, ranging from insufficient capital stock to use the same technologies than in developed countries, the tariff and non-tariff trade barriers, the organisation of international trade, international financial environment to the distribution of national income, and very often the lack of appropriate institutions to use the indigenous technical and economic capabilities of these countries.

This means that the switching towards very contrasted development patterns will depend upon the removing of these barriers, the setting up of a more conducive context by national public policies and the evolution of international economic relationships. Development theory did not provided so far analytical tools to enable modellers to discriminate among very contrasted possible development patterns.

2.2 Modeling Development Paths and Mitigation Costs

It is clear from the preceding discussion both that underlying socio-economic conditions will have an important effect on futures GHG emissions and costs of emission reduction, and also that there exists great uncertainty about how those conditions may evolve over the next century. The very degree of these uncertainties could lead to suspect any attempt to model long term economic development to be a pure futurology. But, on the other side, it has become compulsory to have a scientific understanding of the implication of possible long trends. Efforts to curb down greenhouse emissions over the following decade would indeed appear useless if it would be proven that there exist no additional flexibilities for longer time horizons. But this imply to precise the status of modelling exercises in this context.

2.2.1 Prediction and Simulation: The Need for Multiple Baselines

The uncertainty we have to confront goes beyond the uncertainty that is associated with a conventional "base case" emissions forecast or scenario. The point here is not the familiar one that individual base case forecasts or scenarios are uncertain with regard to exogenous

²⁸ Martin, J.M., 1988. "L'intensité énergétique de l'activité économique dans les pays industrialisés: les évolutions de longue période livrent-elles des enseignements utiles?", n° 4, *Economie et Société*, pp. 9-27; Darmstadter, J.; Dunkerley, J.; Alterman, J.; "How Industrial Societies Use Energy", Washington D.C., Resources for the Future, 1978.

²⁹ Berrah, N.E., 1983. "Energy and Development: the Tunnel Effect", Paris, *Revue de l'Energie*, n° 356, August/September.

parameters such as economic or population growth rates. It is that there exists a range of quite different socio-economic development paths that would give rise to different emissions scenarios and costs of emission reduction. Each of these development paths can be thought of as a base case, and each one will vary given different assumptions about economic or population growth rates (i.e. each is uncertain in the familiar sense). Moreover, to the extent that these different development paths contain the kinds of bifurcations and irreversibilities discussed above, it would be very difficult, and indeed misleading, to estimate a probability distribution for each long-term development path. Such bifurcations can be triggered by short-term decisions and actions that are not predictable.

The logical implication of this is the necessity to use multiple scenarios in order to account for uncertainties with regard to development patterns and the possibility of what economists call "multiple equilibria" in the long term. At time "t", there are several possible market equilibria at "t+n" (i.e. several states of the world characterized by different technical contents), and these are not easily predictable from current trends. From a pure analytical perspective it is possible to resort to some subjective or logical probability distribution in order to narrow these uncertainties among different scenarios and provide some kind of average scenario. But this could be misleading for decision making. The point is that these alternative base cases represent quite different, and internally consistent, patterns of development. Many of the uncertainties about such scenarios are due to the long term consequences of short term decisions or behaviours, and to the collective expectations regarding time "t+n" prevailing at time "t". In turn, these decisions, behaviours and expectations are part of a particular sequence of events, and cannot simply be combined with the components of other such sequences to produce an "average" or "most likely" sequence.

These concerns about the predictive value of models and the existence of possible multiple economic equilibria and their logical implications for policy-making are not new in various fields of socio-economic modelling. The origin of these concerns lies in the recognition of the limits of empirical forecasting methods that appeared by the end of the 1960s. This led to the development of approaches which tend to emphasize the unpredictability of alternative futures, the degree to which they are subject to partial choice, and the need for analysis of multiple alternatives.³⁰ In the energy field, approaches based on the concept of multiple scenarios were pioneered by Shell International Petroleum Company in the early 1970s,³¹ and have been adopted in various forms in the electric utility industry in North America.³² More recently there has emerged a set of more general analyses of long-term futures focusing on questions of surprise and alternative development paths defined in very broad terms³³.

³⁰ For discussion and examples of such approaches see Jantsch, E. *Technological Forecasting*, (Paris: OECD, 1967); Harman, W. *An Incomplete Guide to the Future*; Gault, F. et al. 1987. "The Design Approach to Socio-Economic Forecasting", *Futures* 19(1) 3-25; Gal, F. and P. Fric. 1987. "Problem-Oriented Participative Forecasting", *Futures* 19(6), 678-85; Glimel, H. and S. Laestadius, 1987. "Swedish Futures Studies in Transition", *Futures*, 19, 635-50; Godet, M. 1986. "Introduction to La Prospective", *Futures* 18(2) 134-57; Robinson, J. 1988. "Unlearning and Backcasting: Rethinking Some of the Questions We Ask About the Future", *Technological Forecasting and Social Change* 33(4) pp. 325-338.

³¹ Wack, P. 1985a "Scenarios: Uncharted Waters Ahead", *Harvard Business Review*, No. 5 (Sept/Oct) 72-89; Wack, P. 1985. "Scenarios: Shooting the Rapids", *Harvard Business Review*, No. 6 (Nov/Dec) 139-150

³² Southern California Edison Company. 1988. "Strategies of an Uncertain Future", Rosemead California; Northwest Power Planning Council. 1991. "1991 Northwest Conservation and Electric Power Plan", Volume II, Portland, Oregon.

³³ See FRN. 1987. *Surprising Futures*. Notes from an International Workshop on Long-Term World Development. Forskningsrådetsnamden (Swedish Council for Planning and Coordination of Research) Report 87:1. Stockholm: [SEI backcasting report]

In parallel to methodological concerns about the inadequacy of traditional forecasting techniques, there emerged over the same period a series of critiques of conventional "business as usual" views of the future, usually based on an explicitly "environmental" perspective. One of the most prominent of these early critiques was the Club of Rome's 1972 book *The Limits to Growth*³⁴, the publication of which stimulated a extensive debate about alternative development paths. This debate was fueled by the publication of a number of subsequent studies³⁵, including the Leontieff report launched to illustrate the International Development Strategy adopted by the United Nations in 1974.³⁶ An attempt to articulate a developing country perspective on these issues led to the publication of the Bariloche report, which presented a rather different development path for the South.

These studies provided fertile ground for the development of alternative energy modelling analyses, which were also triggered in part by the oil shock of 1973-74. These studies expressed concerns about possible long range limits in fossil fuel resources and about the risks likely to be involved in nuclear power. Following a major study by the Ford Foundation in 1974,³⁷ Amory Lovins' provocative "soft energy path" analysis³⁸ helped to launch many exploratory works in North America³⁹ and in many European countries⁴⁰ about the possibility of avoiding possible physical limits and nuclear risks. These studies were based upon what came to be called "bottom-up" methods of analysis and produced energy system projections that were significantly at odds with the "top-down" analyses prepared by governments, the energy industry and energy economists⁴¹ relying on extrapolatory approaches. In the early 1980s, the publication of the results of the IIASA energy study⁴² sparked a vigorous debate about both modelling methods and alternative energy futures.⁴³ Subsequent analyses continued to reflect the split between top-down and bottom-up analysis, but revealed a growing interest in global environmental issues such as global climate change, influenced in part by the publication of the final report of the World Commission on Environment and Development⁴⁴.

³⁴ Meadows, D., et al. (1972) *The Limits to Growth*. London

³⁵ Mesarovic, M. Pestel, *Mankind at the turning point* Ed. Hutchinson 1974

³⁶ Tinbergen, J. (1976) "Reshaping the international order", A report to the Club de Rome, E.P. Duttow and Co, New York, USA; Sachs, I., (1993) *Ecodéveloppement: stratégies de transition vers XXIe siècle*. Coll. Alternatives économiques, Syros, 120 p.

³⁷ Ford Foundation, (1974) *A Time to Choose: America's Energy Future*. Energy policy Project, Cambridge, Mass.: Ballinger

³⁸ Lovins, A. *Soft Energy Paths: Towards a Durable Pace*. (New York: FOE/Ballinger, 1978)

³⁹ CONAES (1980), "Panel on demand and conservation" in *Outlook for energy demand and conservation*, National Research Council, Washington DC; Stobaugh and Yergin (1979); Ross and Williams (1981); Friends of the Earth Canada (1983/4)

⁴⁰ Leach, G. (1979). *A low energy strategy for the United Kingdom*, The International Institute for the Environment and Development, Sciences Reviews Ltd, London; Sorensen, Krause (1981); Norgaard, others

⁴¹ See the country case studies in Baumgartner, T. and A. Midttun. *The Politics of Energy Forecasting. A Comparative study of energy forecasting in Western Europe and North America* (Oxford: Oxford University Press, 1987). See also Caputo, R. "Worlds in Collision", *Futures*, 16, 1984, pp. 233-59. For a discussion of the bases of disagreement, see Robinson, J., "Apples and Horned Toads: On the Framework-Determined Nature of the Energy Debate", *Policy Sciences*

⁴² Haelele, W. *Energy in a Finite World: A Global Systems Analysis*. (Cambridge, Mass.: Ballinger, 1981).

⁴³ Keepin, B. and B. Wynne (1987) "The Roles of Models - What Can We Expect from Science? A Study of the IIASA World Energy Model" in T. Baumgartner, A. Midttun, *The Politics of Energy Forecasting*, Oxford, Clarendon Press, pp. 33-57; See also Thompson, M. "Among the Energy Tribes: A Cultural Framework for the Analysis and Design of Energy Policy", *Policy Sciences*, 17: 321-39

⁴⁴ World Commission on Environment and Development, (1987) *Our Common Future*. Brundtland, G.H., Oxford, New York, Oxford University Press.

and the subsequent UN Conference on Environment and Development in 1992.⁴⁵ Throughout this period, a major bone of contention has been how best to analyze alternative patterns of development and technological change that represent significant departures from past trends.

These debates are not restricted to applied analyses. They have been raised in many fields of social science theory concerning such issues as the plurality of economic equilibria generated by different sets of expectations (such as the works about the so-called "sunspot theory"⁴⁶); self-fulfilling or the self-defeating prophecies⁴⁷; "common-knowledge" and "conventions"⁴⁸; the coordination game⁴⁹ or, more generally the outcome of repeated games in game theory⁵⁰; and chaotic behaviour and surprises.

2.2.2 Economic Modeling and Development Trends: Some Limits

There is perhaps an unavoidable gap between advanced thinking in social science theory, and the empirical tools available, given computational constraints, data availability and the priorities adopted by research funding institutions. Nevertheless, over the past two decades the state-of-the-art of long-term policy-oriented energy system modeling has evolved very rapidly, due in large part to significant progress in energy-economy modeling. This progress has been driven by questions raised by the oil shocks of the 1970s, perceived risks of resource exhaustion, the nuclear debate, and climate change issues.

Progress has also been made in modelling other sectors such as transportation or agriculture. However, less attention has been paid in this work to the linkage between sectoral analysis and a more comprehensive economic framework than in energy sector analyses, where policy-makers have been very interested in the macroeconomic imbalances caused by oil imports and price increases (external debt, inflation, and unemployment). Moreover, the initial focus on energy-related GHG emissions has meant less attention has been paid to the GHG emissions of other sectors. As a result, the state-of-the-art of modelling in the energy field serves as a useful indicator of the difficulties of representing alternative development paths in current models.

Macroeconomic econometrically driven "top-down" models, initially build for the purpose of economic policies usually contained rather aggregate sectoral demand functions (one or two energy services, one composite food product, for example); they consequently capture future development and technological trends in the econometric relationships among standard econometric indicators. Using them in long term analyses amounts to extrapolating current trends in the relationships among key variables, on the assumption that historical changes in these relationships capture the essence of likely future responses to changes in input variables such as the future price of energy, food or wages. Such analysis provides very useful "counterfactual" information on, say, the aggregate impact of a carbon tax relative to some assumed base case, but they do not pretend to have a predictive value on the very long term and as regards to, say, bifurcations in the transportation sector.

⁴⁵ For examples of more recent bottom-up work, see Goldemberg, J. et al. (1988) *Energy for a Sustainable World* (New Delhi: Wiley-Eastern Ltd.; Johansson, T. et al. (1993) *Renewable Energy: Sources for Fuels and Electricity*. Washington, D.C.: Island Press;

⁴⁶ Azariadis, C., Guesnerie, R. (1986) "Sunspots and cycles" *Revue of Economic Studies*, 53: 725-737.

⁴⁷ Henshell, R.

⁴⁸ Lewis, D. K. (1969) *Convention: a philosophical study*, Cambridge, Harvard University Press; Aumann, R. J. (1987) "Correlated equilibrium as an expression of bayesian rationality", *Econometrica*, 55(1), pp. 1-18;

Dupuy, J.P. (1989) "Convention et Common knowledge" in *Revue économique*, vol. 40, n°2, mars, pp. 361-400

⁴⁹ Schelling, T.C. (1960), *The Strategy of conflict*, Cambridge (Mass.), Harvard University Press

⁵⁰ Fudenberg, D. Tirole, J. (1991), *Theory Game*, MIT Press, 579 p.

"Bottom-up" models have historically been designed for the specific needs of a given sector (e.g. energy, transportation, forestry), and in the energy field are sometimes linked to standard macroeconomic models. They give a disaggregated picture of demand and supply, and point out potential gains in efficiency from specific technologies or the potential for substitution to carbon free technics. Such models rely on rather precise descriptions of end use and production technologies (e.g. appliance penetration and usage rates, building heat loss coefficients, tonne-kilometers of freight transportation), but typically do not contain much treatment of feedbacks between these parameters and underlying economic variables (for example feedbacks between energy efficiency savings and employment, or consumption behaviour for other goods and services). The lack of macroeconomic behavioural feedbacks means that such models are best suited for "what if" simulation analyses, rather than prediction.

Virtually all of the modeling analyses of GHG emission reduction undertaken to date have used some form of these two approaches to energy/economy modeling or of coupled models. We will enter a more detailed discussion of the difference between these approaches in sub-section 3. The point here is simply that, to date, neither set of models has been used to address the issues of alternative development patterns and technological change that have just been identified. Instead, the models have been used to analyze the effect of certain policies (typically tax policies in the case of top-down models, and the implementation of specific energy-using technologies in the case of bottom-up models) given implicit assumptions about development paths.

This suggests that existing emission reduction cost studies are meaningful at the margin of a given development path which in turn means that they are valid:

(i) as long as historical development patterns and relationships among key underlying variables will hold constant in the projections period (top-down analyses), and

(ii) if there are no important feedbacks between the structural evolution of a particular sector in an emission reduction strategy and the overall development pattern (bottom-up analyses).

2.3 Multiple Baselines, Uncertainty and Long-Term Mitigation Costs

The preceding discussion explains why there is a growing consensus among experts on the necessity to work with multiple baseline scenarios when long term horizons are under consideration, namely scenarios would represent different internally consistent sets of assumptions concerning the factors discussed above and not simple variants generated by altering input parameters of a given extrapolatory model (which is obviously relevant for short term horizons). The point is not to predict what long-term outcomes are most likely (an exercise at which few have been successful⁵¹), but to explore the economic and technical feasibility and costs associated with quite different development paths. This would make it possible, for example, to respond to the frequent request for the development and analysis of "sustainable development" or other scenarios that represent very different assumptions about economic and technological development paths and "lifestyle change" than those contained in traditional analyses.

⁵¹ Ascher, W. *Forecasting - An Appraisal for Policy-Makers and Planners*. (Baltimore: Johns Hopkins University Press, 1978); Ascher, W. "Beyond Accuracy", *International Journal of Forecasting*, 5, 1990, pp. 469-84.

Despite difficulties involved in broadening the scope of analysis, significant progress in the use of modelling methods have been made to respond to these requirements at least partially. This is in particular the case for developing countries and economies in transition where all the difficulties associated with generation and assessment of baseline scenarios are exacerbated; in these contexts testing several hypothesis about structural change has become common practice⁵². But it is still impossible to address many critical issues such as potential bifurcations in urban form driven by differences in the relative weight of rail, automobile and bicycle traffic in Eastern Europe, or quite different possibilities for land use or consumption patterns in developing countries.

These limitations of current methodologies heightens the need for making explicit what type of structural determinant is explicitly accounted for in each baseline scenario and what type is considered as fixed. sensitivity testing of modelling analysis, together with viability testing to ensure the overall consistency of long term projected trends, given financial, political and institutional constraints. Along this line, note that it is important to avoid the common mistake of using arguments about the inadequacies of existing models to project wishful thinking about future development options and emission reduction strategies.

Beyond these technical difficulties we would like to emphasize two major issues stemming from the existence of several baseline scenario.

2.3.1 Multiple Baselines and the Non-Comparability of Cost Assessments

Given that contrasted underlying assumptions about development patterns can give rise to a number of quite different types and levels of GHG emissions, and of emission reduction costs and potentials, a comparison between cost assessments theoretically requires an evaluation of baseline and mitigation scenario assumptions, including technology data. Such an evaluation should identify key determinants and assumptions behind the cost estimates in order to explain differences. Without a comprehensive and transparent documentation of the full set of scenario assumptions any comparison of cost estimates coming from studies with very different baseline scenarios, will be misleading. For example, an emission reduction scenario derived from a baseline scenario that incorporates substantial air quality improvements for reasons unrelated to climate change is likely give rise to GHG emission reduction cost estimates per unit of reduction higher than an emission reduction scenario derived from a baseline scenario without such improvements.⁵³ Similarly, emission reduction cost estimates would vary depending on the transportation infrastructure assumed in the baseline scenario.

Moreover, given the difficulties of incorporating the feedbacks between development patterns and economic variables discussed above, a baseline scenario that gives rise to lower estimates of emission reduction costs cannot be interpreted as being economically superior to other baselines. Such lower cost estimates simply mean that the incremental costs of emission reduction relative to that baseline are lower than the incremental costs relative to some other baseline. However, this leaves unanswered the question of the relative costs (e.g. transaction or political costs) of achieving these different baseline scenarios. Since different baselines represent different development paths, each of which is potentially an "efficient" scenario, they

⁵² For a discussion of some of these differences, and their implications for different regions of the world, see Paul Kennedy, *Preparing for the Twenty-First Century* (New York: Harper Collins Publishers, Ltd., 1993).

⁵³ Since the former baseline already incorporates such improvements, the cost per unit of further reduction is likely to be higher than relative to a baseline without such improvements.

cannot be directly compared and no overall relative cost assessment is possible. Two historical examples help to illustrate this debate is far from being a simple intellectual fancy.

If the climate debate had emerged in 1973, just before the decision to launch the nuclear program in France, any assessment of emission reduction costs should have considered two possible baseline scenarios:

- the first without the nuclear program, and consequently a higher CO₂ emission level; in this case the projected cost of the nuclear program could have been included in the emission reduction costs; and

- the second including a nuclear program and a resultant lower emission level; the emission reduction requirements would have been lower, but paradoxically the costs of an incremental emission reduction of, say, 20% would be far higher.

Beyond the fact that assessing the relative costs of two totally different energy systems is technically difficult (for example in the non-nuclear case France would not have developed electrical heating to the degree it did), the critical point is that the nuclear choice would not have been made, in practice, purely for climate-related reasons and that in any negotiation French administration would have tend to argue the contrary so that this program would have been considered as a specific contribution to a collective climate policy.

In the opposite direction, both the baseline and emission reduction scenario are very different in the Brazilian case depending upon assumptions about the future of its biomass ethanol program. Eventhough, when it was first implemented in 1975, no environmental consideration was taken into account for its justification, the existence of this program can be shown to lead to both a lower emissions baseline and lower emission reduction costs. So far, many questions are still pending with regard to the overall costs and benefits of this program in terms of macroeconomic impacts, distributional effects, refining structure of oil or innovation. The choice of a baseline with or without "pro-alcool" will entail many types of transaction and political costs and will have many external effects, which are very hard to assess.

In both cases, the best analytical strategy is to recognize that different baselines are possible and that any emission reduction cost estimates are only relevant at the margin of each baseline, not in absolute terms.

2.3.2. Mitigation and Prevention: An Uncertain Baseline

In order to understand the potential for greenhouse gas emission reduction it is necessary to combine natural science information about the possible biophysical implications of various types and levels of GHG emissions with social science information on the human causes and consequences of such emissions and the potential for various forms of response to those consequences. This requires the development of baseline scenarios that combine this information. In the short term, it seems reasonable in building such baselines to project human and natural systems and their interactions in ways that do not depart radically from past experience. In the longer-term time horizons required to assess the evolution of changes to the global climate system, however, such a procedure is more problematical even if it remains the only one possible under current modelling constraints.

An example of this difficulty is illustrated in the conventional distinction between adaptation to, and mitigation of, climate change. In the short term, the meaning of that distinction is clear:

mitigation means reducing sources of emissions and/or increasing sinks (i.e. reducing the causes of climate change), while adaptation means improving our capability to withstand changes in the global climate system (i.e. responding to the effects of climate change). In the longer term, however, the distinction between mitigation and adaptation begins to blur. Not only will measures adopted to serve one goal have significant consequences for the other (e.g. some energy efficiency measures adopted to reduce emissions may make energy systems more resilient to climate variability) but many policies adopted for other reasons will have both adaptive and mitigative effects (e.g. urban planning decisions).

Indeed, in the long term, both "mitigation" and "adaptation" measures are part of the long-term adaptive responses of societies to a whole host of conditions and perceived problems, only a small number of which have to do with climate change. From this point of view, it is not entirely clear what should be understood by a "reference case" or "non-intervention" scenario in the long term even if, for practical reasons, all the existing studies adopt this convention.

All of these issues suggest that there is considerable work to be done to improve our capability to assess alternative patterns of development and technological change and their interactions with the costs and impacts of alternative emission reduction strategies. That being said, there is much that can be learned from existing cost analyses, to which we now turn. Before presenting a review of such studies, however, it is important to examine in more detail the manner in which one category of these development patterns characteristic, namely technological change, is treated in existing modelling analyses and, in particular, the debate between "top-down" and "bottom-up" approaches that was introduced above.

3. Modeling technology dynamics, consumption behaviours and economic feedbacks of climate policies

3.0 General Methodological Considerations

It is difficult to disentangle the various reasons for the apparent disparities in modelling results, given (1) the diversity of tools used to calculate cost estimates, (2) the many and varied assumptions employed, and (3) the disparities in geographical coverages of different studies.

Historically the debate has been framed by the distinction between "top-down" and "bottom-up" studies. Basically, top-down models analyze aggregated behaviours based on economic indices of prices and elasticities; these models began mainly as macro-economic models that try to capture the overall impact of a climate policy, that policy being usually in the form of tax because of the difficulty of assessing other types of policy instruments. Bottom-up models rely on detailed analysis of technical potential, focusing on the integration of technology costs and performance data.

In fact, as explained further, not all models fall neatly into one of these two categories and several "hybrid models" are now available in which analysts attempted to merge top-down and bottom-up model characteristics. We will see also that divergences are increasingly recognized as coming from assumptions behind the models and not from the modelling techniques per se. However, the discussion in this text will maintain the dichotomy to the extent that each approach was historically used to sort out different pieces of informations required for setting up climate policies and that this distinction remains meaningful for understanding some critical policy issues.

The top-down/bottom-up categorization has indeed been portrayed as opposing the optimism of the "engineering paradigm" to the pessimism of the "economic paradigm" (Grubb, Edmonds et al 1993). From an engineering standpoint the evidence is that the best available technologies have not been adopted so far; this "efficiency gap" is for example the gap between the energy efficiency of equipment actually chosen by consumers and the energy efficiency of the technology that could theoretically minimize the costs entailed for providing a given amount of energy service. Bottom-up models are capable to put very easily this "efficiency gap" into evidence and concluded that, thanks to "negative cost measures", substantial emission reductions could be achieved with low taxes and low costs or even net savings.

In response, the professional reflex of many economists was to call attention to the reasons why consumers do not adopt technologies that appear to be optimal and tended to suggest that accounting for these reasons together with the economic feedbacks of a given policy would reduce the magnitude of, or eliminate, the efficiency gap that is actually achievable. Top-down macroeconomic models concluded, at least in a first phase, that relatively large carbon taxes would be required to counter current emission trends, which would result in significant economic costs.

In fact, the methodological difficulty is how to describe the processes of technology adoption, the decision making behavior of economic agents, the feedbacks between any public policy measures on the overall economy and how markets and economic institutions actually operate over a given period of time. From this viewpoint the opposition between "top-down" and "bottom-up" methodologies does not fully represents the whole spectrum of critical issues. That

1 is why, before entering the lessons of this controversy in the energy field and in the forestry
2 field, we would like to sketch the critical dimensions of a typology of existing models.

3 3.1. Critical dimensions of a typology of existing models

4 3.1.1 Diversity of models, diversity of purposes

5
6 Numerical figures of a model cannot be interpreted in the same way for decision making
7 depending upon a given scenario is used to predict (forecast) the future, to explore it, or as a
8 tool for "backcasting" exercises.

9
10 Many models try indeed to "predict" (forecast) the future and to determine the implementation
11 of the policy likely to minimize the costs of achieving a target of GHG emission reductions.
12 This purpose imposes very strict methodological constraints on the modeler. He must execute
13 a base case forecast, which amounts to a best guess projection of the most likely future; to do
14 this requires an endogenous representation of economic behavior and general growth patterns.
15 Indeed, to forecast means, for an economic modeler, that it is possible to derive
16 econometrically from current trends the description of the laws of motion of economic growth
17 in a given period so that it becomes possible to extrapolate these laws without, or with the
18 minimum of, exogenous ad hoc hypotheses. This approach has been typical of government and
19 sectorial forecasting activities (in energy, transport, heavy industries such as steel industries)
20 and in early climate change scenario analysis. It remains both necessary and convenient for
21 analyzing the short term impacts of climate policies; a number of critical underlying
22 development variables can reasonably be assumed to remain constant for these time periods.
23 Most of short-term, econometrically driven macro-economic models work in this perspective;
24 for the long-term (middle of the next century), the Jorgenson-Wilcoxon model is the only one
25 of these type of models that can be classified in this category. It is noteworthy that none of
26 these models tries to work on the basis of forecasts of explicit technological trends, in the
27 engineering sense.

28
29 Because of the difficulty to extrapolate past trends over the long run, the purpose of some
30 modellers is to "explore" the future and in so doing to provide counterintuitive assessments.
31 This leads to a scenario analysis approach⁵⁴, which involves building up different coherent
32 visions of the future (each of which, of course, can undergo sensitivity testing) based on
33 different values for key assumptions about economic behavior, physical resources endowments
34 or technical progress together with assumptions on economic or population growth. The first
35 step in such analyses is the generation of a "reference" or "non-intervention" scenario. This is
36 then contrasted to alternative cases involving an array of policy measures, such as carbon taxes
37 or energy efficiency regulations, giving rise to one or several "policy" or "intervention"
38 scenarios, but the policy analysis is relevant only in the context of each baseline scenario. This
39 approach is increasingly used for climate change analysis and was the basis for the 1992 IPCC
40 scenarios.⁵⁵ It is shared by both the bottom-up and top-down type⁵⁶ models and indeed tends

54. This comes to recognize the range of uncertainties in the long-term; some attempts have been made to resort to some kind of probability analysis such as the Monte-Carlo approach in which one tries to determine the scenario with the maximum expected value (REF); this procedure meets a logical impossibility in the case of possible bifurcations in development trends.

55. Leggett, J. et al, 1992 "Emissions Scenarios for the IPCC: An Update", in Intergovernmental Panel of Climate Change, *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment* Cambridge; Cambridge University Press.

56. For example, Environmental Protection Agency. 1990 *Policy Options for Stabilizing Global Climate*. Report to Congress, edited by D. Lashof and D. Tirpak, EPA, Washington, D.C.; Edmonds, J. et al. 1986.

1 to favour the development of hybrid models (which will be discussed at greater length below).
2 In terms of representing and simulating the behavior of economic agents, two methodologies
3 predominate. One involves an assumption of least-cost optimization, in which society
4 maximizes over the long-run the utility of consumption. The other involves the effort to
5 predictively simulate real world behavior in terms of technology adoption leaving aside the
6 optimisation hypothesis.

7
8 Finally, another possible purpose of models is to assess the feasibility of alternative futures,
9 often defined in terms of desirability rather than likelihood. This contrasts with the two
10 previous approaches in so far as it involves the development of a vision of a future state of the
11 system being studied, and then an analysis of how that future system might be realized. This
12 "backcasting" methodology allows for identification of major changes as well as
13 discontinuities in present trends that might be required if a desirable future is to be attained.⁵⁷
14 Two types of research can be carried out in this approach. Most involve normative scenarios
15 about desired futures such as the many alternative energy studies referenced as belonging to
16 this category. But it is also possible to use a backcasting methodology as a purely analytical
17 tool by simply linking bottom-up analyses about technology evolution to a macro-economic
18 framework such as in the preliminary attempts at Imacim model (Hourcade, 1993), so as to be
19 able to assess the economic consistencies behind different and competing views about the long
20 run.

21 3.1.2. Two different representations of technology: the meaning of the "aggregation gap"

22
23 The terms "top" and "bottom", in the usual jargon of the economic modeler, are commonly
24 linked to the distinction between aggregate models and disaggregate models. This demands
25 clarification. The top-down label is indeed derived from the way in which the first
26 energy-economy models were constructed. The developers of these models applied
27 econometric techniques to data on consumption, prices, incomes and other variables to
28 estimate price and income elasticities of final goods and services such as energy,
29 transportation, food, industrial products. These models were criticized for not providing a
30 complex enough description of the determinants behind sectoral demand dynamics. Simulation
31 technico-economic models were then developed in order to understand why the income
32 elasticity of energy or transportation demand could evolve over time and to explore the
33 potential for a possible decoupling between these needs and economic growth. This required
34 "bottom-up" disaggregated analysis of technical alternatives and demand for specific services.

35
36 In fact, many macro-economic models are also very detailed, but not in the same way: they
37 account for two digit typologies of economic activities and can broke down the consumer
38 demand into many household types. In many models the so-called aggregate demand functions
39 of consumer expenditure are constructed by summing "individual demand functions", which
40 dispenses with the simplistic notion of there being a "representative consumer". More
41 precisely, each category corresponds to a "representative consumer" and this level of
42

Future Atmospheric Carbon Dioxide Scenarios and Limitation Strategies. Noyes Publications, Park Ridge, New Jersey; Manne, A. and L. Schrattenholzer, L. 1993. "Global Scenarios for Carbon Dioxide Emissions", *Energy*, Vol 18, No. 12, 1207-1222; Johansson, T., et al. 1993. "A Renewables-Intensive, Global Energy Scenario", in Johansson, T. et al. *Renewable Energy: Sources for Fuels and Electricity*. Washington, D.C.; Island Press.

57. Robinson, John B.: "Futures Under Glass: A Recipe for People Who Hate to Predict", *Futures* 22:9 (1990) 820-843; Robinson, John B. "Unlearning and Backcasting: Rethinking Some of the Questions We Ask About the Future", *Technological Forecasting and Social Change* 33:4 (1988) 325-338.

disaggregation allows for testing the income distribution effects of various types of climate change policies.

But, from an engineering standpoint, the most detailed top-down models are considered to be too aggregated because even detailed individual household demand functions only allocate that demand among a very limited number of commodity groups such as energy, food, non-durable goods, other services and investment. Energy is thus portrayed as two or three composite services whereas it would be useful to account for technological margins of freedom for cooking, heating, air conditioning and each type of transportation, etc. In the same way, even in a disaggregation of the industrial sector into around 40 to 60 sectors, energy will be grouped into two or three commodities whereas a process model would have to account for more complex representations of electrical load-curves and for a number of petroleum products (feedstock, gasoline, diesel, heavy fuels, light fuels, etc.). In the same way the specialist in agriculture will consider that to group agriculture into a single aggregated sector does not permit representation of the actual forces behind long term trends in food markets and other agricultural products and the impacts of these trends on land use, given the specifics of each region.

This initial dichotomy, which tends to be overcome by the building of coupled models, is in essence related to fundamental differences in the focus of the analysis. Macro-economists focus on financial flows across the whole economy and provide rather sophisticated analytical tools at this level, while sectorial specialists focus on the market dynamics stemming from a given industrial structure but with little consideration devoted to overall feedbacks with the rest of the economy, and, finally, engineers or (engineer-economists) focus on technical margins of freedom likely to be evidenced at a micro-economic level.

This aggregation gap tends obviously to be enlarged when longer time periods are under consideration. Many modelers consider the application of very disaggregated macro-econometric models to be impossible over too long time periods because of the lack of reliability of econometric relationships over such periods. The common practice used to achieve robust models over longer time periods is to choose higher levels of aggregations simply because the econometric relationships among these aggregated variable are generally more reliable and the behavior of the model more stable (the error terms for five original variables for example can compensate each other in the error term of a new composite variable). This explains why the most of medium term and long term models work with between 2 to 10 goods and services.

But, behind this difference in the aggregation level, lie two ways of representing technology. On the one side, one tries to capture technology in the engineering sense: a given technique (coke oven steel versus electric-arc steel, an incandescent light bulb versus a fluorescent light bulb) with a given technical performance at a given micro-economic cost. On the other side, the term technology in macro-economic models, whatever the level of disaggregation of the model, is represented by the share of the purchase of a given input in intermediate consumption (steel products to make cars for example) and by the allocation of the output (sales revenue) among the cost of intermediary inputs, returns to labour, and returns to capital. These shares constitute the basic ingredients of the economic description of a technology in which, depending upon the choice of production function, the share elasticities represent the degree of substitutability among inputs.

This characterization makes it difficult to establish explicit links between production functions in economic models, on the one hand, and technology projections, on the other. For example,

there is a gap between the findings of Jorgenson (1983) and Hogen-Jorgenson (1990) with respect to the negative correlation between technological change and energy prices in the U.S. economy and the observation of accelerated innovations at a technical level. The reason is that the term technology refers to two different things. For an economist, productivity growth is correlated with many other factors than mere technology characteristics; a depressed demand or growing uncertainties can result in a lower economic productivity even if the technical efficiency of equipments is very high. Consequently both descriptions can be internally consistent, but each may represent a different definition of technological change.

In the same way, the substitution among capital, energy and labour described in macroeconomic models does not necessarily mean that, at a micro level, enterprises confronted to a carbon tax will actually choose more labour-intensive processes in order to lower their energy requirements. This may of course happen but the macroeconomic substitution between energy and labor in macroeconomic models encompasses other processes than this technical substitution: energy savings due to changes in the use of equipment, changes in the structure of final demand in the direction of less energy-intensive goods, a decrease in the level of risk taken by an entrepreneur when employing someone, etc. All such factors will affect the substitution between energy and labor, even without any change in the technical characteristics of the production technique itself.

These factors mean that both descriptions of technology and technological change make sense but each captures a different aspect of that change. Many misunderstandings result from ignoring these differences.

3.1.3. Representing how do market mechanisms operate with regard to innovation and technology adoption?

Both top-down and bottom-up models operate under the presumption that firms and households exhibit some form of profit or utility maximization: a firm is assumed to minimize costs subject to a given output requirement and a household is assumed to minimize costs subject to a given service requirement.

Since their approach is more normative than positive - demonstrating what ought to occur rather than predicting what might occur - bottom-up models operate from the presumption of life cycle cost minimization. The models use all available information on capital and operating costs, and then apply a social discount rate to determine the optimal technology for each end-use services, be that for production decisions or consumption decisions. These type of models use linear and dynamic programming techniques and apply them to the entire energy, transportation or agricultural system in order to find the set of cost minimizing technologies over time and space. Because these models optimize over the entire system, their solution algorithm requires iterative resolution in which each technology must be optimal within a whole set of technologies.

If this approach were assumed to be descriptive - as opposed to prescriptive - it would require the assumption that all economic agents had perfect knowledge across time and space of the optimal technologies for each component of the system under consideration. Without such an assumption, analysts would need to modify the model's solution matrix somehow to incorporate real world attributes of decision making. For example, discount rates could be changed so that time preferences approximated private decision making instead of socially optimal behavior, and market shares of various technologies could be constrained to reflect some real world limitations.

While optimization models represent perhaps the extreme normative bottom-up approach, other bottom-up models and analysis focus more on the constraints over technical adoption and do not represent a fully optimized system.

Hybrid bottom-up approaches are emerging, in which the solution algorithm is modified in order to better reflect real world decision making behavior, nonetheless in the context of a technology centered simulation. Thus, discount rates will be modified between types of decisions (retrofit versus new) and types of decision makers (industrial versus residential). Technology life cycle costs may be converted from single point estimates into probability distributions, thereby incorporating market randomness attributes into the simulation of decision making. Differences in taxation practices may be incorporated into the calculation of life cycle cost. Survey perceptions of future price evolution may be applied to the calculation of life cycle cost. An additional "intangible cost" factor may be included to account for differences in consumer preferences between technologies. Finally, another way to account for these individual elements of real world decision making, is to use time series and cross section data to estimate econometrically the relationships between technology life cycle costs and technology adoption. These estimated relationships then become the internal behavioral parameters in a hybrid bottom-up model that attempts to descriptively simulate the response to various policies intended to reduce GHG emissions.

In macro-economic modelling approaches, the representation of economic behavior is still based on the same notion of cost minimization, but once again the resolution of the camera is different.

All macro-economic models include the requirement that supply equals demand and stipulate rules for how prices are formed. The simplest rule is that producers receive the same price that consumers pay, and that both producers and consumers take prices as given. These are the standard assumptions for characterizing a competitive market economy, and with these assumptions the model is solved by finding prices that cause supply and demand to be equal. In this case, the price of each good and services is equal to its marginal cost. But, this general equilibrium constraint is not sufficient to characterize the way markets operate.

With regard to market mechanisms, most of the long run models rely of either general equilibrium hypothesis or an optimal growth path hypothesis; this comes to assume that over the long run markets have time enough to overcome existing inertia and current inefficiencies. Conversely, many short and medium term models allow for many imperfections in the market structure; these imperfections are expressed by pricing rules (for example the average cost pricing rule, or the addition of a mark-up to the production cost) in order to account for the existence of monopolistic or oligopolistic structures not likely to change over the considered time period. These pricing rules have important implications for the efficiency of a market economy and tend for example to reduce price-effects. Second, most of these models rely on "keynesian dynamics", allowing for overcapacities and underemployment due to insufficient final demand, and include "putty-clay"⁵⁸ forms of production functions which introduce some rigidities in the adjustment. But this type of imperfections accounted for in the short and medium term models do not address the type of market imperfections under consideration in

⁵⁸ In a function putty-clay, the producer is assumed to choose without any constraints the new equipment the most efficient in function of the current (or anticipated) price-structure; but he can replace the old equipment vintages only under the constraint of some obsolescence rate; his productive capacity is then never totally optimal as regards to current price structure.

the top-down/bottom-up debate, which have to do with the adoption of technology and consumers behaviors.

Technically, the standard "top-down" solution comes to consider that the complexity of behavioural determinants in captured in econometric relationships about the own and cross price elasticities emerging from the estimated model parameters. But this can be interpreted in two different ways:

- markets behaves perfectly and the apparent "imperfections" pointed out by bottom-up models are simply due to the complexity of consumer preferences behaviours and of the existence of hidden transactions costs; the result will then be that there is actually no negative costs potentials,

- markets do not behave perfectly in a given activity field and econometric relationships implicitly convey these informations. There is then a room for no-regret improvement but this must be entered in the models in form of exogenous and ad-hoc assumptions. Calibrated models are flexible enough to convey such informations when econometrically driven models must accept "ad hoc" assumptions which confronts unsolved consistency problems when large departures from business as usual behaviours are to be considered.

3.1.4. Behaviors over the short term or the long term, two different questions addressed

There is no standard definition of the division line between short term and long term because this varies as a function of the technologies and infrastructures under consideration. For the specialist in energy, transportation or urban planning, the short term is generally up to five to ten years, whereas an analyst of economic policy assessing the impact of a devaluation or of a change in credit policy will consider the medium term to begin beyond two years. In terms of the linkages between climate issues and inertias in energy, transportation or land use, many models go beyond forty years.

This is why, instead of setting an arbitrary division line to distinguish between time horizons, it seems more convenient to define short term models as those focusing on the transitional response to a climate policy (disequilibrium effects, capital constraints, inflation) and long term models as those focusing on the long term equilibrium stemming from these policies. This distinction, perhaps unfamiliar to non-economists, is straight forward. Over the short term, constraints due to existing equipment together with inertia in adapting behaviors to changes in price or non price signals and the overall context of an economy (full or under employment of existing productive capacities, financial constraints on industry) are to be accounted for. Conversely, over the long term, uncertainties are obviously greater (in terms of the content of development patterns for example) but paradoxically the theoretical rules describing a market equilibrium can be applied; they indeed put into evidence some logical consistencies that will dominate in the long run over the short term parameters when markets will have succeeded to remove prevailing inertia and the outcome of conjunctural hazards. An example is the utilization rate of the capital stock. In the short-term this can vary significantly, as a consequence of the economic cycle. But in the long-term, an average rate of capital stock utilization is generally quite appropriate for simulating the response to changing conditions and/or policies.

That is why most existing econometrically driven macro-economic models are designed for shorter-run analysis of the dynamic responses of economies; they aim at some kind of realistic prediction. That is why, also, an increasing effort is now devoted to another type of top-down

1 model, the general equilibrium models for long run equilibrium analysis that seek to reflect an
2 idealized equilibrium economy with optimal allocation of resources.

3
4 On the bottom-up side, the distinction is also very clear; over the short term, the challenge is to
5 tap efficiency potentials given a basket of technics and to calculate the magnitude of the
6 margins of freedom provided by the existence of the efficiency gap. Once tapped, however,
7 these potentials disappear and the critical issue becomes the new margins of freedom brought
8 about by continuing technological innovation.

9
10 In all the models, the assumption is that, over the long term, the economy tends to become
11 optimal either in the form of general equilibrium in top-down models or in the form of a
12 maximum of technical efficiency in bottom-up models. This may seem surprising, given
13 historical evidence of the non-optimality of existing economies over decades (unemployment,
14 poverty for example, erratic technological choices for example). But one must cautiously
15 distinguish between a tool aiming at pointing out some logical implications and a forecasting
16 exercise aiming at predicting the future real world.

17
18 To this respect, it must be explained that the way expectations about the future can be
19 incorporated into models are currently evolving. So far two contrasted solutions were adopted
20 (1) The myopic assumption is that economic decisions are based on static expectations, namely
21 static projections of current price conditions prevailing at time zero (2) The perfect foresight
22 assumption is that economic decisions are based on all available information about the future,
23 future long term price trends being part of this available information. Today probabilistic
24 models and other forms of expectations are going to be accounted for; however these
25 progresses were not introduced in the overwhelming majority of models reported hereafter
26 who remain mathematically deterministic.

27 28 3.2 Lessons from Modelling Energy-Related GHG Emissions

29 30 3.2.1 The Structure of Existing Models

31
32 Various attempts have been made to categorize the large variety of models that have been used
33 to analyse the costs of reducing emissions of energy-related GHGs.⁵⁹ For our purposes here,
34 the important thing is to provide a general description of some of the main characteristics that
35 differentiate these models, in order to make clear what each type of model describes, and what
36 kind of policy question it can best address. In order to accomplish this, we need to distinguish
37 between those characteristics which have to do with the structure of the models themselves
38 (i.e. those assumptions that are embedded in the model equations), and those that have to do with
39 external assumptions (i.e. assumptions expressed in terms of inputs to the models).

40
41 It is possible to characterize the differences among existing energy and emissions models in
42 terms of four main dimensions. This description abstracts from a number of more detailed
43 distinctions among models but captures the points that differentiate the models in a way that
44 helps to show the connection between model structure and policy questions. These four
45 dimensions, and some of the related policy questions, are sketched in figure 3.1.

59 For a recent example, which characterizes individual bottom-up and top-down models, see Grubb, M. *et al.*
(1993) "The Costs of Limiting Fossil-Fuel CO₂ Emissions: A Survey and Analysis" in Socolow, R.H.,
Anderson, D., Harte, J. (eds) *Annual Review of Energy and the Environment*, vol. 18, pp. 397-478.

Figure 3.1

Key Structural Characters in Energy/Economy Models

Structural characters

Policy Issues

1. The degree to which behavioural relationships are endogenized in the model equations, or left to be supplied as exogenous assumptions	Models that endogenize behaviour are suited to predict actual outcomes; those that exogenize it are more suited to simulate the effects of changes in historical patterns
2. How detailed the description is of the non-energy sector components of the economy (investment, trade, consumption of non-energy goods and services, income distribution, etc.).	Models that describe these sectors in more detail are more suitable for analysing the wider economic effects of energy policy measures)
3. How detailed the description is of energy end-uses	Models that describe these end-uses in more detail are more suitable for analysing the technological potential for energy efficiency
4. How detailed the description is of energy supply technologies	Models that describe these end-uses in more detail are more suitable for analysing the technological potential for fuel substitution and new supplies.

8
9
10 Each of the four structural characters shown in Table 3.1 represents a spectrum from more to
11 less, and individual models can be located on that spectrum for each dimension. This means
12 that individual models are more or less suited to answering particular policy questions,
13 depending on where they are located on the spectrum for each dimension. Traditionally, top-
14 down models represented one end of the spectrum on each of these dimensions, and bottom-up
15 models the other, as illustrated on Figure 3.1.

Figure 3.1
Key Structural Distinctions Between Bottom-Up and Top-Down Models

Structural Dimension	Early Models		More Recent Models	
	Top-Down	Bottom-Up	Top-Down	Bottom-Up
1. Endogenization of Behaviour	HIGH	LOW	HIGH	MORE
2. Detail on Non-Energy Sectors	HIGH	LOW	HIGH	MORE
3. Detail on Energy End-Uses	LOW	HIGH	MORE	HIGH
4. Detail on Energy Supply Technologies	LOW	HIGH	MORE	HIGH
5. Predictive Nature	HIGH	LOW	LOWER	HIGHER

It is clear from Figure 3.1 that the early top-down and bottom-up models represented virtual mirror images of each other, with respect to these four dimensions. Bottom-up models tended to describe the energy system in great detail, with little endogenization of behaviour, or description of other parts of the economy. Top-down models tended to have very little detail on the energy sector but explicit treatment of behaviour and larger economic relationships. As discussed above, this led to each type of model being most useful at answering somewhat different questions: with bottom-up models useful for looking at detailed technological substitution potentials and top-down models aimed at predicting wider economic effects.

Figure 3.1 also shows that this simple characterization of the differences between top-down and bottom-up approaches is increasingly misleading, as more recent versions of each approach have tended to move in the direction of greater detail in those dimensions that were relatively less developed in the past. This is possible because the four dimensions shown in Figure 3.1 are independent of each other. Thus any particular model can be located at virtually any point on the spectrum represented by each dimension. It is this independence of these key structural characteristics that makes it so hard to classify the large population of existing models on any single spectrum, whether bottom-up to top-down, or any other. Instead we increasingly have a wide range of models, which, in terms of their structure, occupy different places on each of the four dimensions shown here. While the differences represented by these four dimensions remain important, no simple classification scheme is adequate.

The most critical and sophisticated dimension of this typology is probably the internalization of behaviours. Some models indeed try to internalize behaviours so as to represent, as far as possible, current practices; that is the case for many top-down econometric models (generally over the short run) and for some versions of bottom-up simulation models used as predictive tools. Others tend to describe optimal resources allocations; that is the case for sectoral bottom-up models who have then to be interpreted as having a normative content. That is also the case for the top-down models over the long run but the interpretation of the results is

substantially different than for the sectoral optimization models and may go in two different ways; the first is the assumption that this allocation mechanism captures the long term with a good degree of realism, the other is that, mainly in non econometric top-down models benchmarked on a given year, this provides useful insights on long term economic coherences who will ultimately prevail, but only within a given set of exogeneous assumptions about structural changes or technical progress over the long run. These models are principally tools for "thought experiments".

3.2.2. The Role of some Key Features of Modelling Techniques

All bottom-up models describe energy use in significant technological detail. However, models will differ in their level of detail and efficiency and cost assumptions as well as and in their means of representing and setting assumptions about decision makers' behaviour in the equipment acquisition process. Two bottom-up approaches are usually distinguished.

- Spreadsheet models. Simple spreadsheets are used to resolve a simultaneous set of equations describing the efficiency with which energy services are (or could be) met throughout the economy. In each equation secondary energy demand is simply a product of end-use energy demand and the efficiency coefficient of the energy using equipment meeting that particular service. End-use service demands change over time because they are linked to aggregate drivers such as population, economic output, and indicators of structural changes in the economy. Assumptions are made about the change in the energy coefficient over time, which allows the spreadsheet to recalculate about energy prices, the efficiencies of new technologies and the rate of penetration of new technologies, this latter being implicitly the result of assumptions about the rate at which consumers acquire new technologies. A spreadsheet model could be prescriptive or descriptive. A prescriptive model for example could examine the effect of consumers acquiring only the most efficient technologies available. A descriptive model, in contrast, would try to estimate the technology mix - and by inference the energy efficiency coefficient - resulting from individual or a package of policies, including information, financial incentives, regulations and R&D.

- Simulation / optimization models. In this second type of model technology turnover is simulated endogenously by a decision algorithm instead of exogenously. This includes decisions on equipment retirement, equipment retrofit and new equipment acquisition. In the first instance, consumers may be assumed to minimize explicit costs, but more ambitious models may try to include other relevant decision factors such as non-price preferences (i.e., differences in consumer surplus with different technologies), intangible costs (differences in cost of acquisition of technologies), capital constraints and attitude to risk (this latter two tend to be manifested via higher discount rates). A simulation model of this type will especially try to reproduce as accurately as possible the observed and expected decision making behaviour. An optimisation model of this type will solve for the set of technologies that minimize costs, maximize profits or maximize the sum of producer and consumer surplus, depending on how decision making is represented.

With either type of bottom-up model, the efficiency of the current base stock of technologies is critical, because this determines the character of both the baseline scenario and the potential change that can be realized because of different paths of technology evolution. Thus, much of the research in bottom-up modelling involves data collection and estimation methods for determining the shares and efficiencies of alternative technologies currently employed to meet energy end-use demand.

Top-down models resort to three main methodologies, neo-keynesian macroeconomic models, computable general equilibrium models and models simulating very long term growth paths, each of them possibly coupled or not to process energy models.

Neo-keynesian macroeconomic models began being used in connection with energy models in order to understand the oil shocks of the 70s. They are econometrically calibrated and their purpose is to trace out the short and middle run dynamics. Unemployment in the short run is allowed in response to shocks and disequilibrium in the economy and for structural unemployment due to inadequate demand for labor. The fact that they assume a non perfect equilibrium economy explains why there is a gap between their findings in the case of no-recycling or lump-sum recycling tax revenues (which shows a high cost) and their findings in the case of efficient recycling (some of them concluding to overall benefit of a carbon tax).

It is useful to call here attention upon the fact that many differences in the results stems from apparently second order differences in the technical modelling solutions. For example if a model uses aggregate or sectorial production functions in which there is a strong complementarity between capital and energy (i.e. no possible substitution), taxing energy induces a decrease in demand for capital which lowers technical progress. In this case a recycling scheme where tax revenue supports investments and technical innovation to reduce energy/capital complementarity will be recommendable (Standaert, 1992). In models where the use of labor per unit of output may increase without this depressive effect on capital to cut the payroll taxes will be proved more efficient.

In many neo-keynesian models the result in terms of curbing down CO₂ emissions is rather pessimistic. This is in part a consequence of the oversimplified representation of the energy supply and demand, of frequent conservatism of technological representation in the econometric estimates of expenditure functions or production functions (for example no improvement of energy efficiency in the existing equipments) and of not accounting for policies aiming at accelerating energy efficiency which are not directly linked to a price effect. The coupling to more detailed energy models will then bring a greater flexibility. But another part of this pessimism stems from the fact that these neo-keynesian models are "demand driven" and give a critical role to the disequilibrium between overall final demand and supply by enterprises; since they presuppose overcapacities in the oligopolistic producers who tend to maintain higher prices; then the model as the bias of minorizing the price effects which can be relevant to the extent that current practices are considered.

Computable general equilibrium models focus mainly on a long term analysis of the effect of climate policies after adjustment of the economics. They rely on a resource allocation principle and a market clearing mechanism of the market of all goods by alignment of prices on marginal costs. As indicated in their labelling the dynamic of the models is given by capital accumulation and/or by the exogenous growth of factors and productivity. Contrary to the neokeynesian models they do not rely systematically on econometric relationships; they are commonly benchmarked on a given year in order to guarantee the consistency of the parameters. This allows for a greater flexibility for using information coming from other models (or expert judgments) when the econometric relationships are not reliable enough given the time period considered.

Compared to neo-keynesian models the features of computable general equilibrium models tilt the balance between high or low abatement costs in two different directions. First, when no ad hoc assumption is made to account for unemployment and when there is no obvious distortion embedded in the base line equilibrium, they logically tend to conclude to net costs. Conversely,

because they can easily convey informations about higher energy price elasticities and higher flexibilities in the capital allocation, this cost remains generally moderate and anyway higher than in keynesian models who would be run without efficient recycling of tax revenues.

3.2.3 The Role of Key Input Assumptions

Model structure is only one factor important to consider in evaluating the meaning of the specific modelling studies. It is also very important to consider the nature and value of the assumptions that make up the external inputs to those models. Changes in the values of these assumptions will have a significant impact on the results of the study.

The assumptions listed in Table 3.2 represent assumptions that are important for any findings regarding costs of GHG emission reduction.

Table 3.2

Key Input Assumptions in GHG Emission Reduction Costing Studies

Assumption	Meaning and Relevance
1. Population	Other things being equal, population growth increases GHG emissions.
2. Economic Growth	Increased economic growth increases energy-using activities, and also increases the turnover of energy-using equipment (e.g. allowing penetration of more efficient equipment).
3. Energy Demand	
a) Structural Change	Degree to which the structure of the economy changes. Since different sectors of the economy have different energy intensities, this will have a significant impact on overall energy use.
b) Technological Change	Energy intensity of energy-using equipment and processes. This "energy efficiency" variable influences overall energy demand.
4. Energy Supply	
a) Short-term Availability of Alternative Supplies	This determines the potential for fuel substitution.
b) Backstop Technology	The cost at which an infinite alternative supply of energy becomes available. This sets an upper bound on the cost of emission reduction.
5. Price and Income Elasticities of Energy Demand	These elasticities measures the relative change in energy demand given relative changes in energy prices and in incomes. Higher elasticities cause larger changes in energy use.
6. Tax Recycling	Whether carbon tax revenues are used to reduce the distortionary effects of existing taxes. This has a large impact on the overall cost of carbon taxes.

3.2.4 The Top-Down Down versus Bottom-Up Modelling Controversy

As the next chapter will show, it has become apparent that, especially with early work, some types of models have been associated with particular kinds of results: the bottom-up models tended to suggest that the costs of GHG emission reduction might not be high and top-down models tended to suggest the opposite. The prevalence of this dichotomy is the reason we have reported the results of bottom-up and top-down analyses separately in the next chapter.

However, the question arises as to whether these differences are the result of methodology (i.e. the structure of the models) or simply the results of different assumptions (the inputs to the models). To respond to this question, it is useful to sketch the general characteristics of these two approaches. However, it is also important to point out at the outset that the dichotomy between these two approaches is increasingly misleading. As discussed below, different models can have similar results with similar input assumptions, at least for parts of the questions being addressed. Moreover, more recent practitioners are incorporating features of each other's models, so the top-down/bottom-up distinction is becoming blurred.

Top-down models attempt to examine a broad equilibrium framework, meaning that they are interested in feedbacks between the energy system and other sectors of the economy, between all sectors of the economy and the macro-economic performance of the economy, between national energy markets and global energy markets, and, in some cases, between the national economy and the global economy. Given all of these feedbacks, early top-down models generally included little detail of the energy-consuming side of the economy, including especially at a technology-specific level. In contrast, bottom-up models attempt to examine in detail the technological options, especially on the energy-consuming side of the economy. This detailed representation of different energy end-uses and the technologies serving those end-uses, generally meant that larger feedbacks were ignored. In a sense, bottom-up models hold a magnifying glass up to the energy demand-side of the economy, and other connections and feedbacks tend to be obscured or lost from the picture.

Generally, there is no a priori reason for the two modeling approaches to give different results. Top-down models account for the technological changes so valued by bottom-up analysis via two parameters: (1) the autonomous energy efficiency index (AEEI), and (2) the elasticity of substitution between the aggregate inputs to household and firms. AEEI is a function of time (a proxy for all the long-run reasons for equipment turnover) and suggests the rate at which the penetration of new technologies may change the energy intensity of the economy. The elasticity of substitution is a function of relative prices of inputs, and allows measurement of the degree to which capital or labour can be substituted for energy (i.e. energy intensity can be reduced) as energy prices rise relative to these other inputs. The values of AEEI and elasticity of substitution can be adjusted to provide results that match those frequently suggested by bottom-up modellers. Thus a relatively high value for AEEI, say a 2% decline per year, and a relatively high value for the elasticity of substitution between fossil fuels and other factors of production (labour, capital), could lead top-down simulation results in which the cost of carbon emission stabilization, and even a 15-30% reduction, were below or close to zero.

At the same time, adjustments to bottom-up modeling approaches can lead to results comparable to the earlier top-down models. If bottom-up models seek to be more descriptive of energy-using behaviours, they could include behavioural parameters of firms, households and institutions estimated from actual market evidence. Once such behaviour was included, simulation of these types of bottom-up models could show relatively high costs of GHG emission reduction.

Most of the results presented in the next chapter will show little of this potential for overlap in the results of either method. This is because efforts to use similar assumptions have only affected a few recent study efforts. Most of the top-down and bottom-up studies referred to in this report were conducted with distinct differences in their assumptions.

One should be careful not to emphasize this, but top-down modellers are usually economists who, while recognizing imperfections in market (oligopoly, natural monopoly, subsidies, etc.) are generally reluctant to engage in substantial second guessing of firm and household consumption choices. This is in part because economists are aware of both consumer surplus (the value a consumer gets in excess of the market price of a good or service) and intangible costs (costs that do not show up in the price of a good or service). An example of consumer surplus would be the extra satisfaction or value that a consumer derives from a particular automobile that may not be reflected in its capital or operating costs. Common examples of intangible costs are (1) the cost of becoming sufficiently informed about a new technology in order to consider it seriously as an option, (2) the perceived risks associated with capital or operating costs of a technology, (3) the various transaction costs associated with finding, ordering, shipping, installing, operating and maintaining a technology, (4) externally or internally-imposed restrictive investment criteria that differ from the social time preference of consumers and the opportunity cost of capital of firms. One or a combination of these intangible cost factors or consumers surplus could differ sufficiently between two goods so as to offset differences in intangible costs. Most economists will tend to assume that if a technology does not penetrate the market to the extent that an engineering/economic analysis (which focuses only on tangible costs) suggests that it should, it is probably at least in part because the intangible cost and/or consumer surplus differences are at least large enough to make the investment unattractive. As a consequence of this general assumption, most economists are more likely to put their faith in the value for AEEI and elasticity of substitution that have emerged from studies of the economy using statistical regression of historical aggregate data sets. Since the historical data is based on actual behaviour, behavioural parameters estimated from it may represent a synthesis of all tangible and intangible costs including differences in consumer surplus.

However, as noted above, this assumption no longer holds when faced by the very long time frame required by the climate change issue. Recently, top-down modellers have proven to be much more willing to abandon historically-derived parameter values in favor of various subjectively-derived values, both for AEEI and the elasticity of substitution. They have also worked to develop model forms that achieve greater disaggregation of energy end-use activities, if not a detailed representation of technologies.

As with top-down modellers, it is hazardous to make sweeping generalizations on the bottom-up side. However, bottom-up analysts in the past were more likely to be engineers and physicists. Their detailed knowledge of thermodynamic potentials and the energy-using characteristics of new and emerging technologies has led them to be aware of the apparent economic potential for society to adopt new technologies more quickly than in the past, at rates that, in aggregate, would imply values for AEEI and elasticity of substitution far higher than the values emerging from the historical data relied on originally by top-down modellers. Bottom-up modellers are also interested in pointing out that the results of their analysis may provide crucial information for decision-makers on the direct relationship between concrete policies and a particular objective such as GHG emission reduction. Bottom-up modellers have also noted the significant successes in fostering technological innovation resulting from (1) government initiatives during the energy crises of the 1970s, and (2) utility and government

initiatives in the 1980s. Thus, bottom-up modellers are very sensitive to the notion that effects in R&D can have significant effects on the evolution of the AEEI terms and perhaps even the elasticity of substitution.

Given these experiences and assumptions, bottom-up modellers tend to argue that energy efficient products may have lower transaction costs and risks than are generally assumed by firms and households, and perhaps even higher consumer surplus, but that government and utility efforts will be required to provide better information to all these decision-makers. Efforts should proceed immediately therefore for targeted R&D incentive for industry, special demonstration incentives for consumers, information programs, regulations, experiments in ecotaxation, and a host of other measures.

INTRODUCTION

An historic Framework Convention on Climate Change was signed by 154 countries at the United Nations Conference on Environment and Development (UNCED) in Brazil in June 1992 (see Grubb, et al., 1993). A goal of the convention is to have countries work towards stabilizing concentrations of greenhouse gases in the atmosphere at a level that would prevent undesirable anthropogenically induced effects on the climate system. Ultimately, the appropriate course of action for each country will depend on its assessment of the costs and benefits of policy intervention.

There remain large uncertainties, however, about likely greenhouse gas emission levels in the future, about the relationship between emissions of greenhouse gases and their atmospheric concentrations, about the link between atmospheric concentrations and global climate change, about the changes in climate that will occur, about the impacts of climate change on people and ecosystems, and about how these impacts ought to be evaluated. Over the past few years a number of "integrated assessment" models that represent these links have been developed. The purpose of this paper is to compare the various approaches to "integrated assessment" that have been developed in order to start the process of assessing their usefulness and identifying areas for improvement.

Many processes and interactions might be considered in performing an integrated assessment of climate change. Future economic activity might be projected as well as the link between it and greenhouse gas emissions, between emissions and atmospheric concentrations of greenhouse gases, between atmospheric concentrations and climate change, between climate change and the physical impacts on economies and ecosystems that result, and between those physical impacts and their valuation. Integrated assessment models should be able to produce insights that can not be easily derived from the individual natural or social science component models that have been developed in the past, and, indeed, such insights have already begun to emerge.

The integrated assessment models that have been developed - or are currently being developed - have a number of distinct, but interrelated objectives, including: (1) calculating the optimal amount of greenhouse gas control according to some criteria, (2) calculating the best way to meet any greenhouse gas emission control strategy according to some criteria, (3) better understanding the natural and anthropological processes leading to climate change - and the responses to it - as a precursor to further research in these areas, and (4) better understanding the natural and anthropological processes leading to climate change - and the responses to it - as an aid to climate change policy and climate change research policy development. This mix of policy-oriented and knowledge-acquisition oriented objectives explains, in part, the diversity of approaches to "integrated assessment" and

the tension between these two objectives can confound the process of understanding what has been assumed and concluded in each study.

STRUCTURAL ORGANIZATION OF INTEGRATED ASSESSMENT MODELS

Figure 1 shows a typical conceptual block diagram for an "end-to-end" climate change assessment model. This diagram implies the possibility of substantial interactions and feedbacks among the processes represented within each module, but that only a limited set of information is passed sequentially from one module to the next. Feedbacks can be carried through in subsequent iterations through the whole system, but equilibrium is driven by the values for the information that passes between modules. Thus, the way the diagram is drawn has operational as well as conceptual significance. One definition of an integrated assessment model is a model that projects future economic activity and the links between it and greenhouse gas emissions, between emissions and atmospheric concentrations, between atmospheric concentrations and climate change, between climate change and the physical impacts on economies and ecosystems that result, between those physical impacts and their economic valuation. Following Parson (1994), however, for our purposes here we define any climate change focused model that links together information and analysis from disciplines that have not traditionally been combined as an "integrated assessment" model. Operationally, this definition covers any model that encompasses two or more of the blocks shown in Figure 1. This expanded definition allows us to include consideration of some of the more innovative work that has been done on the linkages and feedbacks among the various components of the climate change cause and effect analysis system.

Some research teams dismiss the linear structure shown in Figure 1 as being overly simplistic; in their view interactions and feedbacks between the individual modules shown in Figure 1 exert great influence on the results that emerge from the overall assessment process and may be of direct importance to both analysts and policy makers. At a minimum, these researchers would prefer a conceptual representation like that shown in Figure 2. Here we allow for linkages and feedbacks among modules in both directions. In addition, consideration of the requisite interactions and feedbacks may require more process disaggregation within each module than when information is passed forward one module at a time.

In addition to the degree of complexity (including disaggregation) considered within and between modules, a third major design consideration in an integrated assessment model is the treatment of the considerable uncertainties about virtually every major relationship in the climate change assessment system. Future population and economic growth are uncertain, future greenhouse gas emissions given population and economic activity are uncertain, future greenhouse gas concentrations given emissions are uncertain, future climate given atmospheric concentrations of greenhouse gases

are uncertain, future physical impacts of climate change are uncertain, and the future valuation of the physical impacts attributable to climate change are uncertain.

Uncertainty can be handled in a number of ways in integrated assessment modeling. Extensive sensitivity analysis can be performed on key model inputs and parameters, or explicit subjective probabilities can be assessed for these inputs and parameters and input into a formal risk or decision analysis framework. If a formal risk or decision analysis approach is pursued, it is generally possible to calculate the value of information with respect to wholly or partially resolving the uncertainty associated with each key input or parameter. The usefulness of this calculation depends on the accuracy of the risk assessment model, when the uncertainty will be reduced and by how much, and the accuracy of the projection of how much the information will cost. If these tasks can be completed credibly, the results can be extremely useful in setting research priorities.

Overview of Existing Integrated Assessment Models

Prior to 1992, only two integrated assessment of climate change models had appeared in the literature (Nordhaus, 1989, 1991); Rotmans (1990). Since 1992 a host of new models have emerged. Table 1 lists 16 integrated assessment models that are in active use or are under active development; in addition, a number of additional modeling efforts are underway, so the number of existing integrated assessment models might be expected to double or more in the next few years. Even within the group of models listed in Table 1, though, there is a wide variation in level of model maturity. Some models are fully operational and documented, others are up and running, but not yet fully operational or documented, still others are in module development and testing phases, with some modules not yet fully specified. It is anticipated that all the models shown here will be fully operational, albeit in preliminary versions in some cases, by the end of 1995. The modeling in this area is so active that even models that are fully operational are continually being refined and updated substantially every 3-6 months. Table 2 summarizes the current development status and most recent documentation available for the 16 models listed in Table 1.

The models included in Table 1 can be compared structurally according to the amount of emphasis they place on each of the six blocks shown in Figure 1. The results of this process are shown in Table 3. Note that some of the models do not explicitly consider the relationships included in each of the blocks. In particular, several of the key models omit direct modeling of economic activity and rely on exogenous greenhouse gas emission trajectories. In addition, more than half of the existing models consider both the physical impacts and their valuation through aggregate damage functions that relate economic damages directly to mean global temperature change.

Although Table 3 addresses the degree of complexity of the models

in the various modules, it does not consider how the models deal with intermodule interactions, or with uncertainty. These are covered in Tables 4 and 5, respectively. Table 4 shows that very few of the operational models include interactions and feedbacks between modules other than a straight pass through of information from one module to the next. The Image-2 and AIM models are notable exceptions.

Several key model features, including how uncertainty is handled, are shown in Table 5. Only 7 of the 16 models reviewed explicitly deal with uncertainty, and only 3 of those (ICAM-2, PAGE, and PEF) allow the user to execute full value of information calculations. Another issue regarding uncertainty is that some of the models work with a deterministic model, superimposing a probabilistic structure on the exogenous inputs and parameters to determine optimal public policy decisions under uncertainty; this type of formulation does not, however, directly consider the impact of uncertainty on the decision making of individual producers and consumers in the economic system.

Some additional information regarding the key inputs to - and outputs from - the models is provided in Table 5. The key inputs and outputs follow from the coverage and degree of complexity of the modules included in the models.

State of the Art in Integrated Assessment Modeling

It is difficult to characterize the state of the art in integrated assessment modeling of climate change simply - a great deal of model development is underway at present, involving a large number of research teams, with members drawn from a myriad of relevant disciplines, focusing on different dimensions of the problem, using different types of methodologies. Nonetheless, a focus on the tradeoffs between natural systems model complexity, economic model complexity, and effort devoted to the explicit incorporation of uncertainty can help us understand the model development that has been completed, that is occurring today, and that is planned or anticipated for the future.

Integrated assessment models can be classified as being: (1) either more or less complex in representing the natural science processes associated with climate change, (2) either more or less complex in representing the economic processes associated with climate change, and (3) either explicitly incorporating uncertainty or not explicitly incorporating uncertainty. The models that are less complex and that do not explicitly incorporate uncertainty were the first integrated assessment models, and results produced by many of the models in this category have already been published. Although highly aggregated in their representation of the natural science processes governing climate change and not explicitly incorporating uncertainty, they typically include the dynamics of capital stock adjustments inside and outside of the energy sector, and often consider multiple world regions; thus, they are simple in some respects, but not in others. It is also possible that further disaggregation and more explicit treatment of uncertainty would not

lead to different insights than produced by these simpler deterministic models.

The models that are more complex and that do not explicitly incorporate uncertainty add significant detail to either the natural science or economics modules. This added detail makes it easier to incorporate various interactions and feedbacks among the various modules. For example, the fertilization effect of higher atmospheric concentrations of CO₂ in the atmosphere on the growth of vegetation, and feedback effect of this growth on CO₂ concentrations might be considered in models in this category, but not in the simpler models where the terrestrial biosphere is not explicitly represented. On the other hand, a model with a complex economics module might consider the impact of climate change on agricultural output, or the impact of a carbon tax on capital investment, a key driver of the growth in economic output. Figure 3 shows the relative emphasis of the models on economic system versus natural system complexity.

The models that are less complex, but that do explicitly incorporate uncertainty generally imbed very simple aggregate integrated assessment models (often even simpler than the aggregated deterministic models) within a decision or risk assessment framework. This allows for extensive testing of the sensitivity of key model outputs to variations in model inputs and parameters. This is particularly important if there are significant non-linearities and asymmetries in the processes represented in the model. The inputs, parameters, decisions, and objectives to which results are most sensitive to plausible variations would merit further study. If meaningful objectives for policy and a comprehensive set of policy options can be identified, then an explicit value of information can be calculated for reducing all or part of the uncertainty associated with each uncertain input by some specific date. Figures 4 and 5 put the uncertainty dimension together with the natural system and economic system model complexity dimensions, respectively.

Differences in Treatment of Uncertainty

Figure 4 places the models reviewed here in a two dimensional natural systems model complexity/uncertainty space. The models in the upper left hand quadrant generally include simple aggregate representations of the three natural systems modules included in Figure 1; those in the upper right hand quadrant add significant detail in one or more sectors; those in the lower left hand quadrant generally imbed simplified deterministic representations of each module in a decision or risk assessment framework - here uncertainties are explicitly incorporated in the analysis via the use of subjective probabilities on key inputs and model parameters; and those in the bottom right hand quadrant attempt to incorporate both uncertainty and complexity in the analysis. Some general comments can be made about the models in each category.

The models in the upper left hand quadrant of Figure 4 were the first integrated assessment models, and results produced by them have already been published in a number of places. Although

neither complex in their representation of the natural science processes governing climate change and not explicitly incorporating uncertainty, they typically include the dynamics of capital stock adjustments inside and outside of the energy sector, and often consider multiple world regions; thus, they are simple in some respects, but not in others. It is also possible that further disaggregation and more explicit treatment of uncertainty would not lead to different insights than produced by these simpler deterministic models.

The models in the upper right hand quadrant of Figure 4 add significant detail to the natural science modules of Figure 1. This added detail makes it easier for to incorporate various interactions and feedbacks among the various modules shown in Figure 1. For example, the fertilization effect of higher atmospheric concentrations of CO₂ in the atmosphere on plant growth, and feedback effect of more plant growth on CO₂ concentrations might be considered in models in this category, but not in the simpler models where the terrestrial biosphere is not explicitly represented.

The models in the lower left hand quadrant of Figure 4 generally imbed very simple deterministic integrated assessment models (often even simpler than those in the upper left hand quadrant) within a decision or risk assessment framework. This allows for extensive testing of the sensitivity of key model outputs to variations in model inputs and parameters. This is particularly important if there are significant non-linearities and asymmetries in the processes represented in the models. The inputs and parameters to which results are most sensitive to plausible variations would merit further study. If a meaningful objective for policy and a comprehensive set of policy options can be identified, then an explicit value of information can be calculated for reducing all or part of the uncertainty associated with each uncertain input by some specific date.

The modeling approaches in the lower right hand quadrant of Figure 4 are the most ambitious - they seek to incorporate all significant complexities and uncertainties into the same analytical framework. This is a formidable task, but one that can be immensely valuable if completed successfully. Successful completion of this enterprise will require model integration and management that has rarely be achieved in the past.

Common Challenges

The three biggest challenges facing integrated assessment modelers are: (1) developing a credible way to represent the impacts of climate change, (2) developing a credible way to handle low probability, but potentially catastrophic events, and (3) model integration and management. Existing general circulation models produce mean steady-state global temperature projections that are very uncertain. The process of projecting transient regionalized changes in the key climate variables - e.g., temperature, precipitation, etc., that lead to impacts on economies and ecosystems in a way that is consistent with the operation of the

global circulation models is in its infancy, making them subject to considerable additional uncertainties. The climate information required to most effectively project the impacts has in many cases not yet been determined, the most appropriate measures of climate impacts have not yet been determined, and ecosystems may not currently be in equilibrium. Finally, it may be necessary for this information to be input to valuation methods that are still under development and not tightly linked to the natural systems impacts in order to provide policy makers with the information they need to decide what to do.

The first results from integrated assessment models which considered only the expected costs and benefits of controlling greenhouse gases, have generally concluded that only a modest current level of control is warranted. However, it may not be expected conditions, but relatively low probability catastrophic events, that are irreversible or from which it would be very difficult to recover, that should be our main concern. Unfortunately, lack of data, understanding of the relevant processes, and analytical intractability has prevented such events from receiving adequate attention in the integrated assessments that have been performed to date.

The complexity and multi-disciplinary nature of the climate change issue creates another challenge for integrated assessment modelers - linking a vast amount of data, analysis, and computer code developed by different researchers together into a unified whole. It is particularly important to maintain consistency between the assumptions made in different parts of the analysis and the integrity of the information passed from one module to another. For example, some of the early integrated assessments made very optimistic assumptions about technical change in some parts of the analysis, but not in others.

Conclusions About Model Structures

A number of approaches to integrated assessment of climate change are being pursued. Each of these approaches has strengths and weaknesses relative to the others. Moreover, each modeling team has chosen to focus on different aspects of the climate change issue. At this point in time, the significant complexities and uncertainties associated with the operation of the climate system, and how it impacts and - is impacted by - human activities, make it impossible to know exactly what to focus on and what methodology to employ. Thus, there is an advantage to the use of multiple research teams pursuing a plethora of alternative approaches. The approaches may provide complementary insights into the causes and effects of climate change, or provide identical re-enforcing results that increase our confidence level about the results from any one approach.

There is also a natural complimentary between the different types of analyses in that the more aggregate models (particularly if imbedded in a probabilistic framework) can be used to focus the development of the more complex models, and the more complex models can, in turn, be used as one source of parameter values for the

more aggregated models, and to test the effects of the aggregation employed in them on the results of interest. Moreover, the simple models can be used to cross check results from the more complex models for consistency (i.e., they can be used as benchmarks), and to help communicate results from them to the policy development community and to the public. Finally, as each research team continually modifies its work plan, and builds on the work of the others, all the approaches may tend to look similar. Even if this were to be the case at some point in the future, it is not clear which approach pursued today would lead most efficiently to that ultimate model. This once again suggests the efficacy of pursuing a multitude of alternative analytic approaches to the study of climate change, and potential responses to it. A number of approaches to integrated assessment of climate change are being pursued. Each of these approaches has strengths and weaknesses relative to the others. Moreover, each modeling team has chosen to focus on different aspects of the climate change issue. At this point in time, the significant complexities and uncertainties associated with the operation of the climate system, and how it impacts and - is impacted by - human activities, make it impossible to know exactly what to focus on and what methodology to employ. Thus, there is an advantage to the use of multiple research teams pursuing a plethora of alternative approaches. The approaches may provide complementary insights into the causes and effects of climate change, or provide identical re-enforcing results that increase our confidence level about the results from any one approach. Finally, as each research team continually modifies its work plan, and builds on the work of others, all the approaches may tend to look similar. Even if this were to be the case at some point in the future, it is not clear which approach pursued today would lead most efficiently to that ultimate model. This once again suggests the efficacy of pursuing a multitude of alternative analytic approaches to the study of climate change, and potential responses to it.

FIRST RESULTS FROM INTEGRATED ASSESSMENT MODELS

It has only been since 1992 that most of the integrated assessment of the climate change models have been constructed. By the end of 1994, however, results from a number of these models had already been published. This section gives an overview of these results, highlighting the insights that seem most relevant to the current debate on appropriate global change policies. The variety of different approaches that have been employed to study the climate change issue make the comparison and reconciliation difficult.

In what follows, we group the available model results (described previously) into two main categories: (1) results from cost-benefit type models, and (2) results from systems models that include many linkages and interactions between the several key elements of the climate/biosphere system, but do not directly produce cost/benefit results.

There are also large differences in the outputs that individual modelers report from their integrated analyses, and the time

periods for which those outputs are reported. Some of the more common outputs from the cost-benefit type models are projections of the cost of controlling greenhouse gas emissions, the damages resulting from climate change, the "control rate," stated in terms of the percentage reduction in greenhouse gas emissions in each year relative to level of emissions projected to occur in the absence of new policy initiatives, and the carbon tax required in each year to limit greenhouse emissions to the levels specified in the scenario under consideration. Since the initial control rate and initial carbon tax results have emerged as de facto standards in the literature owing to their critical importance to the policy debate, much of our discussion here revolves around results for those two metrics.

Given the large uncertainties inherent in the various elements of the climate system, it is not surprising that analysts have pursued a number of alternative approaches to incorporating those uncertainties into their analyses. The discussion here deals with results obtained from these approaches in the following order: (1) results from deterministic analyses, (2) sensitivity analyses over key model inputs/parameters, (3) analyses where all model inputs and parameters are treated stochastically, and (4) uncertainty analyses that focus on the implications of a small number of uncertainties that seem particularly relevant to the policy issues being addressed. We end our discussion of integrated assessment models with a number of modeling challenges that have been identified as high priority areas for future improvements in integrated assessment modeling.

Results from Deterministic Analyses

In this section we consider results from integrated assessment models run with all inputs and parameters set at that median or best guess values. Notwithstanding the immense uncertainties inherent in the climate change issue, a number of analysts have suggested that the results from the deterministic analyses provide a useful benchmark for near-term decision making, if not an adequate approximation of the results obtained from more complex approaches that explicitly include consideration of the key uncertainties.

There are a growing number of published studies that attempt to balance the deterministic costs and benefits of controlling greenhouse gas emissions. As of the end of 1994 these included: Cline (1992); Hammit, Lempert, and Schlesinger (1992); Hope, et al. (1993); Kolstad, (1993); Manne and Richels (1993); and Peck and Teisberg (1992, 1993, 1994).

Table 6 shows the key results from the models that balance the costs and benefits of greenhouse gas emissions reductions. For example, the "optimal run" results from the DICE model (Nordhaus, 1994) show a 1995 control rate of 8.8 percent of baseline greenhouse gas emissions with an associated carbon tax of \$5.29 per ton of carbon, and about a 15 percent control rate by 2100 with an associated carbon tax of about \$20 per ton of carbon. This program leads to an increase in the discounted present value of consumption

of \$271 Billion 1989 dollars or about .04% of discounted baseline consumption. Similar results are obtained from the CETA, MERGE models, and the Kolstad (1993) studies .

A study by Hammit, Lempert, and Schlesinger (1992) traces out alternative control strategies to attain certain temperature constraints; while not determining an optimal path, this study shows that a "moderate control strategy" is less costly than an aggressive approach if either the temperature-concentrations sensitivity (T_{2XCO2}) is low or if the allowable temperature change is above 3° C.

In The Economics of Global Warming, Cline (1992) analyzes the time profile of abatement and damage costs under a policy of limiting carbon emissions to 4 Giga-tons annually and similarly reducing other greenhouse gas emissions. The abatement cost curve is low at first, then peaks at about 3.5% of gross world product, and thereafter declines to a plateau of about 2.5% as a consequence of widening technological alternatives.

The cost-benefit decision for greenhouse policy involves a tradeoff between substantial abatement costs early in the horizon, in return for avoidance of potentially large damages later in the horizon. The discounting methodology is critical in such a tradeoff. Cline also stresses the importance of taking the asymmetry in the desirability of high damage and low damage cases into account instead of just the central case. On the grounds that policy makers should be risk averse, Cline weights the representative high-damage case three times as heavily as the low-damage case. Discounting at zero rate of time preference, he finds that the overall benefit-cost ratio for aggressive action limiting carbon emissions to 4 Giga-tons is a favorable 1.3. Thus, the Cline deterministic case results in a much more aggressive optimal control policy than most of the other studies. Much of the difference in results stem from Cline's use of a zero rate of pure time preference, the other studies generally employing a pure rate of time preference of about 3 percent. In fact, Cline has shown the optimal control rate in 2100 in the DICE model would be 50% if a zero rate of pure time preference is employed as opposed to the 15% reported above for the 3 percent rate of time preference in the DICE baseline. Moreover, as discussed below, Nordhaus (1994) reports that the pure rate of time preference is the input to which DICE results are most sensitive. The subject of the appropriate rate of pure time preference was a major focus of chapter 4.

Although the year 2100 optimal control rates and carbon taxes shown in Table 6 vary widely, they are not all that disparate in the 1990s. This reflects the time dynamics of climate change; the costs of control are related to decreases in the rate of emissions as soon as the controls are applied, while the benefits of control are related to temperature change which responds to changes in atmospheric concentrations of greenhouse gases with a long lag, with atmospheric concentrations responding only slowly to changes in emissions rates because of the large stock of greenhouse gases already in the atmosphere. Thus, the marginal costs of controlling

greenhouse gases tend to be highly non-linear with respect to the control rate while the marginal benefits tend to be delayed and much more linear. Even with a relatively low discount rate this implies an optimal control rate that is modest over the next decade.

Sensitivity Analyses

Given the sizable uncertainties inherent in virtually every major input and model parameter employed in any analysis of global climate change, it is important to assess the implications of the key uncertainties on model results. A common first step in this effort is sensitivity analysis which involves looking at how key model outputs respond to changes in input or parameter values over plausible ranges.

Table 7 shows control rate and carbon tax sensitivities for several models. For example, for the CETA model the initial control rate moves from 0% (2%) below baseline emissions in the base case in 1990-2000 (2090-2100) to 11% (82%) in 1990-2000 (2090-2100) when the sensitivity of global mean surface temperature to a doubling in the atmospheric concentration of CO₂ is increased from 1° C to 5° C. In addition, the initial carbon tax rate moves from \$2/tonne (\$9/tonne) below baseline emissions in the base case in 1990-2000 (2090-2100) to \$29/tonne (\$198/tonne) in 1990-2000 (2090-2100) over the same range of global mean surface temperature sensitivities. Similarly, in the DICE model the initial control rate moves from 9% (14%) below baseline emissions in the base case in 1995 (2095) to 19% (28%) in 1995 (2095) when the pure rate of time preference is changed from its base value of 3% to 1%.

Another type of sensitivity analysis involves focusing in on a small number of more carefully designed scenarios that are expected to lead to fundamental changes in key model outputs. A recent analysis of carbon-free advanced energy technologies was performed by Edmonds, et al. (1994b). In this study the implications of advanced energy technologies (including very low cost biomass fuels) on greenhouse gas emissions and temperature change were investigated. Obviously, the introduction of very low cost non-carbon fuels leads to lower carbon emissions and less temperature rise in the long run (post 2050). A surprising result of this analysis, though, is an increase in temperature prior to 2050 as the replacement of carbon-based fuels with carbon-free fuels leads to less sulfur emissions and, therefore, less climate-cooling sulfur aerosols in the atmosphere.

Baseline Projections and Uncertainty

Manne and Richels (1993) have argued that any deterministic projection of baseline carbon emissions may be upwardly biased because individual energy consumers should already be reducing their consumption of carbon-based fuels because of the possibility of constraints on carbon emissions in the future. For example, Figure 6 shows the implicit carbon tax they compute in the year 2000 as a function of the probability that a constraint limiting U.S. carbon emissions to year 1990 levels. For example, if consumers feel there is a 50-50 chance that carbon emissions will

be constrained in 2010, they will reduce carbon emissions in 2000 as if a carbon tax of \$17.50 were already in place.

Results from Stochastic Simulation Models

Stochastic simulation models generalize the sensitivity analysis idea by including probability distributions on all major inputs and model parameters. Each input distribution is sampled and the value chosen is used in the subsequent calculations of the model, and the process is continued until probability distributions are derived for each output variable of the model (this process is sometimes referred to as Monte Carlo simulation). The PAGE (Hope, et al., 1993) and ICAM-2 models (Dowlatabadi, 1994) are prominent examples of integrated assessment models that take this approach.

An analysis with PAGE of no control and stringent control options results in a recommendation for adaptation rather than mitigation as a first best policy initiative. Conditions under which both adaptation and aggressive mitigation options ought to be pursued are also identified.

It is also possible to do a more comprehensive type of sensitivity analysis with the stochastic simulation approach by computing the partial rank correlation coefficient of output measures of interest with respect to variations in each input. For example, Hope, et al. (1993) report that "cheaper preventative costs of CO₂" and "no action CO₂ emissions (i.e., baseline emissions) of CO₂ have the greatest effect on total cost uncertainty, and "global temperature sensitivity to doubling of CO₂ and "half life of global warming response to change in forcing" have the greatest effect on total impact uncertainty.

Uncertainty, Decision Analysis, and the Value of Information

Climate change may have severe impacts on individuals and societies. On the other hand, the impacts may not be very severe at all. Individuals and societies often attempt to reduce the impact of low probability - high consequence events through various means. Nordhaus (1994) groups activities designed to mitigate the effects of uncertainty on economic welfare into three categories: (1) traditional insurance, (2) consumption smoothing, and (3) precautionary investments.

Traditional insurance involves pooling together large groups of people each of whom is subject to a small probability of a large loss (like having their house burn down). Thus, each individual pays the a priori expected value of a loss plus a small transaction fee to get compensated for the catastrophe should it occur. The pooling necessary to implement this approach requires that the occurrence of the catastrophe among the members of the population be more or less independent; this is not the case with climate change for which the impacts are likely to be pervasive throughout the globe. On the other hand, since some individuals (e.g., people who live on coastlines) will be impacted more severely than others, traditional insurance may help allocate the costs of the total damages resulting from climate change in a way that improves welfare.

Consumption smoothing over time amounts to the social equivalent of "saving up for a rainy day." If there are significant thresholds in the impacts of climate change, it is possible that societies will incur large adjustment or mitigation costs. Thus, welfare may be improving by saving capital now to consume when the threshold impacts occur.

The third type of policy that can be used to mitigate the uncertainty associated with climate change are precautionary investments in mitigation, adaptation, or information. Such actions enable societies to hedge against the possibility of bad climate outcomes before the major uncertainties determining the severity of the climate change problem have been resolved.

It appears that all three types of policies for coping with climate change uncertainty are valuable. In terms of overall payoff, however, the traditional insurance approach is the most tactical and the precautionary societal investment the most strategic. Thus, a number of precautionary investment analysis have started to appear in the literature. One innovative example is the stochastic optimization model driven analysis included in chapter 4 of Buying Greenhouse Insurance: The Economic Costs of CO₂ Emission Limits (Manne and Richels, 1992). This analysis only deals explicitly with the cost of CO₂ emission reductions, but it is assumed that U.S. decision makers must act initially without knowing what ultimate limit on carbon emissions will emerge from further scientific research and international negotiation. However, it is assumed that by 2010 it will be revealed whether: (1) no limits will be necessary, (2) a 20% emissions reduction will be required, or (3) a 50% reduction will be required. Each of these future policy outcomes is assigned a probability of occurrence. This formulation makes the idea of hedging against a range of future outcomes explicit with the initial control rate and carbon tax for the optimal hedging strategy (the one that maximizes the expected future utility of consumption) lying between the maximum control and no-control strategies, with the exact level depending on the probabilities assigned to the different control outcomes. Put differently, there is a risk premium associated with emitting carbon owing to the fact that carbon emissions may be constrained (and possibly severely constrained) in the future.

In Managing the Global Commons: The Economics of Climate Change, Nordhaus (1994) performs a decision analysis with his dynamic global cost-benefit model (DICE) using an innovation 5 state of the world representation (derived from an extensive stochastic simulation analysis with the model) of the relevant uncertainties associated with climate change. He concludes that "Roughly speaking, the optimal carbon tax doubles when uncertainty is taken into account, and the optimal control rate increases by slightly less than half. The increased stringency of controls results from the interaction of different uncertain variables, whereby extreme events may cause significant economic costs (Nordhaus; 1994, p. 188)."

REFERENCES

- Alcamo, Joseph, editor (1994) Image 2.0: Integrated Modeling of Global Climate Change, Kluwer Academic Publishers, Dordrecht, the Netherlands.
- Cline, William R., (1992) The Economics of Global Warming, The Institute for International Economics, Washington, D.C.
- Cohan, David, Robert K. Stafford, Joel D. Scheraga, and Susan Herrod (1994), "The Global Climate Policy Evaluation Framework," forthcoming in the Proceedings of the 1994 A&WMA Global Climate Change Conference: Phoenix, April 5-8, Air & Waste Management Association, Pittsburgh.
- Commission of the European Communities (1992), "PAGE User Manual," Brussels.
- Dowlatabadi, Hadi, and M. Granger Morgan (1993), "A Model Framework for Integrated Assessment of the Climate Problem," Energy Policy, Vol. 21 (March), pp. 209-221.
- Edmonds, Jae, Hugh Pitcher, Norman Rosenberg, and Thomas Wigley (1994a). "Design for the Global Change Assessment Model," Proceedings of the International Workshop on Integrative Assessment of Mitigation, Impacts, and Adaptation to Climate Change, International Institute for Applied Systems Analysis, Laxenburg, Austria, October 13-15.
- Edmonds, Jae, Marshall Wise, Chris MacCracken (1994b), "Advanced Energy Technologies and Climate Change: An Analysis Using the Global Change Assessment Model (GCAM)," presentation to the Air and Waste Management Meeting, April 6, Tempe AZ.
- Fujii, Yamumasa, Yoichi Kaya, and Kenji Yamaji (1993), "The New Earth 21 Model,"
- Grubb, Michael, Matthais Koch, Abby Munson, Francis Sullivan, and Koy Thomson (1993), The Earth Summit Agreements: A Guide and Assessment, Earth Scan Publications, London.
- Jain, Atul, Haroon Kheshgi, and Donald Wuebbles (1994), "Integrated Science Model for Assessment of Climate Change," Lawrence Livermore Laboratory, Livermore, CA., May.
- Maddison, David (1994), "A Cost-Benefit Analysis of Slowing Climate Change," Center for Social and Economic Research on the Global Environment (CSERGE), University College of London, May.
- Manne, Alan S., Robert Mendelsohn, and Richard G. Richels (1993), "MERGE: A Model for Evaluating Regional and Global Effects of GHG Reduction Policies," Electric Power Research Institute, Palo Alto, CA.

Massachusetts Institute of Technology (MIT, 1994), Center for Global Change Science and Center for Energy and Environmental Policy Research, "Joint Program on the Science and Technology of Global Climate Change," Cambridge, MA.

Morita, Tsuneyuki, Yuzuru Matsuoka, Mikiko Kainuma, Hideo Harasawa, and Keiko Kai (1993), "AIM -- Asian-Pacific Integrated Model for Evaluating Policy Options to Reduce GHG Emissions and Global Warming Impacts," National Institute of Environmental Studies, Tsukuba, Ibaraki, 305 Japan, September.

Nordhaus, William D. (1989), "The Economic of the Greenhouse Effect," paper presented to the June 1989 meeting of the International Energy Workshop, Laxenbourg, Austria, June.

Nordhaus, William D. (1991), "To Slow or Not to Slow: The Economic of the Greenhouse Effect The Economic Journal, Vol. 101, July, pp. 920-937.

Nordhaus, William D. (1994), Managing the Global Commons: The Economics of Climate Change, MIT Press (forthcoming).

Parson, Edward A. (1994), "Searching for Integrated Assessment: A Preliminary Investigation of Methods and Projects in the Integrated Assessment of Climate Change, John F. Kennedy School of Government, Harvard University, February.

Peck, Stephen C., and Thomas J. Teisberg (1992), "CETA: A Model for Carbon Emissions Trajectory Assessment," The Energy Journal, Vol. 13, Number 1, pp. 55-77.

Rotmans, Jan, (1990), Image: An Integrated Model to Assess the Greenhouse Effect, Kluwer Academic Publishers, Dordrecht, the Netherlands.

Rotmans, J., M.B.A. van Asselt, A.J. de Bruin, M.G.J. den Elzen, J. de Greef, H. Hilderink, A.Y. Hoekstra, M.A. Janssen, H.W. Koster, W.J.M. Martens, L.W. Niessen, and H.J.M. de Vries (1994), "Global Change and Sustainable Development: A Modeling Perspective for the Next Decade, "Rijksinstituut Voor Volksgezondheid En Milieuhygiene," Natioanl Institute of Public Health and Environmental Protection, Bilthoven, The Netherlands, June.

Wigley, Tom, Michael Hulme, and Sarah Raper (1993), "MAGICC: Model for the Assessment of Greenhouse Induced Climate Change," University Consortium for Atmospheric Research, Boulder, Colorado.

Table 1
INTEGRATED ASSESSMENT MODELS

AIM (Asian-Pacific Integrated Model)	Tsuneyuki Morita (NIES, Japan) Yuzuru Matsuoka (Kyoto University) Mikiko Kainuma (NIES, Japan)
CETA (Carbon Emissions Trajectory Assessment)	Stephen Peck (EPRI) Thomas Teisberg (Teisberg Assoc.)
CSEGE (Center for Social and Economic Research into the Global Environment)	David Maddison (University London) Sam Fankhauser (University London)
DICE (Dynamic Integrated Climate Economy)	William Nordhaus (Yale University)
GCAM (Global Change Assessment Model)	Joe Edmonds (Pacific Northwest Lab) Hugh Pitcher (PNL) Norm Rosenberg (PNL) Tom Wigley (UCAR)
ICAM-2 (Integrated Climate Assessment Model)	Nadi Dowlatabadi (Carnegie Mellon) Granger Morgan (Carnegie Mellon)
IMAGE 2.0 (Integrated Model to Assess the Greenhouse Effect)	Jan Rotmans (RIVM, Netherlands) Joe Alcamo (RIVM, Netherlands) G.J.J. Kreilman (RIVM, Netherlands) M. Krol (RIVM, Netherlands) G. Zuidema (RIVM, Netherlands)
ISM (Integrated Science Model for assessment of climate change)	Atul Jain (Lawrence Livermore Lab.) Naroon S. Kheshgi (Exxon) Don Wuebbles (Lawrence Livermore)
MAGICC (Model for the Assessment of Greenhouse gas Induced Climate Change)	Tom Wigley (UCAR) Mike Hulme (Univ. East Anglia, UK) Sarah Raper (Univ. East Anglia, UK)
MERGE (Model for Evaluating Regional and Global Effects of GHG Reductions Policies)	Alan Manne (Stanford) Robert Mendelsohn (Yale) Richard Richels (EPRI)
Minicam (Mini Climate Assessment Model)	Joe Edmonds (Pacific Northwest Lab) Hugh Pitcher (PNL) Richard Richels (EPRI) Tom Wigley (UCAR)
MIT	Henry Jacoby (MIT) Ron Prinn (MIT) John Reilly (USDA/MIT)
NEW EARTH 21	Yasunasa Fujii (Yokohama Univ.) Yoichi Kaya (University Tokyo) Kenji Tanaji (CRIEPI)
PAGE (Policy Analysis of the Greenhouse Effect)	Chris Hope (Cambridge University) John Anderson (Env. Res. Management) Paul Werman (Env. Res. Management)
PEF (Policy Evaluation Framework)	Dave Cohen (DFI) Joel Scheraga (EPA) Susan Herrord (EPA) Rob Stafford (DFI)
TARGETS (Tool to Assess Regional and Global Environmental and Health Targets for Sustainability)	J. Rotmans (RIVM) M.B.A. van Asselt (RIVM) A.J. de Bruin (RIVM) M.G.J. den Elzen (RIVM) J. de Greef (RIVM) H. Hilderink (RIVM) A.Y. Hoekstra (RIVM) H.W. Koster (RIVM) W.J.M. Martens (RIVM) L.W. Niessen (RIVM) H.J.M. de Vries (RIVM)

Table 2
DEVELOPMENT STATUS OF INTEGRATED ASSESSMENT MODELS

Model	Status	Reference
AIM	Preliminary Version Operational	Morita, et al. (1994)
CETA	Operational, With Regional and Uncertainty Variants Under Development	Peck and Telsberg (1992)
CSERGE	Preliminary Version Operational	Maddison (1994)
DICE	Operational, With Regional and Uncertainty Variants Under Development	Nordhaus (1994)
GCAM	Various Stages of Module Testing	Edmonds, et al. (1994a)
ICAM-2	ICAM-1 Operational, ICAM-2 in Advanced Module Testing	Dowlatabadi and Morgan (1993)
IMAGE 2.0	Operational	Alcamo (1994)
ISM	Operational	Jain, et al. (1994)
MAGICC	Operational With Demonstration Prototype Links to Impacts Modules	Wigley, et al. (1993)
MERGE	Operational, With Uncertainty Variant Under Development	Manne, et al. (1993)
MinicAM	Operational	Edmonds, et al. (1994b)
MIT	Various Stages of Module Testing	MIT (1994)
NEW EARTH 21	Simple Damage Function Being Added to Operational Carbon Emissions Model	Fujii, et al. (1993)
PAGE	Operational	Commission of the European Communities (1992)
PEF	Prototype Operational, Enhanced Version Under Development	Cohan, et al. (1994)
TARGETS	Prototype Operational; Formal Release Fall 1994	Rotmans, et al. (1994)

Table 3
EMPHASIS ON COMPONENTS IN INTEGRATED ASSESSMENT MODELS

Model	Economy	Emissions	Atmospheric Chemistry	Climate	Physical Impacts	Economic Impacts
AIM	Simple	Moderately Complex	Moderately Complex	Very Complex	Very complex	Not Included
CETA	Moderately Complex	Moderately Complex	Simple	Simple	Simple Damage Function	
CSERGE	Simple	Not Explicitly Represented	Simple	Simple	Simple Damage Function	
DICE	Moderately Complex	Simple	Simple	Simple	Simple Damage Function	
GCAM	Very Complex	Moderately Complex	Moderately Complex	Moderately Complex	Moderately Complex	Moderately Complex
ICAM-2	Simple	Moderately Complex	Moderately Complex	Moderately Complex	Very Complex	Moderately Complex
IMAGE-2	Not Included	Moderately Complex	Very Complex	Very Complex	Very Complex	Not Included
ISM	Not Included	Not Included	Very Complex	Very Complex	Not Included	Not Included
MAGICC	Not Included	Not Included	Very Complex	Very Complex	Complex Climate Interface	Not Included
MERGE	Moderately Complex	Moderately Complex	Simple	Simple	Simple Market and Non-Market Damage Functions	
MinicAM	Moderately Complex	Moderately Complex	Moderately Complex	Moderately Complex	Simple Market and Non-Market Damage Functions	
MIT	Very Complex	Very Complex	Very Complex	Very Complex	Very Complex	Not Yet Determined
NEW EARTH 21	Simple	Moderately Complex	Simple	Simple	Simple Damage Function	
PAGE	Simple	Not Explicitly Included	Simple	Simple	Simple Damage Function	
PEF	Simple	Simple	Simple	Simple	Moderately Complex	Moderately Complex
TARGETS	Simple	Moderately Complex	Moderately Complex	Moderately Complex	Moderately Complex	Simple

Table 4
MODULE INTERACTIONS AND FEEDBACKS IN INTEGRATED ASSESSMENT MODELS

Model	Module Interactions and Feedbacks
AIM	Some Interactions and Feedbacks Included, More Under Consideration
CETA	Straight Pass Through From One Module to Next
CSERGE	Straight Pass Through From One Module to Next
DICE	Straight Pass Through From One Module to Next
GCAM	Many Interactions and Feedbacks Under Consideration
ICAM-2	Straight Pass Through From One Module to Next in ICAM-1, Many Interactions and Feedbacks Under Consideration in ICAM-2
IMAGE 2.0	Many Feedbacks and Interactions Considered
ISM	Straight Pass Through From One Module to Next
MAGICC	Straight Pass Through From One Module to Next
MERGE	Straight Pass Through From One Module to Next
Minicam	Straight Pass Through From One Module to the Next
MIT	Many Interactions and Feedbacks Under Consideration
NEW EARTH 21	Straight Pass Through From One Module to Next
PAGE	Straight Pass Through From One Module to Next
PEP	Straight Pass Through From One Module to Next, More Complex Interactions Under Consideration
TARGETS	Many Feedbacks and Interactions, Only Model with Links to Other Global Change Issues

Table 5
GENERAL DESIGN FEATURES OF INTEGRATED ASSESSMENT MODELS

Model	Purpose	Treatment of Uncertainty	Regions	Key Inputs	Key Outputs
AIM	Policy Impacts Focusing on Asia-Pacific Region	Not Explicitly Considered	19 Economic 5' Square for Impacts	Potential GNP En. Tech. Costs Elas. Subs. Land-Use Trans. Climate Sens.	CO ₂ Emissions CO ₂ Concen. Temp. Change Sea Level Impacts
CETA	Compute Optimal Emissions Trajectories	Not Explicitly Considered	Global or North/South	Population Labor Prod. Ener. Resources Damage Fcn. Climate Sens.	CO ₂ Emissions CO ₂ Concen. Temp. Change Control Costs Damage Costs
CSERGE	Compute Optimal Emissions Trajectories	Two Point Probability Distributions on Key Inputs	Global	Population Labor Prod. Control Cost Fcn Damage Fcn. Climate Sens.	CO ₂ Emissions CO ₂ Concen. Temp. Change Control Costs Damage Costs
DICE	Compute Optimal Emissions Trajectories	Not Explicitly Considered	Global	Population Labor Prod. Control Cost Fcn Damage Fcn. Climate Sens.	CO ₂ Emissions CO ₂ Concen. Temp. Change Control Costs Damage Costs
GCAM	Policy Impacts Initially, Then Opt. Trajectories	Model Designed to Facilitate Uncertainty Analysis	9 Regions	Population Labor Prod.	CO ₂ Emissions CO ₂ Concen. Temp. Change Sea Level Precipitation
ICAM	Policy Impacts	Explicitly Incorporated in Design of Model	2 Regions North/South	Potential GNP Control Cost Fcn Damage Fcn. Climate Sens.	CO ₂ Emissions CO ₂ Concen. Temp. Change Control Costs Damage Costs
IMAGE-2	Policy Impacts, With Focus on Feedbacks Between Systems	Not Explicitly Considered	13 Economic Regions .5° Sq. Land Use 10° Latitude Climate	Regional Econ. Activity Fuel Elasticities Crop Elasticities	CO ₂ Emissions CO ₂ Concen. Temp. Change Precipitation
ISM	Compute Relationship Between Emissions and Climate and Vice Versa	Not Explicitly Considered	Global	CO ₂ , CH ₄ , N ₂ O, and Halocarbon Emissions	Temp. Change Sea Level Change

Table 5
GENERAL DESIGN FEATURES OF INTEGRATED ASSESSMENT MODELS
(Continued)

Model	Purpose	Treatment of Uncertainty	Regions	Key Inputs	Key Outputs
MAGICC	Compute Climate Impacts of GHG Emission Trajectories	Range of Climate Sensitivities Considered	Global, but Regional Climate Impacts can be Scaled	CO ₂ , CH ₄ , N ₂ O, halocarbon, and SO ₂ Emissions	Temp. Change Sea Level Change
MERGE	Compute Optimal Emissions Trajectories	Not Explicitly Considered	5 Regions	Population Labor Prod. Ener. Resources Damage Fcn. Climate Sens.	CO ₂ Emissions CO ₂ Concen. Temp. Change Control Costs Damage Costs
MiniCAM	Policy Impacts Initially, Then Opt. Trajectories	Model Designed to Facilitate Uncertainty Analysis	9 Regions	Population Labor Prod.	CO ₂ Emissions CO ₂ Concen. Temp. Change Control Costs Damage Costs
MIT	Multiple	Not Yet Determined	12 Economic .5° Square Impacts	Population Labor Prod. Base Sec. I/Os Base Eco-System Climate Sens.	CO ₂ Emissions CO ₂ Concen. Temp. Change Control Costs Ecosystem Imp.
NEW EARTH 21	Policy Impacts	Not Explicitly Considered	9 Regions	Population Labor Prod. Ener. Resources Damage Fcn. En. Tech. Costs	CO ₂ Emissions CO ₂ Concen. Temp. Change Control Costs Damage Costs
PAGE	Policy Impacts	Explicitly Incorporated in Design of Model	4 Regions	BAU Emissions Control Cost Fcn. Adapt. Cost Fcn. Damage Fcn. Climate Sens.	CO ₂ Emissions CO ₂ Concen. Temp. Change Control Costs Damage Costs
PEP	Policy Impacts & Optimal Emissions Trajectories Considering Adaptation	Linked Deterministic and Uncertainty Models	U.S. and Rest of World	Base Emissions Mitigation Costs Adaptation Costs Damage Fcns. Climate Sens.	CO ₂ Emissions CO ₂ Concen. Temp. Change Sea Level Control Costs Damage Costs
TARGETS	Policy Impacts Across Global Change Issues	Explicitly Incorporated in Design of Model	Hierarchy With Various Levels of Aggregation	Highly Endogenous Model Almost Nothing is Exogenous	CO ₂ Emissions CO ₂ Concen. Temp. Change Sea Level Impacts

Table 6
Key Results From Deterministic Cost Benefit Analyses

Model	Control Rate (percent)		Carbon Tax (1990\$/tonne)		Discounted Net Benefit (% Disc Cons.)
	1990-2000	2090-2100	1990-2000	2090-2100	
CETA Linear Damages Cubic Damages	5% 7%	5% 33%	\$8 \$12	\$12 \$165	
DICE	9%	15%	\$5	\$18	.04
GCAM					
MERGE					

Table 7
Key Sensitivities From Deterministic Cost-Benefit Analyses

Model Sensitivity Cases	Control Rate (percent)		Carbon Tax (1990\$/tonne)		Discounted Net Benefit (% Disc Cons.)
	1990-2000	2090-2100	1990-2000	2090-2100	
CETA					
Warming per 2XCO ₂					
Low - 1°	0%	2%	\$2	\$9	
Baseline - 3°	5%	9%	\$10	\$60	
High - 5°	11%	82%	\$29	\$198	
Damage Function Power					
Low - 1	2%	3%	\$6	\$18	
Baseline - 2	5%	9%	\$10	\$60	
High - 3	7%	47%	\$16	\$162	
Utility Discount Rate					
Low - 2%	8%	10%	\$6	\$38	
Baseline - 3%	5%	5%	\$10	\$60	
High - 4%	1%	29%	\$22	\$136	
DICE					
Rate of Time Preference					
3% Baseline	9%	19%	\$5	\$18	.04
1% Low	14%	28%			
GCAM					
MERGE					

Table 8
Alternative Policies to Mitigate Uncertainty

Category	Source of Uncertainty	Policy
1. Traditional Insurance	1. Diversifiable (individual) risk	1.a) Private insurance b) Social Insurance (against terms-of-trade or income losses)
2. Consumption smoothing over time	2. Risk of large or catastrophic loss	2. Investment (for a rainy day)
3. Precautionary investments	3. Uncertain scope of damage or abatement costs	3.a) Precautionary abatement (higher carbon tax) b) Precautionary adaptation (retreat from coastline) c) Investment in knowledge (geophysical and social-science research)

Source: Nordhaus (1994).

Figure 1. Basic Building Blocks of Integrated Assessment Models

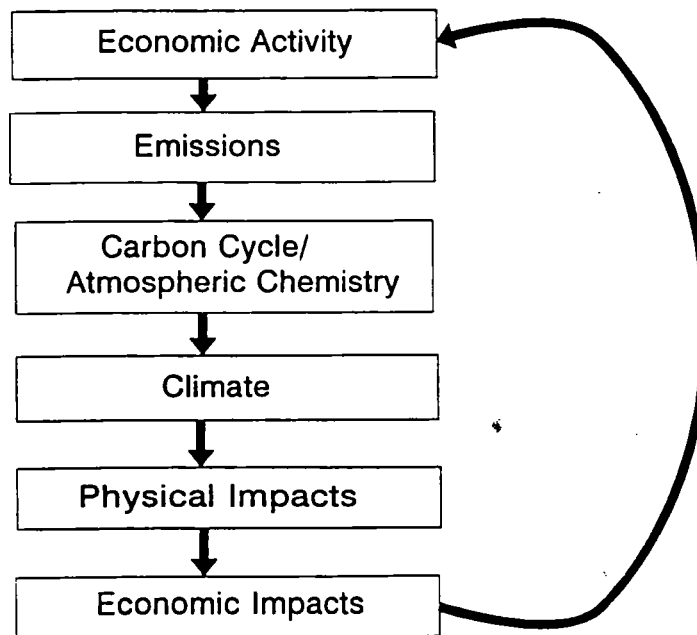


Figure 2. Basic Building Blocks With Interactions and Feedbacks

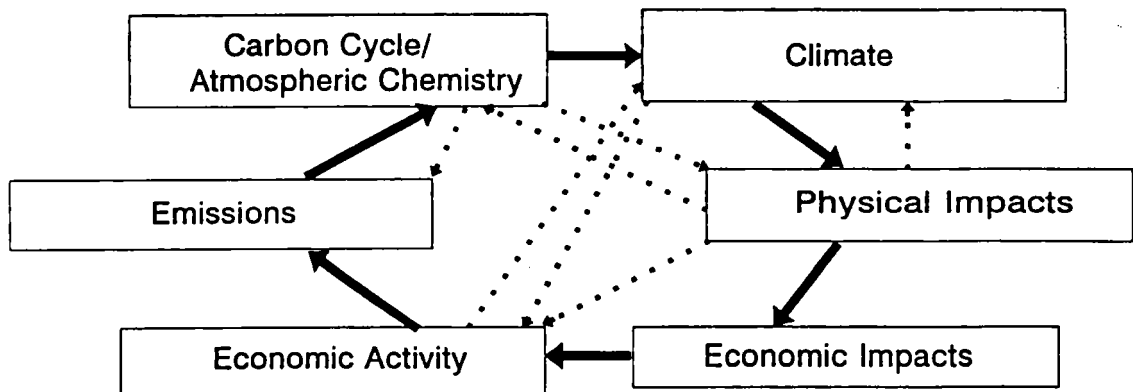


Figure 3. Tradeoff Between Natural and Economic System Complexity in Integrated Assessment Models

	Model (Date Operational)	
	Simpler Models of Natural Systems	More Complex Models of Natural Systems
More Complex Models of Economic Systems	PAGE (6/92) CSERGE (5/94) PEF (9/94)	MAGICC (10/93) ISM (1/94) Image-2 (6/94) ICAM-2 (9/94) TARGETS (9,94)
	CETA (1/92) DICE (10/92) MERGE (10/93) MiniCAM (9,94) New Earth 21 (1/95)	AIM (9/93) GCAM (6/95) MIT (12/95)

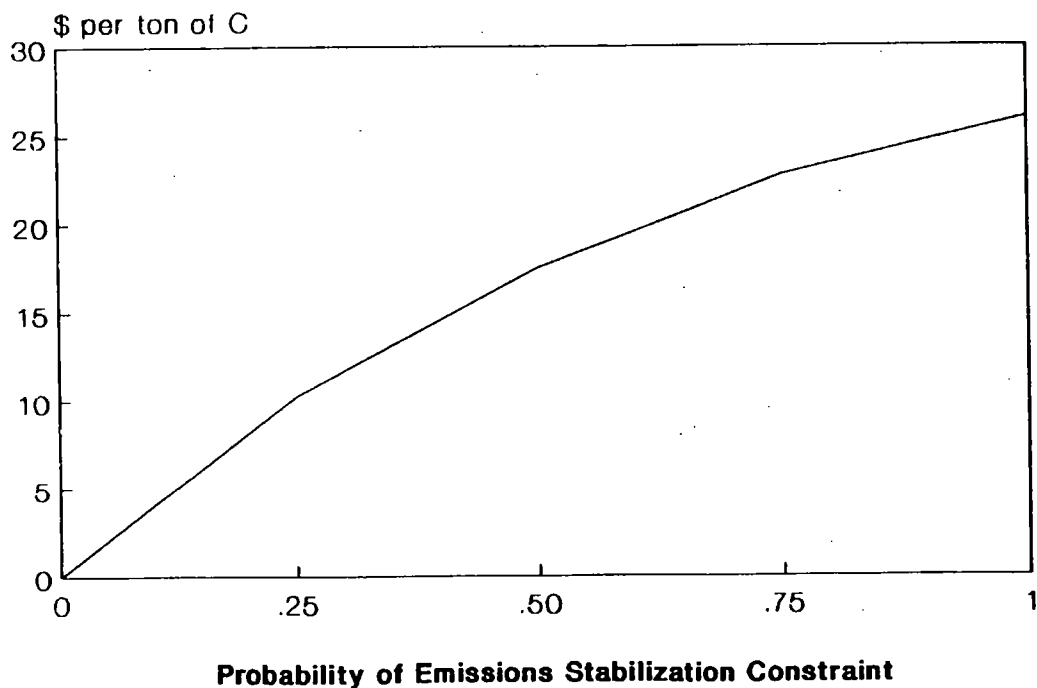
Figure 4. Natural Systems Complexity Versus Uncertainty in IA Models

	Model (Date Operational)	
	Simpler Models of Natural Systems	More Complex Models of Natural Systems
Deterministic	CETA (1/92) DICE (10/92) MERGE (10/93) MiniCAM (9,94) New Earth 21 (1/95)	AIM (9/93) MAGICC (10/93) ISM (1/94) Image-2 (6/94) GCAM (6/95)
Uncertainty Focused	PAGE (6/92) CSERGE (5/94) PEF (9/94)	ICAM-2 (9/94) TARGETS (9,94) MIT (12/95)

Figure 5. Economic Complexity Versus Uncertainty in IA Models

Model (Date Operational)	
Uncertainty Focused	Simpler Models of Economic Systems
	More Complex Models of Economic Systems
Deterministic	MAGICC (10/93) ISM (1/94) Image-2 (6/94)
Uncertainty Focused	CETA (1/92) DICE (10/92) AIM (9/93) MERGE (10/93) MiniCAM (9,94) New Earth 21 (1/95) GCAM (6/95)
	PAGE (6/92) CSERGE (5/94) ICAM-2 (9/94) PEF (9/94) TARGETS (9,94)
	MIT (12/95)

Figure 6. Implicit Tax on Carbon in 2000



CHAPTER 9

EVALUATING THE COSTS OF MITIGATION OF GREENHOUSE GAS EMISSIONS BY SOURCES AND REMOVALS BY SINKS

Report of Writing Team 6/7:
Costs of Mitigation of Greenhouse Gas Emissions

Convening Author : J. C. Hourcade

Principal Lead Authors : R. Richels, J. Robinson

Lead Authors : W. Chandler, D. Finon, M. Grubb, K. Halsnaes, K. Hogan,
M. Jaccard, D. Jorgenson, F. Krause, E. D. Montgomery, E. La Rovere, P. Nastari,
K. Richards, D. Siniscalco, P.R. Shukla, P. Sturm, J. Weyant

Contributors : C. Carraro, O. Davidson, A. Kolesov, R. Shackleton, Y. Sokona,
C. Stokes, A. Tudini, P.J. Wilcoxon

October, 1994

4. Review of Existing CO2 Abatement Costing Studies	46
4.1 Studies of the Costs of Reducing CO2 Emissions in the U.S.	46
4.1.1 A Review of Top-down Studies	46
4.1.1.1 Key Assumptions	46
4.1.1.2 Emission Scenarios	47
4.1.1.3 Carbon Taxes	47
4.1.1.4 GDP Losses	48
4.1.1.5 The Nature of the GDP Losses	49
4.1.1.6 The Relationship Between Timing, Costs and the Potential Role of R&D	49
4.1.1.7 The Issue of Revenue Recycling	50
4.1.2 A Review of Bottom-up Studies	51
4.1.2.1 Comparison of Various Bottom-up Methodologies	51
4.1.2.2 Key Assumptions and Results	52
4.2 Studies of the Costs of Reducing CO2 emissions in Other OECD Countries	54
4.2.1 A Review of Top down Studies	54
4.2.1.1 Regional Studies	54
4.2.1.2 The Effects of Revenue Recycling on Employment in Europe	55
4.2.1.3 Energy versus Carbon Tax, Some Additional Comments	57
4.2.2 A Review of Bottom-up Studies	58
4.2.2.1 Methodology of the Studies	58
4.2.2.2 Main Objectives and Definitions	58
4.2.2.3 The Results	59
4.2.2.3.1 The Dependence of the Results on Modelling Approach	61
4.3 Studies of the Costs of Reducing CO2 Emissions in Transitional Economies	62
4.3.1 A Review of Top-down Studies	62
4.3.2 A Review of Bottom-up Studies	63
4.3.2.1 Summary of Studies	63
4.3.2.2 Evaluation of Cost Estimates	64
4.4 Studies of the Costs of Reducing CO2 Emissions in Developing Countries	65
4.4.1 A Review of Top-down Studies	65
4.4.1.1 The costs of emissions Reduction in China	66
4.4.1.2 The Impacts of Energy Subsidy Removal	66
4.4.1.3 The Impacts of Carbon Taxes on Non-Commercial Energy Consumption	66
4.4.2 A Review of Bottom-up Studies	67
4.4.2.1 Main Assumptions and Findings: Trends and Margins of Freedom for Curbing GHGs Emission	67
4.4.2.2 Emission Reduction Costs; A Survey for Some Countries	69
4.4.2.3 The Special Case of China	70
4.4.2.4 Comparing Numerical Results: The Assumptions on Technical Options	70
4.4.2.5 Cost Assessments and Definition of Reference Scenario	71
4.4.2.6 Conclusion	72

4.5 Global Studies of the Costs of Reducing CO ₂ Emissions	73
4.5.1 A Review of Top-down Studies: The Importance of International Cooperation	73
4.5.1.1 The Costs of Stabilizing Global Emissions	73
4.5.1.2 The Costs of Meeting Alternative Emission Targets	74
4.5.1.3 The Potential Gains from International Cooperation	75
4.5.1.4 Allocation of Emission Rights	76
4.5.1.5 Carbon "Leakage"	76
4.5.2 A Review of Bottom-up Studies: The Critical Role of Innovation	77
5 General Conclusions	80

4. Review of Existing CO₂ abatement Costing Studies

One of the goals of this chapter is to demonstrate that, despite widely varying and even contradictory findings, the impressive accumulation of modelling exercises over the past decade provides useful information for policy-making in the face of climate risks.

Figures 4.1.1 from Grubb et al (1993) is illustrative of the current lack of consensus about the costs of reducing CO₂ emissions. Whereas some studies place losses at several percent of GDP, others question whether there will be any losses at all. There are many possible explanations for the disagreement -- choice of methodologies, underlying assumptions, emission scenarios, policy instruments, reporting year, etc. In section 3 we have explored some of these reasons, focussing on the representation of technological change in the models used. In this section, we present a review of the results; this review is organized by region, with results presented successively for the U.S., other OECD countries, the transitional economies of Eastern Europe and the former Soviet Union, and developing countries, followed by a discussion of global studies. For each region, we have first presented results from top-down studies, then from bottom-up studies. In section 6, some general conclusions about these results, we will elaborate further on the issues raised by the apparent disagreements.

4.1. Studies of the Costs of Reducing CO₂ Emissions in the U.S.

4.1.1 A Review of Top-down Studies

There have been several attempts in the US to systematically compare the results of modeling analyses of GHG emission reduction costs. (For a list of U.S. studies, see Table 4.1.1.) One of the most notable is a study conducted by the Energy Modeling Forum of Stanford University (EMF, 1993). A diverse group of economic models, employing common assumptions for selected numerical inputs, were used to analyze a standardized set of emission reduction scenarios. In all, 14 top-down models participated in the study. See Table 4.1.2

The EMF exercise provides the most comprehensive application of top-down methodologies to date and gives a wealth of useful information for policy making specifically because the harmonization of exogenous hypotheses made it possible to verify to what extent the disagreements were due to differences in methodologies, and to understand better the economic meaning of these differences.

4.1.1.1 Key assumptions

In selecting parameters for standardization, the EMF study focused on what were felt to be most influential determinants of emission reduction costs. These included: GDP, population, the fossil-fuel resource base, and the cost and availability of long-term supply options.

Given its importance as a determinant of future carbon emissions⁶⁰, the GDP growth rate was obviously the first parameter to be harmonized. To this respect, EMF adopted the average of the IPCC high and low economic growth cases (Report of the Response Strategies

⁶⁰ See for example, Nordhaus and Yohe (1983), Edmonds and Reilly (1987) and Manne and Richels (1994)

4.1.2
Table Models used in Energy Modeling Forum (EMF) Study

Model/Modelers	Model type	Time horizon	Regions
CETA (Peck and Teisburg)	Aggregate economic equilibrium	2100	1 global
CRTM (Rutherford)	Disaggregated economic equilibrium	2100	5 global
DGEM (Jorgenson and Wilcoxon)	Disaggregated economic equilibrium	2050	US
ERM (Edmonds and Reilly)	Energy-sector equilibrium	2095	9 global
Fossil 2 (Belanger and Naill)	Energy-sector equilibrium	2030	US
Gemini (Cohan and Scheraga)	Energy-sector equilibrium	2030	US
Global 2100 (Manne and Richels)	Aggregate economic equilibrium	2100	5 global
Global Macro-Economy (Pepper)	Energy-sector equilibrium	2100	9 global
Coulter	Disaggregated economic equilibrium	2030	US
GREEN (Martin and Burniaux)	Disaggregated economic equilibrium	2050	8 global
IEA (Vouyoukas and Kouvaritakis)	Energy-sector equilibrium	2005	10 global
MARKAL (Morris)	Energy-sector optimization	2025	US
MWC (Mintzer)	Energy-sector equilibrium	2095	9 global
T-GAS (Kaufmann)	Energy demand simulation	2010	14 global

1 Working Group, 1990). Also, for consistency with the IPCC, the study adopted the
2 population growth projections of Zachariah and Vu (1988).

3
4 Although the EMF models differed considerably in their technology representation, the study
5 attempted to impose uniformity with regard to world oil prices, the oil and gas resource base,
6 and the cost of backstop technologies. For the reference case, world oil prices were assumed
7 to be \$24/barrel in 1990 and to increase at a real rate of \$6.50 per barrel each decade until
8 2030. Oil and gas resources were based on the optimistic 95th percentile estimates of Masters
9 and Root (1987).

10
11 To help comparisons, the study assumed that three types of backstop technologies would
12 ultimately become available: 1) a liquid synthetic fuel derived from coal or shale at \$50/barrel
13 of oil equivalent; 2) a non-carbon based liquid fuel at \$100/barrel of crude oil equivalent; and
14 3) a non-carbon based electric option at 75 mills/kWh. Although these technologies are
15 initially available in 2010, the models impose constraints on the rate at which they can enter
16 the marketplace. The models also included a variety of carbon and noncarbon based supply
17 options that are available at rising marginal costs.

18 4.1.1.2 Emission scenarios

19
20 Table 4.1.3 describes the principal EMF emission scenario. Figure 4.1.2 compares emission
21 projections for the US. Though in all models emissions increase well beyond 1990 levels in
22 the reference case, there are, however, substantial differences in the rate of increase.

23
24 The models employed common assumptions about GDP growth, but they differed with regard
25 to the last two terms in the identity. The more optimistic one is about the prospects for
26 reducing energy intensity or the availability of low-cost substitutes, the lower the CO₂ growth
27 rate. Any average of this kind risks obviously to be misleading by ignoring or masking critical
28 debates. In this case however the convergency toward or steady increase of CO₂ emissions in
29 very strong.

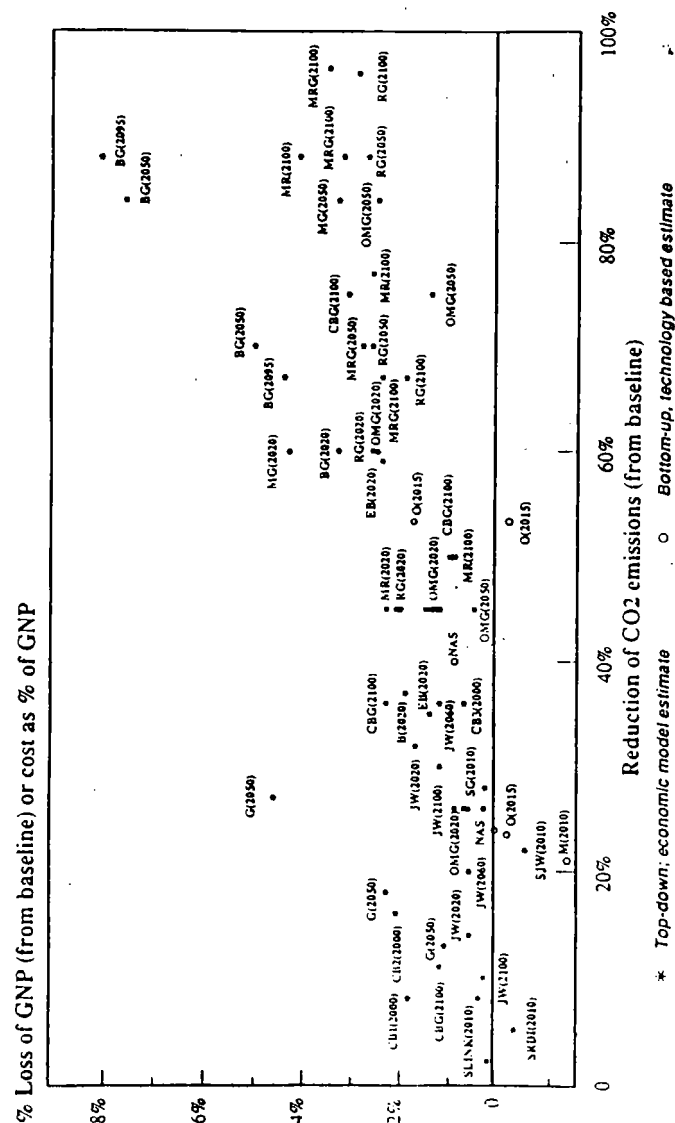
30 4.1.1.3 Carbon taxes

31
32 The modelers generally used taxes based on the carbon content of the fossil fuels in order to
33 achieve a prescribed emissions reduction. The magnitude of the tax provides a rough estimate
34 of the degree of market intervention that would be required to achieve a given emission
35 target.

36
37 Table 4.1.4 compares model results for the stabilization and 20 percent reduction scenarios.
38 Estimates range from \$20 to \$140 per ton for the carbon taxes required to hold emissions at
39 1990 levels in 2010. Estimates of the carbon taxes required to reduce emissions by 20 percent
40 below 1990 levels in 2010 range from \$50 to \$330 per ton.

41
42 Two parameters are particularly important in explaining the differences in tax projections: the
43 price elasticity of energy demand and the speed with which the capital stock adjusts to higher
44 energy prices. Neither were controlled and harmonized in the EMF experiments and left to
45 the choice of the modelers. Unsurprisingly, those models using lower price elasticities
46 required higher taxes to achieve the same emissions goal. Those models which assumed
47 greater malleability of capital required lower taxes.

4.1.1 U.S. Studies: Cost of CO₂ Abatement Relative to Baseline Projection
 Figure (Labels are not attached to all points given danger of crowding. For key see Table 1.1)



Source: Grubb et al (1993).

4.1.1 Table U.S. CO₂ Abatement Cost Modelling Studies

Author (year)	Key ^a	CO ₂ reduction from baseline	GNP impact/cost (reduction) from baseline
Barns et al (1992)	BC (2020)	26%, 45%, 60%	0.6%, 2.0%, 3.2%
Barns et al (1992)	BC (2050)	45%, 70%, 84%	1.9%, 4.9%, 7.5%
Barns et al (1992)	BC (2095)	67%, 88%, 96%	4.3%, 8%, 10.9%
DRI (1992)	B (2020)	37%	1.8%
CBO-PCAEO, DRI (1990)	CB1, CB2, (2000)	8%, 16%	1.9%, 2%
CBO-DGEM (1990)	CB3 (2000)	36%	0.6%
CBO-IEA-ORAU (1990)	CBG (2100)	11%, 36%, 50%, 75%	1.1%, 2.2%, 0.9%, 3.0%
Edmonds & Barns (1991)	EB (2020), EB (2100)	35%, 59%	1.3%, 2.3%
Goulder (1991)	G (2050)	13%, 18%, 27%	1.0%, 2.2%, 4.5%
Jackson (1991)	J (2005)	34%, 40%, 46%	-0.2%, -0.1%, 0.1%
Jorgenson & Wilcoxon (1990a)	JW (2060)	20%, 36%	0.5%, 1.1%
Jorgenson & Wilcoxon (1990a)	JW (2100)	10%, 20%, 30%	0.2%, 0.5%, 1.1%
Jorgenson & Wilcoxon (1990b)	JW (2020)	8%, 14%, 32%	0.3%, 0.5%, 1.6%
Manne & Richels (1990a)	MR (2020)	45%	2.2%
Manne & Richels (1990a)	MR (2100)	50%, 77%, 88%	0.8%, 2.5%, 4.0% ^c
Manne (1992)	MRG (2020)	26%, 45%, 60%	0.8%, 2.2%, 4.2%
Manne (1992)	MRG (2050)	45%, 70%, 84%	1.4%, 2.7%, 3.3%
Manne (1992)	MRG (2100)	67%, 88%, 96%	2.3%, 3.1%, 3.4%
Mills et al (1991)	M (2010)	21%	-1.2% ^d
NAS (1991)	N	24%, 40%	0%, 0.8%
Oliveira Martins et al (1992)	OMG (2020)	26%, 45%, 60%	0.2%, 1.1%, 2.4%
Oliveira Martins et al (1992)	OMG (2050)	45%, 75%, 84%	0.4%, 1.3%, 2.4%
OTA (1991)	O (2015)	23%, 53%, 53%	-0.2% ^e , -0.2% ^e , 1.8%
Rutherford (1992)	RG (2020)	26%, 45%, 60%	0.5%, 1.3%, 2.5%
Rutherford (1992)	RG (2050)	84%, 45%, 70%	2.4%, 1.2%, 2.5%
Rutherford (1992)	RG (2100)	67%, 88%, 96%	1.8%, 2.6%, 2.8%
Shackleton et al (1993)	SJW (2010), SLINK (2010)	22%, 2%	-0.6%, 0.1%
Shackleton et al (1993)	SDRI (2010), SG (2010)	5%, 28%	-0.4%, 0.2%
U.S. Energy Choices (1991)	USEC (2030)	67.5%	-0.6%

^a If the model used is a global model, the Key includes the letter "G" before the date.

^b The first two results use multilateral taxes, others use unilateral taxes; taxes are flat only in the first and third estimates, rising in other estimates.

^c Values represent different assumptions in technological developments; an optimistic, an intermediate, and a pessimistic view.

^d Arising from 11 specified regulatory changes; estimated from claimed savings of \$85 billion per year.

^e The benefit shown in the OTA cost estimates is only an indicative value; no explicit modelling value has been calculated.

Table 4.1.4 Comparison of Carbon Taxes and GDP Losses in 2010

Model	Carbon tax (\$ per ton of C)		GDP loss (% of GDP)	
	stabilization	20% reduction	stabilization	20% reduction
CRTM	150	260	.2	1.0
DGEM	20	50	.6	1.7
ERM	70	160	.4	1.1
Fossil 2	80	250	.2	1.4
Gemini	120	330		
Global 2100	110	240	.7	1.5
Global Macro	20	130		
Goulder	20	50	.3	1.2
Green	80	170	.2	.9
MWC	70	180	.5	1.1

The wide spread in the numerical results, however, should not obscure the fact that the models were in agreement on a number of important points. First, despite the inclusion of improved technologies and improved energy efficiencies in the reference case, all of the models projected that intervention would be required to achieve the emission targets (the reference case in figure 4.1.3. represents the average of the results).

Secondly, the size of the required tax increases with the stringency of the carbon limit. The tax paths shown in Figure 4.1.4 represent averages of the model results. Note that the size of the required tax doubles as the limit is tightened to 20% below 1990 levels. And nearly doubles again for a 50% reduction. This suggests that the economic efforts to be devoted are nonlinear with respect to the level of controls in any given year. That is, incremental reductions are apt to cost more as the absolute level of allowable emissions is reduced.

Figure 4.1.4 also suggests that the size of the carbon tax is apt to vary over time -- even for the same target. Recall that the purpose of the tax is to raise the price of carbon-intensive fuels to the point where consumers will turn to price-induced conservation and less carbon-intensive supply alternatives. Hence, the size of the tax is determined by the cost differential between the marginal sources of supply with and without a carbon constraint. This cost differential is apt to change over time.

4.1.1.4 GDP losses

Table 4.1.4 shows a marked variation in GDP losses across models. Stabilizing emissions at their 1990 levels is estimated to reduce GDP by .2 to .8 percent in the year 2010 -- roughly a \$20 billion to \$80 billion loss for that year. Estimates of the costs of reducing emissions by 20 percent below 1990 levels in the year 2010 range from .9 to 1.7 percent of GDP.

In making these calculations, the modelers assumed a lump sum redistribution of tax revenues. That is, tax revenues are used to keep constant tax payments by individuals and corporations without affecting marginal tax rates; the tax revenues are then paid back in the form of global transfer; there are no credits or penalties for this lump-sum recycling. As it will be explained further there are many other ways to recycle carbon tax revenues, but the matter becomes then far more complicated; the GDP losses calculated in this manner had the advantage to provide a first measurement the cost of the distortions to the economy caused by the imposition of the carbon tax in such a way that comparisons about the impact of different ways of handling the reactions to energy prices of the production and consumption systems remained relatively easy.

Figure 4.1.5 shows the average GDP losses across models. Holding emissions at 1990 levels results in a .3 percent loss in 2000. This rises to 1.5 percent by the middle of the next century. That GDP losses increase over time should come as no surprise within a given set of assumptions on other parameters: increasing amounts of carbon must be indeed removed from the energy system in order to hold emissions to a particular target.

GDP losses also increase with the stringency of the target. With a 20 percent reduction, losses exceed 2 percent of GDP in 2050. With a 50 percent reduction, losses exceed 3 percent of GDP.

The stringency of targets to be met in future years. All three emission reduction scenarios in this figure require indeed that emission be equal by the year 2000 to the 1990 level. Yet losses are higher in 2000 for scenarios requiring a 20% and a 50% reduction than in the stabilisation

4.1.2
Figure U.S. Carbon Emissions

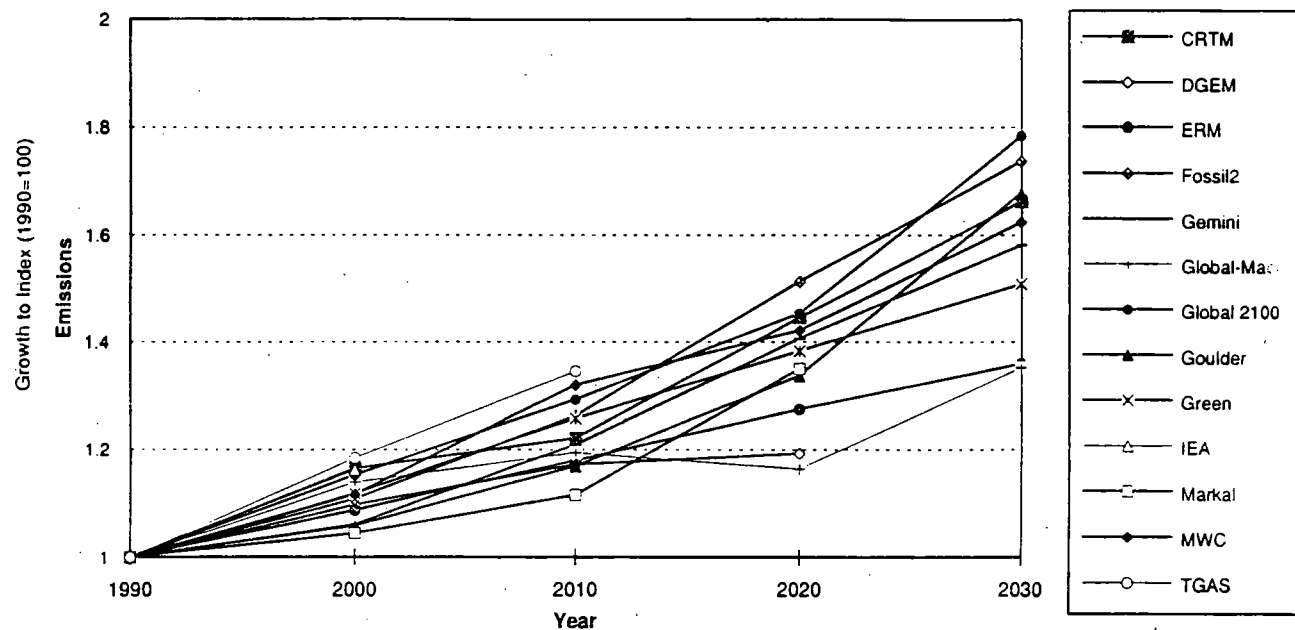
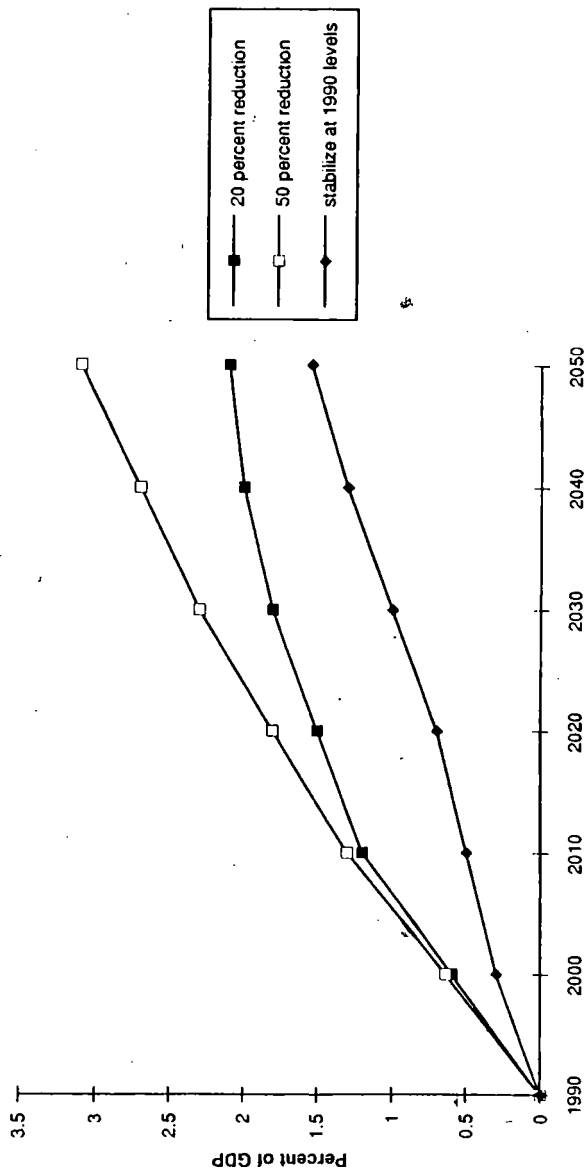


Table 4.1.3 Description of EMF Scenarios

Scenario	Description
1) Reference	No controls
2) Stabilization	Stabilize CO ₂ emissions at their 1990 levels by 2000
3) 20% reduction	Stabilize CO ₂ emissions at their 1990 levels by 2000, reduce by 20% below 1990 levels by 2010
4) 50% reduction	Stabilize CO ₂ emissions at their 1990 levels by 2000, reduce by 20% below 1990 levels by 2010, reduce by 50% below their 1990 levels by 2050

4.1.5 U.S. GDP Loss Projections – Average of all Models
Source: EMF (1993).



scenario. The reason is that energy investment are typically long lived and that meeting this two last targets over the long run implies decisions to be taken between 1990 and 2000.

4.1.1.5 The nature of the GDP losses

Figure 4.1.6 is helpful in understanding the nature of the GDP losses. Losses occur when the carbon taxes lead to investments in the energy system or conservation that are more expensive than those that would take place in the absence of the taxes and who imply either lowering investments in other sectors or lower household final consumption. Economists include these costs in the category of the deadweight losses of a carbon tax. The higher the carbon taxes, the greater the investment in price-induced conservation and the more fuel switching toward the less carbon-intensive substitutes. Hence, the higher the deadweight losses.

In the reference case, carbon emissions and GDP grow at average annual rates of 1.0 and 2.2 percent, respectively. In the absence of carbon taxes, there is some minor fuel switching toward more carbon intensive fuels but this is more than offset by the decline in energy use per unit of economic activity.

It is worth noting in figure 4.1.6 that these top-down models, on average, project sizable reductions in energy intensity -- even in the absence of explicit measures to reduce emissions

In the stabilization case (the right-most bar in Figure 4.1.6), the carbon taxes induce sufficient investment in supply-side substitutes and conservation to eliminate growth in carbon emissions. That is, carbon emissions and GDP are virtually decoupled. Note that this is done without significantly reducing the growth of the economy. Whereas the losses may be considered large in absolute terms, the agreement is that they are relatively small when measured in terms of a reduction in the GDP growth rate.

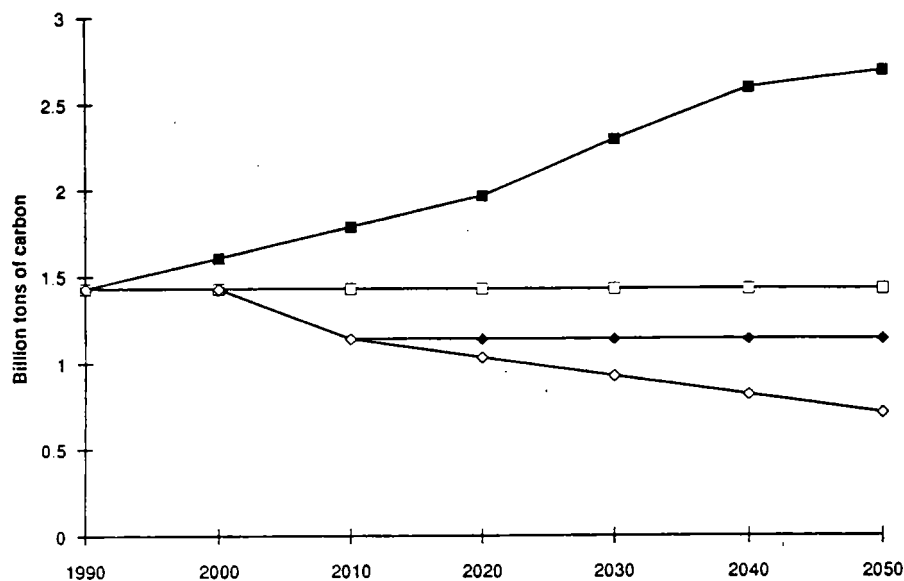
4.1.1.6 The relationship between timing, costs and the potential role of R&D

The EMF study also addressed the issue of the timing of the carbon constraint. An important question is whether the costs of CO₂ emission reduction will increase or decrease if emission reductions are deferred to the future. This is a complex issue on which we will come back in section 6. If marginal costs increase with the level of emission reduction in each period, deferring a ton of emission control from the near term to a more distant time would raise costs, all else equal. But all else is not equal.

There are indeed three reasons why deferring emission reductions may reduce costs. First, large emission reductions in the near term will require accelerated replacement of the existing capital stock. This is apt to be costly. There will be more opportunities for reducing energy use cheaply once the current capital equipment turns over. Secondly, the availability and cost of technologies for fuel switching will improve over time. As a result, the costs of reducing a ton of carbon will decline. Finally, even if the costs of removing a ton of carbon were the same in all periods, a positive discount rate will favor deferred reductions.

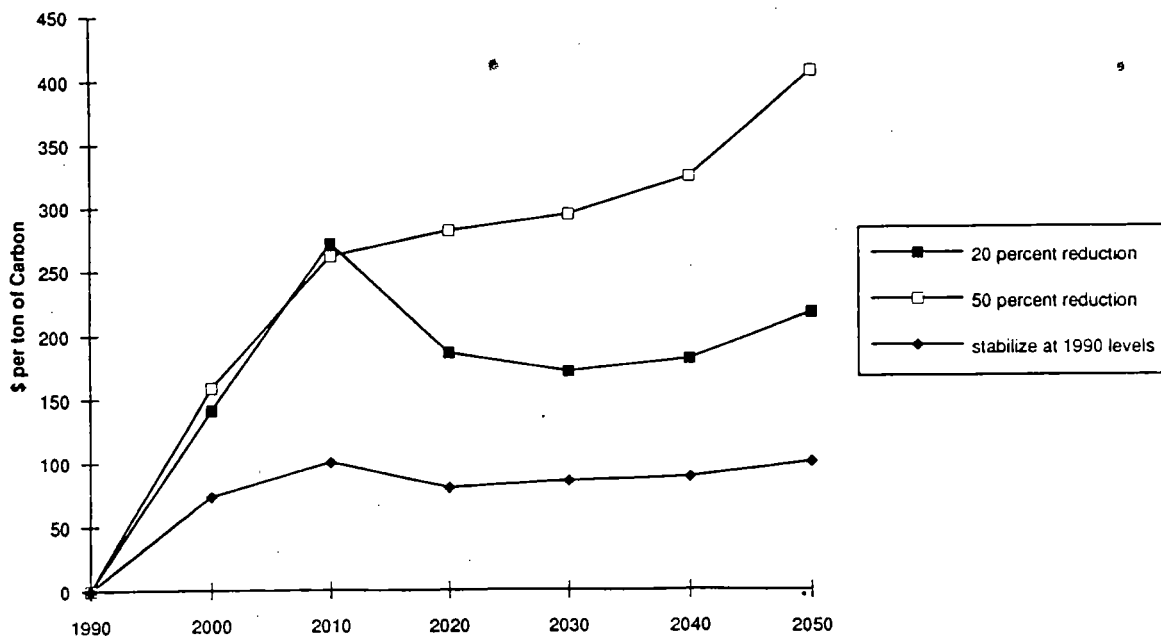
Model simulations by Cohan et al (1992) suggest that deferring emission reductions can reduce costs substantially. For example, they find that delaying the target date from 2010 to 2015 for stabilizing US emissions at 20 percent below 1990 levels can reduce control costs by as much as 20 percent.

4.1.3
Figure EMF Reference and Emission Reduction Scenarios



4.1.4
Figure U.S. Carbon Taxes – Average of All Models

Source: EMF(1993).



4.1.7
Figure Two Alternative Paths Leading to Identical Cumulative Emissions

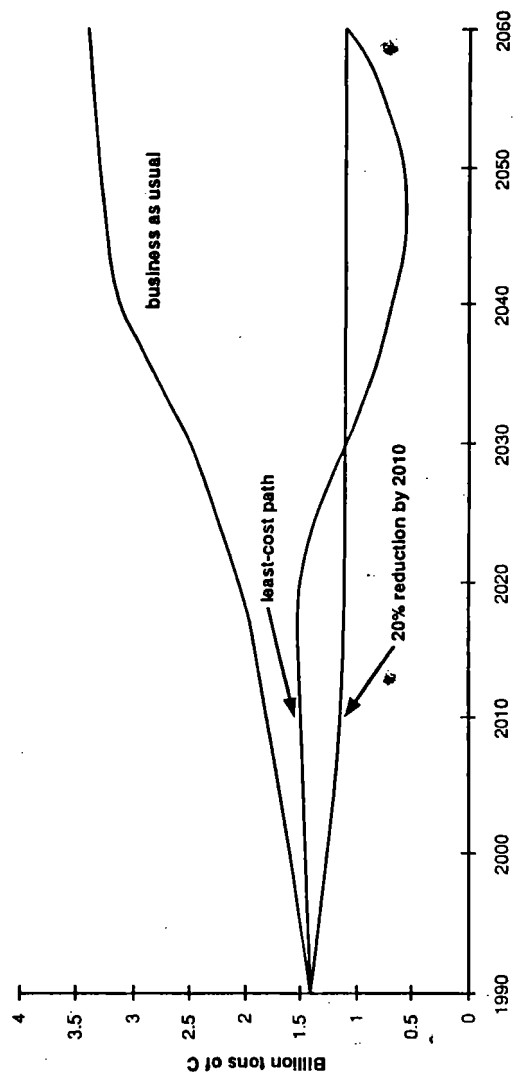
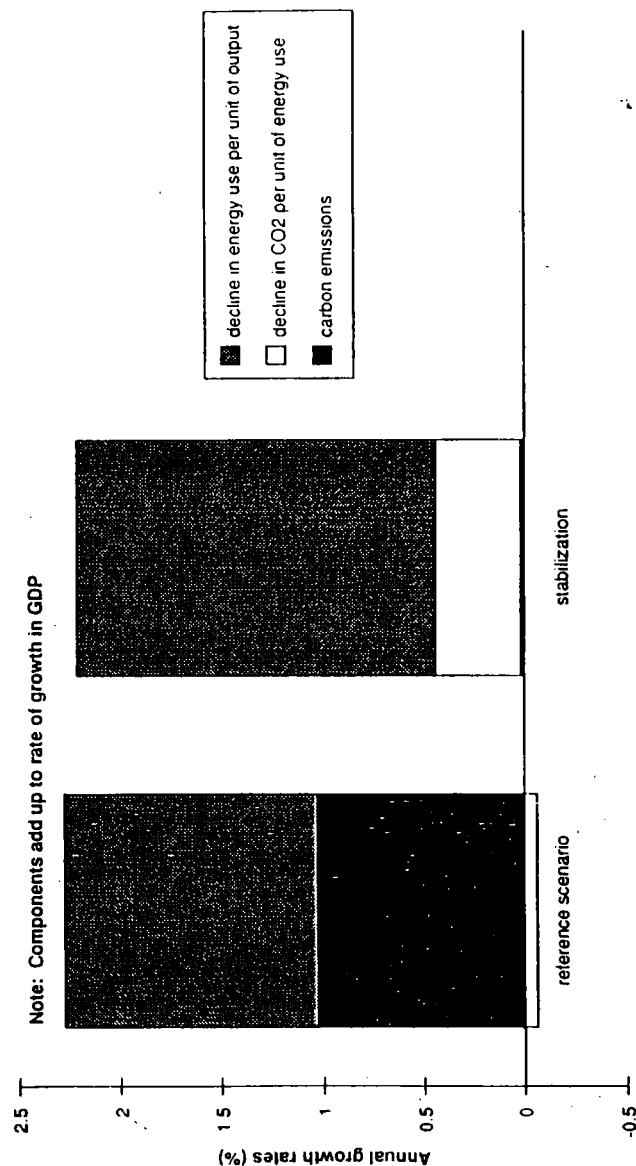


Table 4.1.5 GNP Loss, 1990-2010
(Percentage of discounted constant price GNP)

	<u>DRI</u>	<u>LINK</u>	<u>I/W</u>	<u>Goulder</u>
Lump Sum Tax Cuts	-0.58%	-0.46%	-0.62%	-0.24%
Revenue Raising	-0.40%	-1.02%		-0.24%
Personal Income Tax Cuts	-0.56%	-0.53%	-0.16%	-0.16%
Corporate Income Tax Cuts	0.40%	-0.11%	0.60%	-0.17%
Payroll Tax Cuts				-0.18%
(Employee Only)	-0.58%	-0.53%		
(Employer Only)	0.19%	-0.25%		
Investment Tax Credit	1.55%	1.67%		0.00%

4.1.6
Figure 4.1.6 Decoupling Between Carbon Emissions and GDP Annual Growth Rates (1990-2010)



octipcc07/10/94 17:50

The tradeoff in this scenario is that delaying stabilization of CO2 emissions increases cumulative emissions. To control for this difference, Manne and Richels (1992) examine emission reduction costs for the two emission reduction paths shown in Figure 4.1.7. The lower line represents the EMF 20 percent reduction scenario. The middle line represents a scenario with the same cumulative emissions, but emissions are allocated among periods in a manner that minimizes total costs. As a result, losses are reduced by 25 percent.

The interpretation of such results must be made very cautiously and not to be made in terms of a "wait and see" policy. Given that this issue is important far beyond the US context we will take advantage of comparisons with other works to give this interpretation in section 6. It is important however to underline here to what extent this issue is closely related issue with the potential role of R&D in reducing the costs of a carbon constraint. In a separate set of experiments, the EMF modelers were asked to examine an "accelerated R&D" scenario in which the cost of the nonelectric backstop is reduced from \$100 to \$50 per barrel and the cost of the electric backstop is reduced from 75 to 50 mills/kWh. In such a scenario, the carbon free backstops are economical in their own right. That is, they will enter the marketplace even in the absence of a carbon constraint.

Four models (ERM, Fossil2, Global 2100 and CRTM) were used to examine the accelerated R&D scenario. The models were remarkably consistent in their estimates of the potential savings. With the more optimistic technology assumptions, GDP losses for the 20 percent emissions reduction scenario were reduced by approximately 65 percent.

Another implication is that approximately 35 percent of the discounted losses are incurred during the transition. The remaining costs accrue once we enter into the backstop phase. That is, once the backstops are available in unlimited quantities

4.1.1.7. The issue of revenue recycling

The overall impact of a carbon tax will depend not only on the size of the tax but also on the uses to which the revenues are put. In the standard EMF scenarios, it was assumed that tax revenues will be redistributed in a neutral manner (i.e., without affecting the marginal tax rates). There are, of course, numerous ways in which tax revenues can be used. These include: reducing budget deficits; reducing marginal rates of income, payroll, corporate or other taxes; granting tax incentives to preferred activities; or increasing the level of government expenditures. The costs of the tax will vary widely depending on how the revenues are recycled.

Table 4.1.5 shows the range of GDP losses associated with a carbon tax rising from \$15 per ton in 1990 to \$40 per ton in 2010, with alternative methods of recycling the revenues. The analysis is performed using four different economic models of the US economy, two macroeconomic models and two general equilibrium models.

Obviously, this leads generally to the conclusion that the overall cost are lowered in comparison with the previous results where the recycling is made in the form of lump sum pay-back to households and enterprises. But this demonstrates also to what extent the GDP costs of the carbon tax vary considerably depending on how the revenues are recycled and the use made of these revenues. In some models, the costs are more than offset with tax policies which encourage investment. In others, the offset is only partial, but one model suggests that the GDP costs of the tax would be increased over the neutral case if the revenues were used simply to reduce the government budget deficit.

Table 4.1.6: Bottom-Up Studies of U.S. Emissions Mitigation Costs
Major Assumptions (annual growth rates, %)

Study	Base Year	Forecast Year	GDP	Disc. Rate	Energy Prices			
					Oil	Coal	Gas	Electricity
Alliance to Save Energy et al, 1991	1988	2000	2.4	3	6.5	0.9	7.8	
		2010	2.4	3	8	1.4	10	
		2030	1.8	3	4.3	1.8	7.1	
National Academy of Sciences, 1991	1990	n/s	-	6				
Office of Technology Assessment, 1991	1987	2015	2.3	-				
US EPA, 1990	1988	2005	2.5	7				
		2010	2.5	7				
SEI/Greenpeace, 1993	1988	2030	2.1	8				
Carlsmith et al, 1990	1988	2010	2.5	7	5	1	5	0.2
Chandler & Kolar, 1990	1985	2030	2.5	7	2.5	1	2.5	1
Chandler & Nicholls, 1990	1989	2000	-	-	27	141	29	
		2000			100			
Chandler, 1990	1989	2010	2.5	7	4.8	0.8		0.2
Lovins & Lovins, 1991	1988	n/s	-	5				
Mills et al, 1991	1988	2000	2.5	6				
Nordhaus, 1990	n/s	n/s	-	-				
Rubin et al, 1992	1989	n/s	-	8				

Table 4.1.7: Results, U.S. Emissions Mitigation Studies

Study	Forecast Year	CO ₂ Reduction, % (from Base Year)	Cost of Reduction	
			% of GNP	Avg Cost, \$/TC
Alliance to Save Energy et al, 1991	2000	28	-0.4	
	2010	53	-0.5	
	2030	82	-0.8	
National Academy of Sciences, 1991	n/s	24	0	0
		40	0.8	9
Office of Technology Assessment, 1991	2015	23	-0.2	
		53	-0.2/1.8	
US EPA, 1990	2005	3	0	0
		0		
SEI/Greenpeace, 1993	2030	74*	0	0
Carlsmith et al, 1990	2010	0	0	0
		20	0.5	
Chandler & Kolar, 1990	2005	0	0	0
		20	0.5	
Chandler & Nicholls, 1990	2000	7		
		20		82**
Chandler, 1990	2010	0		0
		20		92
Lovins & Lovins, 1991	n/s	58*	0	0
Mills et al, 1991	2000	21	-1.2	-231
Nordhaus, 1990	n/s	8		13
Rubin et al, 1992	n/s	35	0	0 - <0
RIGES	2025	61	<0	<0
FFEF	2030	75	<0	<0

4.1.2 A Review of Bottom-up Studies

The results of selected bottom-up modelling exercises for the United States leads to the conclusion that future US emissions could plausibly be cut over several decades by three-quarters at low or no cost to GDP. It is important to recall nevertheless that these scenarios require explicit and effective efforts in technological development and that the results are less optimistic in models where policy constraints and behavioural routines are considered in some form or other.

Even if the bottom-up models come indeed generally to the rather optimistic conclusion in terms of negative costs of abatement policies, and are presented in this way in literature, some of them suggest, for example, that cutting US emissions by 20 percent in 2010 would cost half of a percent of GDP in the United States. These differences are due both to the methodology applied and to specific assumptions for technological options.

4.1.2.1 Comparison of various bottom-up methodologies

All bottom-up models describe energy use in significant technological and behavioural detail. But assessment of costs and emission reduction is handled in fundamentally different ways. Three approaches to modelling consumer behaviour can be identified in the set of studies collected and summarised here. These approaches are:

- Technical Substitution Method: substituting new technical options into pre-existing scenarios.
- Accounting method - using GDP to drive physical indexes which, in turn, drive energy demand.
- Behavioural method - using GDP, prices and standards to drive energy-using behaviours.

The adaptation method begins with any future scenario of energy supply and demand. It proceeds from analysis suggesting that technologies with lower costs and lesser rates of greenhouse gas emissions will become available and can substitute for the technologies in the pre-existing scenario. For example, Johansson et al. (1993) produced future scenarios for their "Renewables Intensive Global Energy Strategy (RIGES)" by borrowing the energy and economic projections of the IPCC Rapidly Changing World Scenario (IPCC 1992) as a reference scenario. Alternative supply and demand options were then substituted into this framework so as to meet the level of demand for energy services. Costs are computed using the difference between the sum of the costs of these technologies in the reference scenario and the one of the alternatives. No economic equilibrium solution was sought; that is, no energy price feedback effect was incorporated.

A US National Academy of Sciences study approached the question of cost of emissions reduction in a very simple fashion. The study asked, How would emissions in 1989 differ if all available cost-effective energy-efficiency potential were adopted? That is, the best-available technology was substituted into all vintages of energy-using equipment to calculate the cost-of-energy-saved. This cost was then related to the estimated amount of emissions reduction. The cost ranged over positive and negative values.

The accounting method is illustrated by the study American Energy Choices (Alliance to Save Energy et al. 1991). This study used the "Long-term Energy Analysis and Planning" (LEAP) model. Energy demand was driven by GDP and population growth functions that related

income level and growth to physical variables such as living space and materials production. For example, residential demand for space heat in LEAP is a function of GDP growth, area per household, energy per unit of floor space, and technological change per unit of energy of space. Industrial energy demand is driven by GDP, a factor relating materials use to GDP per capita, and technologies for reducing the energy use per unit of materials.

Still another type of bottom-up model uses income- and price-elasticities of demand to simulate energy demand behaviour, in a way rather similar to the practice of top-down models do. One example, the EPA Energy End-Use Model was driven by exogenous GDP growth and energy price assumptions, and uses income-, own-, and cross-elasticities of demand to model future energy demand in a set of highly-disaggregated end-use sectors. However, the model is switchable, meaning that the price and income functions can be switched off or modified and taken over by functions relating demand to materials input, floor space, vehicle-distance travelled, and minimum energy performance standards for appliances and vehicles. This model can thus be used to test tax and regulatory policy. However, like all existing bottom-up models, it does not reiterate its demand and supply functions in order to calculate an equilibrium solution.

4.1.2.2 Key assumptions and results

An overview of the main assumptions and results of the major US bottom-up studies is given in Tables 4.1.6 and 4.1.7.

In most bottom-up models GDP growth drives the models demand functions, and it is always assumed exogenously. Considerable variation may be seen in GDP growth rate assumptions over time, though they tend to converge within specific time frames. Most studies have tested the sensitivity of their models to changes in GDP.

Energy prices are also assumed exogenously, and assumptions vary widely. RIGES, for example, assumes low cost fossil energy in 2030 in order to anticipate the effect of successful implementation of energy efficiency. Others, such as Carsmith et al (1990), assume high rates of near-term energy price increases.

The outcome of these models is nevertheless rather convergent: cost estimates for a 20 percent reduction in the United States in 2010, for example, range between -0.6 and +0.5 percent of GDP (see Table 4.1.1).

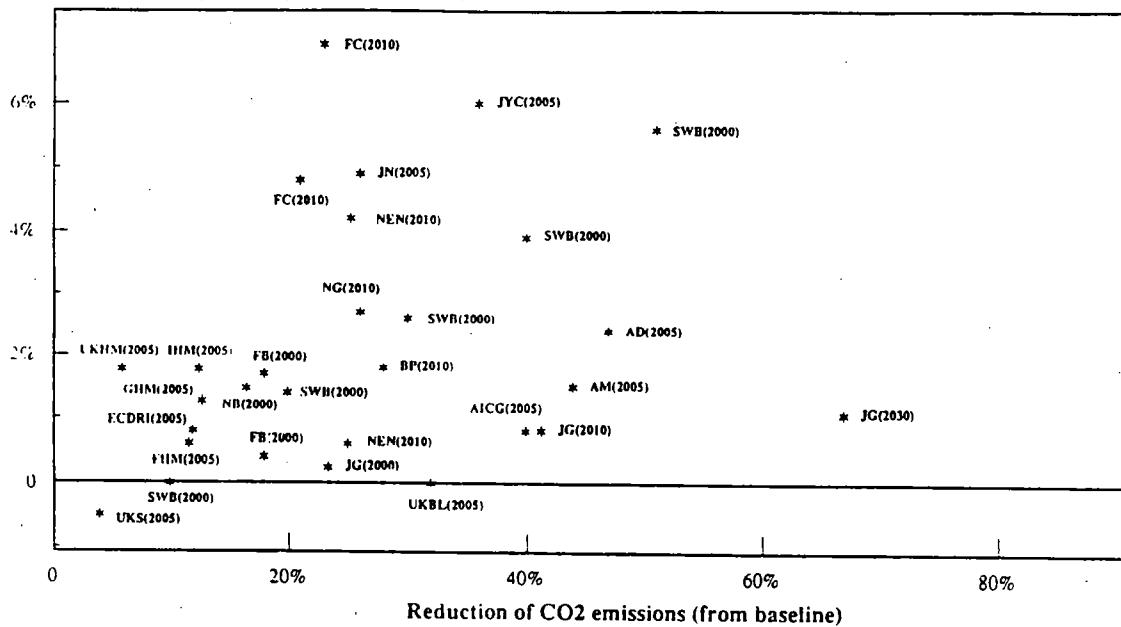
If one is concerned by the reasons of these differences it can be said that they are probably far more due to the key assumptions adopted than to the differences in methodology, even if no harmonized comparative exercise is available for these models such as it is the case for the US top-down models.

The differences due to methodology involves the pace of implementation of alternative energy sources or efficiency measures. For example, RIGES simply assumes penetration of markets for cost-effective technologies. Carsmith et al., however, constrained their model to link all market penetration to a price elasticity or a specific policy constraint, such as a standard. Because price elasticities were assumed to be less than one, price response did not produce the market penetration that other methods show.

More important in magnitude, however, are the assumptions for the cost of the alternatives. Strict comparison is difficult because of the number of technological details accounted for.

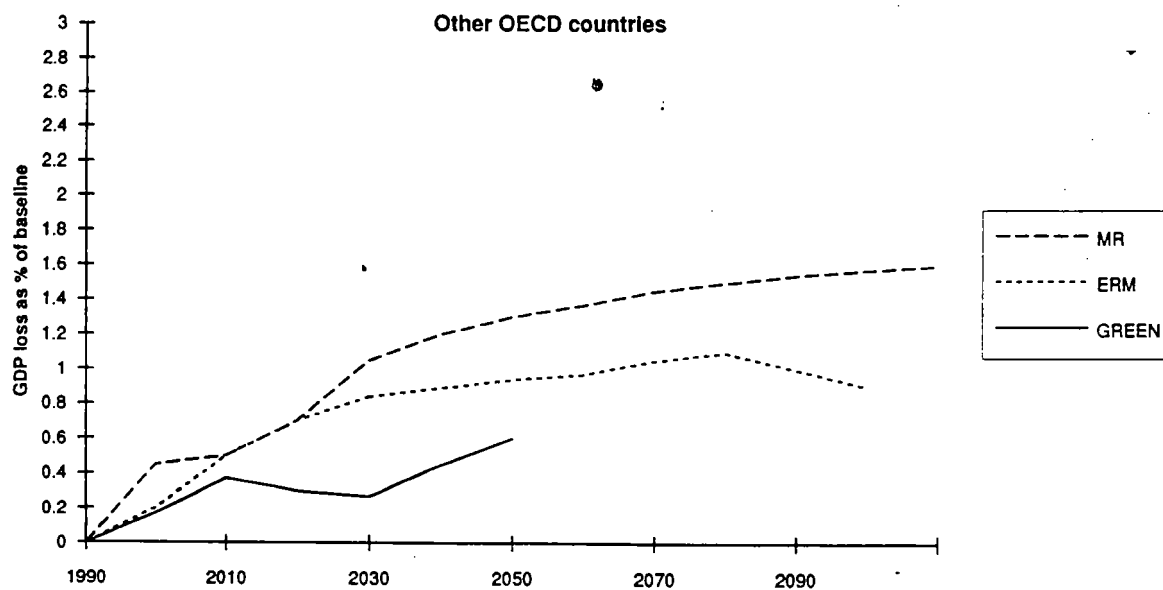
4.2.2
 Figure Non-U.S. OECD Studies: Cost of CO₂ Abatement Relative to Baseline Projection
 (Labels are not attached to all points given danger of crowding. For key see Table 2.1)

Loss of GNP (from baseline) or cost as % of GNP



Source: Grubb et al (1993).

4.2.1
 Figure GDP Losses in the Stabilization Scenario



But, to quote one example, the assumed cost of biomass energy differs by a factor of 5 or more across the studies. Clearly, the key question becomes one of obtaining high resolution on the price of alternatives, as recent top-down modelling efforts using low-cost renewables has shown (Edmonds et al, 1994).

The convergence about low or slightly negative abatement costs despite the spectrum of differences on energy price assumptions, technology and behaviours could be a matter of surprise. It stems however clearly from the fact that the different set of assumptions at each level are combined in such a way that the effect of pessimist or optimist bias on each specific parameter compensate each other to reach the zero or negligible cost conclusion. The zero or negligible cost conclusion can be consequently held as demonstrated under the restrictions about the transaction cost and feed-back effects described in section 3.

4.2. Studies of the Costs of Reducing CO₂ emissions in Other OECD Countries

Much of the early work on the costs of CO₂ emission reduction was US based and, as a result, tended to be US focused. More recently, there has been a flurry of analytical activity elsewhere in the OECD, mainly in Western Europe. In general, these studies have had relatively shorter time horizons than in the US, focusing on the costs of stabilizing emissions in 2000 or a 20 percent reduction by 2005 (the "Toronto target").

4.2.1 A Review of Top-down Studies

Top-down studies of non-US OECD countries have been of two types: those focusing on individual nations and those focusing on an entire region or a subset of countries such as the European Community or non US-OECD countries as a whole. In this section, we review the results of both. Such as in the US, the types of policies tested, have been limited to taxes on CO₂ and energy, under alternative domestic fiscal recycling schemes

4.2.1.1 Regional studies

The advantage of the regional studies is that they have been carried out by the same models who also have been applied to Europe. One notable attempt at a systematic model comparison of non-US OECD models was conducted by the OECD in the early 1990s (Dean and Hoeller, 1992). The exercise was patterned after the parallel study being undertaken by the Energy Modeling Forum. The two studies used many of the same models and shared a common set of input assumptions. For purposes of the model comparison, the OECD was divided into two regions: the US and "other OECD countries."

The OECD analysis covered a much longer time horizon than the national studies analyzed hereafter, and encompassed both the transition and backstop phases.

Among the more interesting emission reduction scenario is one in which emissions are permanently held to 1990 levels. Figure 4.2.1 compares annual GDP losses for three models: ERM, GREEN and MR. The models are fairly consistent in their projections of losses in 2010 -- between .3 and .5 percent of GDP. The convergence is due in part to the standardization of key input parameters. But it is also important to note the aggregation effect. Combining all non-US OECD countries into a single region masks important intercountry differences. As suggested by Figure 4.2.2, the variance around the mean is likely to be large.

The models are in less agreement as we move beyond 2010. The differences can be traced to several uncontrolled parameters. MR, for example, employs a lower rate of autonomous energy efficiency improvements than ERM and GREEN. As a result, its baseline emissions path is somewhat higher. More carbon must be removed from the energy system to maintain emissions at 1990 levels. Hence annual emission reduction costs are apt to be higher⁶¹. Intercountry differences, however, do not explain the wide variety of results for an individual country as for example can be seen for the reported studies for Australia and Japan. Here, as in the case of the US, we must turn to the models and their underlying assumptions. It is difficult to sort out the reasons for differences, because the studies were conducted independently and there has been no opportunity to standardize key inputs. Nevertheless, based on the discussions

⁶¹The IEA model is an econometric model designed for analysing short term policies; this explains why it is very pessimistic about the prospects for energy conservation and fuel switching and concludes that so high energy prices are needed to bring down emissions.

to an increase of the GDP between 0,5% to 0,93% if rather complex set of recycling measures are implemented (Godard, Beaumais 1994). In the English context Barker (1994) and Barker, Baylis and Bryder (1994) point out the importance of the accise of the tax: the use of the road duty escalator introduced by the UK government in 1993 is shown to reduce inflation (when the revenues are recycled via reductions in employment taxes) and raise employment.

These difficulties for comparing different results are less important in the case of studies on the proposal for limiting CO₂ emissions put forth by the European Community (E.C. Commission, 1991). They have indeed the advantage of analysing the same measure, a 80 \$/tC in 2000 and to help understanding the relative efficiency of each recycling policy or the role of structural characteristics of the models.

A positive aspect of the European exercise is then the identical application of some of the models (DRI, HERMES, QUEST) to several countries using uniform assumptions. This allows a detailed assessment of differences in responses to a given energy or carbon tax related differences in national industrial structure, tax systems and export/import structure. Table 4.2.3 compares the results from three studies of the impacts of an energy tax on GDP and employment.

Table xx (Finon 6.3) shows the GDP impacts of the energy tax analysis comparing a case without tax recycling with different tax recycling schemes. In all recycling cases the GDP loss are very small amounting to below 1% in 2000. In some cases a GDP gain is assessed assuming the tax is recycled to reduce social security charges (Bureau du Plan, Belgium, 1993). Similarly positive effects on employment has been assessed in the HERMES-linked study assuming recycling through payroll tax cuts. A more detailed picture of effects on GDP, private consumption, employment and inflation are given in table 4.2.4. A remarkable result of this analysis is, that the six European countries in the HERMES analysis in total assess the energy tax to have a positive impact on GDP, private consumption, employment and inflation assuming that the tax revenue is used to reduce social charges. In the DRI model the result is less optimistic because of the content of the policy mix and because the structure of the model tends to emphasize the positive effect of recycling through investment credit ⁶⁶.

4.2.1.3 Energy versus carbon tax, some additional comments

In terms of limiting CO₂ emissions, the impact of a 80\$/t tax is assessed to be limited. Baseline emissions are reduced by between 4,4% and 11,1% for the four major European countries in 2005 in the HERMES-LINK analysis for four European countries. Similarly the unlinked HERMES analysis for twelve European countries assessed an emission reduction from baseline amounting to between 4,1% and 5,6% in 2000 ⁶⁷.

These results can obviously criticised as being too pessimistic because relying on strict econometric assumptions and neglecting both the long term signal effect of such a tax and the accompanying measures likely to trigger an accelerated adoption of energy efficient equipments. But the most interesting debate stems from the fact that the E.C. proposal represents a major departure from other greenhouse initiatives; instead of purely connecting

⁶⁶We must note that the recycling by investment tax credit have not been tested in the European exercises. In the US, the main exercises have found a positive effect on the growth with such a recycling (Shackleton et al., 1992).

⁶⁷The documents of the DRI exercises (1991 and 1993) don't present any impact on CO₂ reduction. This probably reveals the disinterest for the initial purpose of the ecotax.

4.2.4 Effects of Different Types of Tax Revenue Recycling at the Community Level
(Energy Tax of 10\$/bl)

	HERMES ¹ 4 countries	QUEST ² EUR 12 (1995)	HERMES-LINK ³ 6 countries (2001)
Without recycling (revenue raising)			
GDP losses on the last year	-1.6%	-1.2%	-
Employment	-0.9%	-0.4%	-
Payroll tax cuts (employer only)			
GDP losses on the last year	-0.2%	-0.7%	+0.15%
Employment	+0.3%	-0.3%	+0.64%
Personal income tax cut			
GDP losses on the last year	-0.3%	-1.1%	-
Employment	0%	0%	-

¹ Rate of change after seven years by reference to the baseline (Zagarné et al., 1991).

² Rate of change after seven years (DG II-CEC, 1992, p. 59).

³ Bureau du Plan -Erasme- "Un redéploiement fiscal au service de l'emploi" (Rapport à la DGXI-CEC) 1993.

of the previous sections, it is possible to identify several probable causes for the lack of consensus. These relate to differences in assumptions about: 1) the costs and availability of demand-side alternatives, 2) revenue recycling, and 3) the treatment of preexisting energy taxes.

In fact, most of these studies encompass the period in which we are apt to be most constrained on the supply-side, i.e., the next ten to fifteen years. During this time, because of inertia within the supply system, and because of the reluctance to enhance nuclear energy in many countries the amount of fuel switching capability will be mostly restricted to switching among fossil fuels (gas to oil or coal for example). Consequently, much of the burden for the emission reductions will fall on the demand-side of the energy sector. Degrees of optimism or pessimism about the prospects for price and non-price induced conservation will then crucially determine the outcome of the models.

Another parameter likely to influence the interpretation of the results is the assumption about the international context of these policies. In the absence of global world trade model⁶², common practice was to resort to two hypothesis: unilateral initiatives (which places an upper bound to the evaluation) or initiatives coordinated at a level (OECD or European Community) large enough to offset the most of the possible trade distortions (which places a lower bound to the evaluation). Such as in global studies (QUEST, Pezzey) it is shown that the negative effects of a tax on European countries economies could be reduced if the tax is extended to other OECD countries. Note that the differences in national assessments of the impact of similar taxes is linked to specific rigidities of the economies such as: industrial structures (importance of large energy-intensive industries) and the importance of foreign trade for small open economies like The Netherlands and Denmark. Such small economies will be more sensitive to certain type of exemptions on exported goods.

Another reason why estimates of GDP losses differ so widely relates to the revenue recycling issue. The national models embrace an even wider variation of recycling options than those reported for the U.S. Indeed, some models assume that the tax revenues are removed entirely from the economy, likening an imposition of a carbon tax to the oil import price shocks of the 1970s. As one would expect, this leads to much higher GDP losses than would be the case if the revenues were used to stimulate investments or consumption elsewhere in the economy. The focus on this recycling issue was in fact particularly strong in the European countries, especially in the context of the CEE project of a carbon-energy tax.

4.2.1.2. The effects of revenue recycling on employment in Europe

An important rationale for a carbon or a carbon-energy tax in Europe has been the possible use of revenue recycling so as to struggle against structural unemployment. Many European countries are indeed currently suffering from high unemployment resulting, at least in part, from high labor costs. In some countries, for example, taxes on labor nearly double its hourly cost. These taxes create a wedge between what an employer must pay for an hour of labor and what a worker receives, and thus tends to reduce both labor supply and the demand for workers. It is not surprising, therefore, that the revenue recycling debate in Europe has tended to focus on shifting the tax burden from labor to energy. This was not a critical issue in our review of US analyses since US energy taxes are much lower than those elsewhere in the OECD. They are more like user fees, barely covering the costs of highway construction and

⁶²In fact, with the exception of the Quest model in the European Community, no model was able to really assess the effects on trade balances or on delocation of big consuming industries because of the lack of a model of international trade

maintenance when, in Europe they are clearly designed for fiscal revenue rising and as a mean to internalize other environmental and non environmental externalities due to the energy production and consumption.

As was the case with the US studies, the European analyses suggest that GDP losses could be at least partially offset through effective revenue recycling that reduces particularly burdensome taxes. Where the agreement breaks down is in whether recycling through appropriate cut of other taxes can actually increase employment. Some studies suggest that this recycling through a payroll tax cut only slightly reduces the negative impact on employment by comparison with a lump-sum recycling, while others suggest that an energy tax recycled through a payroll tax cut will increase employment.

The structural characteristics of the models explain part of the divergences. The long term general equilibrium models focus on long-term analysis of the effects of global environment policies after adjustment of the economics. Some of these European models have however also been used to study short- to medium term adaptation processes for a 15 years time horizon: Quest model for Europe and national models in Belgium (Proost et al, 1991), in Germany (Conrad, 1993) and in Sweden (Bergman, 1991)⁶³. The Norwegian study (Brendemoen 1994) and the French study encompass longer time periods.

Generally these models have been used with a parametrization of the necessary tax level to reach a given level of CO₂ emissions assuming a lump-sum recycling. The results may seem paradoxical. On the one hand they are generally pessimistic about the necessary tax level to achieve a 25-30% reduction from baseline in 2000-2005 is quite high: 380 \$/t in Belgium, 100 \$/t in Norway, 195 \$/t in Sweden (30% in 2000);⁶⁴ On the other hand the GDP reduction is low: This is explained by the fact that, as explained in section 7, AGE models allow for a greater flexibility than the neo-Keyensian models. But these models do not account for unemployment fluctuations and often contain relationships that offset the favorable effects of payroll tax cuts. For example, they may shift the burden of energy taxes on to workers and thus negate the employment-generating effects of payroll tax cuts. This explains that the most of AGE models conclude to net costs, although moderate, of climate policies⁶⁵.

In fact the majority of studies carried out in Europe so far for studying the short and medium term effect of a carbon or carbon-energy tax have been carried out by neo-keynesian models who account for unemployment in the short run in response to shocks to the economy and for structural unemployment due to inadequate demand for labor. Beyond the specifics of national contexts, what makes comparisons difficult is the variety of the ways the model handles preexisting energy and non energy taxes, of the ways the carbon tax is levied and of the policy judgments about the acceptability of a given "recycling mix".

For example, starting from a cost of 1,5% of GDP in 2000 in the case of a carbon-energy tax (Beaumaïs 1992), a french study by ERASME for the french planning commission concludes

⁶³ Two AGE models have been used in the USA for studying the effect of different types of recyclings (Shakleton et al., 1993).

⁶⁴ this is explained by the high share of hydropower in Norway and hydro- and nuclear power in Sweden means a smaller margin for maneuver for these countries compared with Belgium in contrast with the reported results. The Belgian results are generally high for the short term targets and increases to 700 \$/t, for a cut of 60% in 2025 (which corresponds to the Toronto objectives).

⁶⁵ An exception is the french model Imacilim (CIRED 1991, Hourcade 1993) who allows for an unemployment equilibrium and concludes that a carbon tax recycled through cuts in payroll taxes may slightly reduce unemployment if the assumptions about technical progress are optimistic enough.

Table 4.2.5 Bottom up exercises on European countries

Author	User	Name	Model	Horizon	Region-Countries
Krause et al. (1994)	Dutch Ministry	IPSEP	None		FRG,F,I,UK, NL
ECN (1994)	Dutch ministry		MARKAL	2030	Netherlands and OECD Europe
German Institutes	German ministry	IKARIUS	Yes	20	Germany
RISO (1993)	UNEP Danish Minister	UNEP costing studies	BRUS	2030	Denmark
ECN (1993)			MARKAL	2030	Netherlands
CIRED (1993)			IMACLIM-NEXUS	2030	France
COHERENCE (1991)	CEC-DGXII	Crash program on CO ₂	EFOM-ENV	2010	11 countries
German Institutes (1991)	Bundestag	Prognos	Econometric simulation	2010	Germany
Johansson, Bodlund (1989)	Swedish		None	2010	Sweden

Table 4.2.6 Characterization of sectorial optimisation and technico-econometric energy models

	EFOM-ENV	MARKAL	BRUS (DK)	IKARIUS (FRG)	GRETA's mod
Type of model	Intertemporal optimisation on supply-demand	Intertemporal optimisation on supply-demand	Optimising simulation on supply and demand	Technico economic demand simulation Supply optimisation	Calibrated equal demand and power
Horizon Countries	20 (to 30) years 12 EC countries	1990-2030 Netherlands Switzerland	2030 Denmark	2020 Germany	1989-1994 Italy and OECD E
Demand sectors	3 Industries Transport Commercial Residential	Industry Transport Residential and commercial	Industry Transport Residential and commercial	Industries : 30 processes Transportation (detailed simul.) Households Tertiary (27 consumer groups)	Industry Power plants Residential Transport
Rational use of energy	Optional (40 classified measures by sector) Yes	Yes	Yes	Yes	No explicitly
Influence of relative energy prices Number of energy products	25	30	?	?	Yes (cross elastic) 3
Number of processes of supply/demand	300 approx.	500	Numerous (complex interactivity between local energy grids) Yes	500 to 2000 Special representation by type of user	-
Renewables Link with the global economy	Yes No feed back	Yes No feed back	Yes No feed back	Yes Macroeconomic scenarios Input/output model stimulating sectorial economic development No feedback	Exogenous macroeconomic s
CO ₂ constraints	Ratio to 1988 emissions	Ratio to baseline	Ratio to baseline	?	Tax *

* Test on three tax scenarios 85\$/t, 50\$/t, 100\$/t.

taxes to CO₂ the proposal called for levying new taxes on most major sources of energy. The taxes would be based partly on carbon and partly on energy content and nuclear energy and large scale hydroelectric projects would be taxed at a rate approximately 50 percent lower than of carbon intensive fuels. The goal is both to limit CO₂ emissions and to discourage energy use in general. This solution of a combined carbon and energy tax stemmed from the will to prevent a too systematic switch towards nuclear energy and to account for all the negative externalities embedded in energy production.

The outcome of such a tax differs logically from the one of a tax on carbon-based fuels. Carbon taxes reduce indeed CO₂ emissions both through their effects on energy consumption and through fuel choice. Coupling an energy tax to a carbon tax will conversely lead to additional conservation, but, by raising the price of carbon-free substitutes, the proposal would reduce incentives for fuel switching and lowers the effectiveness of the measure in pure terms of CO₂ emissions. This is confirmed by several studies whose results are reported in Table 4.2.2. For example, in countries like Germany where coal plays a large role in the baseline energy system. An emission reduction of 6.55% is achieved for Germany with an energy tax compared with a 12.9% reduction with a carbon tax in the HERMES-MIDAS analysis for 2005⁶⁸ (See table 6.2).

4.2.2 A Review of Bottom-up Studies

This section summarizes and compares the results of major larger coordinated bottom-up studies for Europe. Main differences in results are discussed in relation to different input and baseline scenario assumptions and to modelling methodology. The studies considered are:

- the COHERENCE (1991) "Cost-effectiveness analysis of CO₂ reduction options" studies carried out for the CEC Joule programme,
- three of the UNEP Costing studies (1994b) (Denmark, France, Netherlands),
- the recent IPSEP study (1993) covering five countries
- the Swedish study of 1989, Bodlund et al. (1989).

4.2.2.1 Methodology of the studies

The COHERENCE study adopted a uniform modelling methodology, the EFOM linear optimization model developed by the research programme of the European Community. The UNEP studies followed a common methodological framework comprising common scenario assumption, input data, time horizon and cost definitions. Optimization as well as simulation models were used in these studies. The latter two studies, IPSEP and Bodlund et al. did not use any formalized modelling framework but focussed on the assessment of technologies and their emission reduction potential.

An overview of the methodologies and models is given in Tables 4.2.5 and 4.2.6.

4.2.2.2 Main objectives and definitions

Primary aims of the European bottom-up studies have been to demonstrate the existence of an energy savings potential with negative or low economic cost and to analyze the cost-effectiveness of energy supply and demand options for achieving a certain emission-reduction goal. An important outcome of such a cost-effectiveness analysis is to enable inter-country

Table 4.2.2 Comparison of the Emissions Reduction Between Energy Tax and Carbon Tax

	Geographical field	Horizon	Carbon tax	Energy tax
Global 2100 (Tax: 10 \$/bl)	Europe	2030	-50%	-46.5%
Hermès-Midas (Tax: 10 \$/bl)	Germany	2005	-12.9%	-6.55%
	UK	2005	-6.55%	-4.40%
Melodie (Tax: 200 \$/t)	France	2010	-15.7%	-12.6%
Midas (10 \$/bl)	Germany	2005	-11.63%	-7.52%
	UK	2005	-3.98%	-3.29%

⁶⁸By comparison in UK, the reduction is 4.40%, instead of 6.55% in 2005.

Table 4.2.7 Comparison of marginal costs of reduction in the EC countries in the CEC bottom up exercise with EFOM-ENV.
(ECU/t of CO₂)
reduction by reference to the level of 1988

CO2 reduction Case in 2010	constant	5%	10%	15%	20%	30%
Belgium	15	15	39	290	-	-
Denmark	0	0	6	-	11	32
France	0	0	19	-	43	-
Germany	0	0	15	18	43	138
Greece	23	56	224	-	-	-
Italy	22	112	413	-	-	-
Netherlands	27	138	-	-	-	-
Spain	18	143	1658	-	-	-
United Kingdom	0	0	12	-	35	63

Source : COHERENCE (1991), p. 50.

The main explanation behind the widely varying marginal emission reduction costs is the heterogeneity of the national technology data. Consequently the CEC is presently organising a new data collection on efficient technologies on a homogeneous basis. Differences in economic growth for instance for Spain and Greece could partly explain the high marginal emission reduction cost in these countries, but cannot fully explain all inter-country differences. Also the high value for Italy needs to be further evaluated and explained.

Another interesting feature is that the initial technology mix of the energy supply system, which is an important determinant of the potential for CO₂ emission reduction by each country, seems to have no influence on the country results of the COHERENCE study. Costs for France (which has limited CO₂ emission reduction potential because of the installed nuclear capacity) are quite similar to the British and German ones, and considerably lower than the Italian costs, whereas the scope for manoeuvre is much higher in the latter three countries because of the predominance of conventional power production.

Different country study results are also seen in the UNEP studies for Denmark, The Netherlands and France. These differences are primarily a consequence of different baseline definition and of the content of national supply systems. Denmark and to a lesser degree The Netherlands have high emission reduction potentials as a consequence of a carbon-intensive power productions system, while emission reduction in France needs to include transportation measures, which often are more costly and difficult to implement.

The Danish study assumed that the emission reduction case included further profitable efficiency improvements and energy-end use savings compared with baseline development. The required measures were introduction of legislation in the form of norms, efficiency standards and obligatory connection to already established natural-gas and district-heating grids, which at present have a low utilisation rate. Other options with positive, but low costs were wind turbines and biomass fuels. The Danish options are listed in Table 4.2.9.

The study for The Netherlands assumed that all possible efficiency improvements in the energy system would be implemented in the reference case. A consequence of the "efficient" definition of baseline for the far-reaching reduction targets includes energy end-use savings amounting to 3-4% percent reductions followed by costly advanced technologies such as CO₂-removal technologies and the import of hydrogen from Sahara. The emission reduction options for The Netherlands are shown in Table 4.2.10.

The French study estimated a tax rate for emission reductions in a macroeconomic model. In one scenario variant, it was assumed that carbon taxes would be combined with complementary measures in the energy sector such as information, efficiency standards, research and development, grants and with measures in other sectors. The tax was estimated to be \$187.5 per tonne CO₂ for a 12.5% reduction in 2005, \$75 per tonne of CO₂ for a 25% reduction in 2030 and \$1425 per tonne of CO₂ for a 50% reduction in 2030. The lower tax rates in 2030 are due to hypothesis in Technical Progress.

Despite the fact that the UNEP country studies followed a common methodological framework (UNEP 1994) the country results still shows differences. In the case of the Danish, The Netherlands and French studies these differences are primarily a consequence of different baseline approaches and emission reduction technology assumptions. This means that the comparison of national results requires a detailed and transparent documentation of

comparison of marginal (or average) costs of reduction justifying the economic benefit of using market-oriented instruments.

The study results are highly dependent on the assumptions on energy efficiency measures included in the baseline scenario (see section 1 of this chapter). The COHERENCE project assumed that all profitable efficiency measures were included in the baseline, which meant that all emission reduction options by definition have positive costs in this analysis. In the UNEP studies Denmark, The Netherlands and France followed different principles for baseline definition. Denmark defined its baseline to include some major inefficiencies to persist in the future implying that a large potential for no-regret emission reduction options was found. The studies for France and The Netherlands study assumed the baseline to be coefficient which meant that all emission reduction options had positive costs. The modelling approach was however different in these two studies; The Netherlands used the linear optimization model, MARKAL, while France used a combined bottom-up/top-down simulation modelling framework. The IPSEP and Johansson and Bodlund studies included major inefficiencies in their baselines and found consequently a potential for no-regrets.

4.2.2.3 The results

Despite differences in baseline definition all the studies demonstrate the existence of an economic potential for the reduction of CO₂ emissions with negative or low costs. For example the COHERENCE programme indicated reductions of 10 to 20% (reduction from the 1988 level) in 2010 with a relatively low marginal cost (15-20 \$/t).

The results demonstrate the importance of assumptions on existence and possible implementation of no-regret options, for the limitation of the marginal cost (or average cost) of CO₂ emission reduction. For example the IPSEP exercise seems to prove the presence of a substantial potential for negative cost emission reduction options. According to that study, stabilisation or reduction of CO₂ could be achieved at negative average cost (-14% to -23% for the global energy service bill in 2020) for any CO₂ emission reduction target between 0 and 40% from the 1990 level. The Swedish exercise of 1989 arrives at higher marginal costs (150 to 250 \$/t) because of the present very low level of CO₂ emissions (with hydro and nuclear power production), and the necessity of using carbon fuels in the future.

The main results of the European COHERENCE study are shown in Figures 4.2.4 and 4.2.5 and in Table 4.2.7. The study found that it is less costly for the UK, Germany and Denmark to reduce emissions from current levels, than for Greece and Spain. The study estimated no cost associated with a 10% reductions in emissions from present levels for the former three EC members. For the latter two, even to keep emissions constant at today's levels would require substantial investment in energy conservation schemes or investment in non-fossil fuel technologies. These differences are partly due to different baseline projections for each of the countries with larger variation than can be explained by "real" differences in expected economic growth and energy requirements. Baseline CO₂ emissions range from a drop of 3% by 2010 in Luxembourg, to stabilisation for Germany, and to increases of 72% and 86% for Greece and Portugal respectively (all from current levels). The differences can be explained by variation in industrial structure, capital stock constraints and different energy technology assumptions.

The COHERENCE (1991) programme also arrived at large differences in the marginal cost of CO₂ reduction between the countries as illustrated in Table 4.2.8 which shows marginal emission reduction costs for a 10% emission reduction from 1988 level.

The cost of CO₂ reduction A Bottom-Up approach for Europe Reduction from reference year

Figure 4.2.4 Marginal cost in ECU/t of CO₂

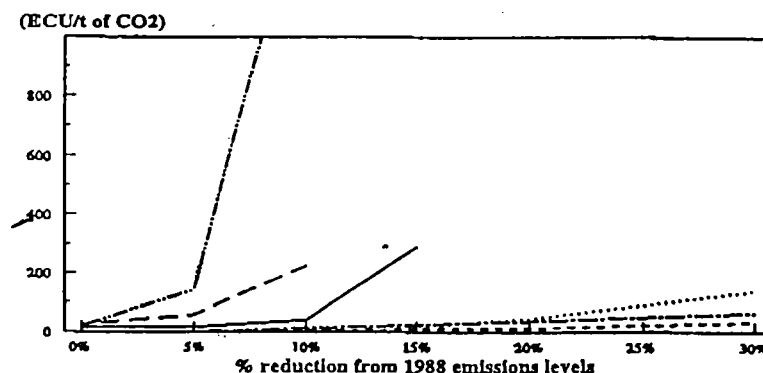
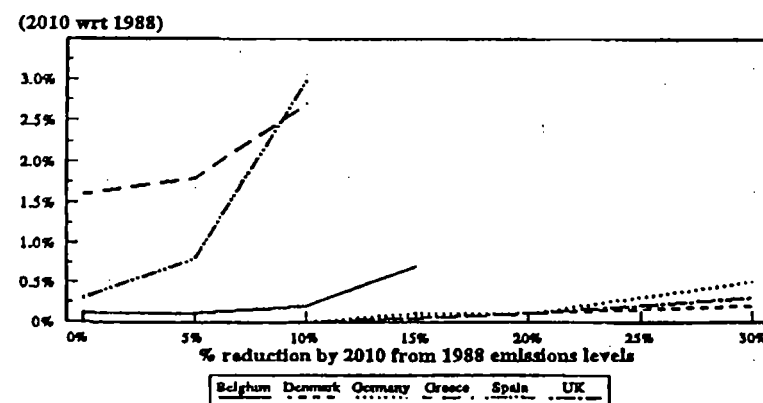


Figure 4.2.5 Cost as a percentage of 1988 GDP



Source: Coherence (1991); Table 4.4

assumptions and national modelling frameworks and that the marginal emission reduction costs cannot be directly compared from one of the countries to another.

In all assessed European bottom-up exercises, the slope of marginal cost curves, notably after a certain level of reduction of CO₂ emissions, is highly dependent on the package of technologies which is considered. The slope may be very steep after a certain level: for instance in the Danish UNEP study, from 10 \$/t to 200 \$/t for a switch of the 2030 goal from a 25% to a 50% reduction (baseline reference). There seems to be a tendency to extend the segment of the cost curve with a slow increase in marginal costs when more emission reduction technologies are introduced into the analysis. This tendency has also been seen when short term reduction targets are compared with long term targets. The marginal emission reduction cost decreases with time for similar reduction targets (from baseline) in the Danish and The Netherlands UNEP studies simply because more technologies are available.

4.2.2.3.1 The dependence of the results on modelling approach

A number of the bottom-up exercises assessed here were based on optimisation models which supposedly introduce a certain degree of consistency between the different supply and demand options and between their respective temporal development. They also take into account some feedback on internal energy prices. Generally speaking the results of such optimization based studies are more pessimistic than those of the simulation-based bottom-up studies, probably because of the use of this sectoral formalisation and the lower degree of disaggregation of the potential for improved energy efficiency.

The French IMACLIM-NEXUS study shows the sensitivity of the results to the assumptions on the industrial and socio-economic content of the reference scenario. A second reference scenario considers that urban transportation problems will become so important that, independent of CO₂ policy, there will be radical change in urban planning and inter-mode substitution. New urban policies could determine, between now and 2030, an change of fuel consumption growth just as significant as a huge taxation of 280 \$/t, compared to the first reference scenario.

4.3 Studies of the Costs of Reducing CO₂ Emissions in Transitional Economies

Modeling emission reduction costs for the formerly planned economies of Eastern Europe is particularly challenging. The region has a long history of highly subsidized energy prices, and other inefficiencies in the structure of incentives. Then, models which assume the existence of market mechanisms will consequently miss many of the important features of these economies who lack both meaningful energy prices and hard-budget constraints. Applying equilibrium models to planned economies amounts to assuming that planned economies mimic the behaviour of market economies. This assumption is impossible to accept empirically, particularly with regard to energy use even if remarkable political and economic changes have shaken the planned economies over the past five years. The term *economies in transition* has come to mark the former Soviet Union and Eastern and Central Europe, implying that market reforms are underway but the extent of the transition varies dramatically by country, and there is no certainty about the type of economic institutions likely which will emerge at the end of this process and the type of development pattern which will stem out.

The problem is further complicated by the fact that the transition process per se generates a state of crisis. The Russian GDP, for example, declined by 18.5 percent in 1992. Economic activity in 1993 was lower than in 1985 (Bashmakov, 1994). Standard econometric techniques aiming at providing some stylised representation of the regularities (the "law" behind the economic mechanisms at work in a given geographical and historical context) that can be derived from reliable numerical statistics cannot be consequently applied without caution. Until these economies achieve a more stable footing, predictions of future growth will be tenuous, at best.

4.3.1 A Review of Top-down Studies

The limitations imposed by the specifics of current context of economies in transition to the application of general equilibrium models and/or econometric models explain why there have been relatively few applications of top-down methodologies to emerging economies, particularly when compared to the growing body of analysis being amassed on developed economies. The few studies that do exist were conducted by US and Western European economists using models that are best suited for application within the OECD. This is not to imply that the studies are without merit. Indeed, as we will see shortly, they have yielded some useful insights about the costs of emissions reduction.

A key contribution in extending the macro-economic models to emerging economies is to point out the importance of the treatment of energy subsidies. Many of the early studies showed relatively high emission reduction costs. See for, example, Dean and Hoeller (1992) or Manne and Richels (1992). Critics claim that the high numbers reflect "the difficulties top-down studies have with economies undergoing restructure (Grubb et al, 1993)." They argue that the high costs are due, in large part, to a failure to adequately capture the demand-side impacts of subsidy removal.

The removal of subsidies will indeed result in costless conservation in addition to that induced by the AEEI factor. The early studies have consequently underestimated the potential for demand-side savings. The importance of existing market distortions is underscored in a new modelling experiment by Manne and Schrattenholzer (1993) using the Global 2100 model. They examined the sensitivity of emission reduction costs for emerging economies to the presumed size of the subsidy. They found that the removal of artificial barriers which insulate

Table 4.2.9 Main categories of CO₂ reduction options and related marginal abatement cost (MAC) in Denmark

CO ₂ reduction option	reduction (%)	MAC (US\$)
Connection to natural gas network	0.5	-255.7
Connection to district heating network	2.0	-100.0
Electricity conservation in households	4.8	-70.0
Increased use of combined heat & power	1.5	-62.9
Electricity conservation in services	2.8	-55.7
Conservation in industry	1.6	-40.0
Conservation in agriculture	0.4	-38.6
Combined cycle - natural gas (1000 MW)	3.8	-8.6
Biogasification (1500 MW)	7.6	-4.3
Wind turbines (1800 MW)	7.0	0.0
Central natural gas comb. (4000 MW)	9.4	12.9
Solar collectors for hot water	0.3	30.0
Insulation in office buildings	0.7	81.4
Photovoltaics (800 MW)	2.9	185.7
Fuel cells (1000 MW)	1.0	614.3
Total CO ₂ reductions	48.9	

Table 4.2.10 Main categories of CO₂ reduction options in the Netherlands

Sector	CO ₂ reduction option
Industry:	Fuel cell combined heat & power More efficient industrial process Gas fired and electric heat pumps Solar heat, biomass and hydrogen fired equipment
Transport:	More efficient engines, brake energy recuperation Biofuel, hydrogen, electric, LPG, CNG and methanol engines Households and services: Condensing gas boiler Gas fired and electric heat pumps Improved building insulation More efficient electric and lighting appliances Solar boilers, biomass and hydrogen fired equipment District heating Greenhouse insulation
Electricity and heat production:	Gas combined cycle and advanced coal combined cycle plants Fuel cell industrial cogeneration and district heat Electricity storage, hydrogen fuel cells CO ₂ removal at gas fired and coal fired plants Wind turbines, biomass power plants, solar photovoltaic
Other supply process:	Methanol production from natural gas and coal Hydrogen production from natural gas and imports from Sahara Liquid and solid biofuel production (from sugar beet, wheat, straw, wood) Combined methanol and electricity production Transport of CO ₂ to depleted natural gas fields and to aquifers

Note: The nature of the energy system optimisation model used in the Netherlands study does not allow percentage reductions and costs to be assigned to individual options. The options here are part of an integrated package of technologies which leads to a reduction in CO₂ emissions of 50% from baseline in 2030, at a total cost of US\$3.8 billion.

Assumptions (or results) for GNP growth and energy prices were not always available. However, when provided, these assumptions or results were similar among the studies.

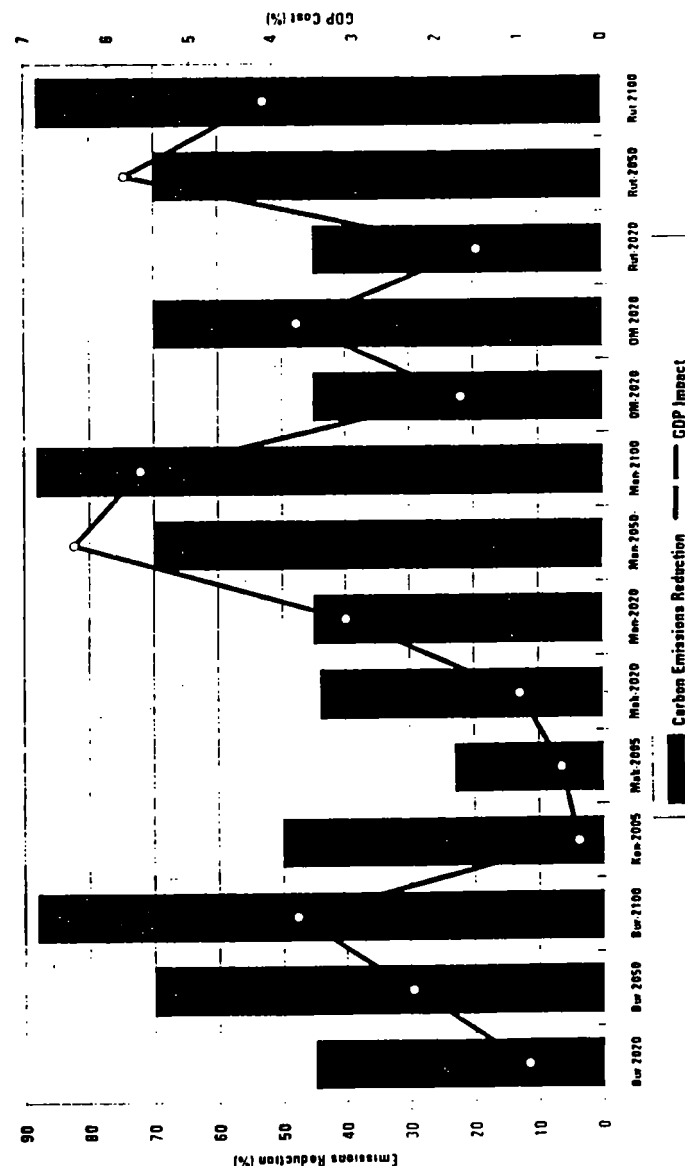
A relationship can be seen between the magnitude of the emissions reductions and costs in the above scenarios, but this factor cannot explain the significant variation in cost estimates across the scenarios. And while the discount rate assumed in each study for discounting financial costs varied among the studies, there seems to be little correlation with cost estimates. Indeed, the one major difference in cost estimates in the studies reviewed appears to be that of methodology, specifically the choice of top-down versus bottom-up models. (See Figures 4.3.2 and 4.3.3 and Table 4.3.1.) This result is not surprising given the special nature of planned and post-planned economies.

4.3.2.2 Evaluation of cost estimates

It is well-known that the most energy-intensive economies in the world--no matter how economic output is measured--are the planned or post-planned economies (Chandler et al. 1990). However, a short digression on the meaning and importance of energy intensity in the formerly-planned economies may be in order. Energy intensity (energy consumed per unit of economic output) is an important, if controversial, indicator of future emissions. This value is difficult to measure accurately because GNP is difficult to quantify in comparable units such as a common currency. Also, differences in economic structures - the share of output produced by manufacturing, for example - may derive from the logical economics of comparative advantage. For example, if Poland produces more steel because it has abundant and cheap coal (now a questionable assumption), the Polish economy will be more energy intensive than, say, Japan, which must import coal or oil for steel processing.

If energy intensity is interpreted simply as a surrogate for energy efficiency, then the measure can be misleading. However, a vast literature has verified that the planned economies use energy inefficiently both because they use technology that is not optimised and because the structures of their economies - that is, the remarkably heavy reliance on heavy industry - is not economically rational (Kornai 1990). Yet, most models of future energy use in this region imply a) continued high energy intensity, and b) high economic growth. The results are sometimes startling when one realises that they indicate that the formerly planned economies would be twice as energy intensive in the year 2050 as Japan is today. One should ask why - or how - growing market economies would maintain energy utilisation rates peculiar to centrally planned economies. One should also ask whether fast growth is even possible without the restructuring and efficiency improvements necessary to enable formerly planned economies to compete internationally.

Figure 4.3.2 Cost Studies: Emissions Reduction in the Former Soviet Union



domestic consumers. These price movements may well lead to a drop in carbon emissions over the next decade.

The same result was confirmed in a subsequent study by Manne and Oliveira Martins (1994). They used the GREEN and 12RT models to estimate the taxes required to stabilize emissions at 1990 levels. Importantly, price reforms and the removal of energy subsidies were included in the "baseline" scenario. This enabled the modelers to separate the impacts of restructuring from those of a carbon constraint.

For purposes of the analysis, the transition economies were divided into two regions: the countries of the former Soviet Union (FSU) and the Eastern European countries in transition (EET). Figure 4.3.1 displays the carbon taxes required to achieve stabilization in each region. The former Soviet Union and Eastern Europe countries have zero taxes before 2010. This is because the stabilization constraint is non-binding. With price reforms and the removal of energy subsidies, there is a decline in emissions relative to 1990 levels. For the GREEN model, the emissions constraint begins to bite shortly after 2010. For 12RT, emissions remain below the 1990 level until 2040.

Despite the intrinsic weakness of numerical outcomes for these regions, the implications of these analyses are important: under the hypothesis of successful transition which is dependency upon institutional and non strictly economic factors. The costs of stabilizing emissions may be relatively small for countries where market failures have undoubtedly limited investment in energy efficiency. The potential for cost-effective reductions in energy use is apt to be considerable under the hypothesis of a successful transition towards a new institutional context in which, under whatever form, prices will actually reflect the full energy cost.

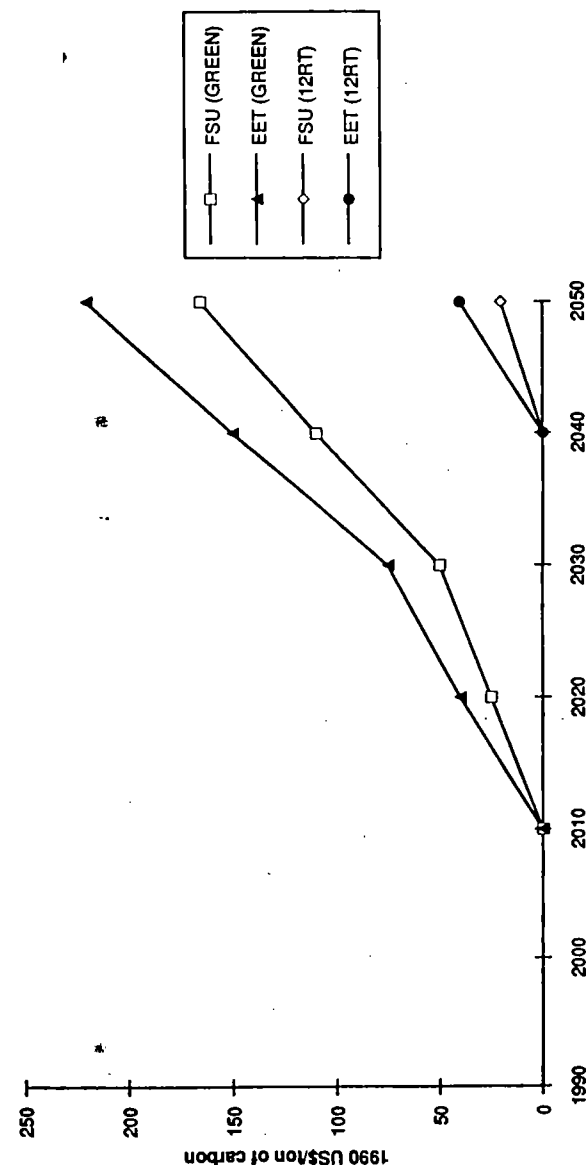
4.3.2 A Review of Bottom-up Studies

This section summarises selected studies of the potential and cost of carbon emissions reduction strategies in the post-planned economies. Bottom-up approaches suffer less than the macro-economic analysis do from the specifics of the current context (lack of data, difficulty to extrapolate current trends and to resort to the market equilibrium hypothesis). They provide interesting insights about the potential for increased energy efficiency, even if one should be careful about the implementation difficulties of such potentials, and some of them make it possible to test the consequences of various hypothesis of structural change in this area.

4.3.2.1 Summary of studies

A comparison of emissions reduction cost studies reveals striking differences with the result of some top-down models (see Table 4.3.1). On the bottom-up side, a number of studies have been completed by Eastern European and Russian experts since the revolutions of 1989. Some of this work was conducted using the EPA End-Use Energy Model, while others used indigenous models. The EPA model projected future energy demand to the year 2030 in five year increments, giving results for the major fuel types and future aggregate industrial energy intensity. The model estimates energy demand on the basis of economic growth, structural change, price response, and technical energy-efficiency improvements not attributed to price response. Like Makarov et al. (1991), most of the bottom-up studies incorporated economic restructuring as a driving force of the energy content of economic growth.

4.3.1 Comparison of Carbon Taxes in the Stabilization Scenario



4.4 Studies of the Costs of Reducing CO2 Emissions in Developing Countries

To some extent, the development of knowledge of the CO2 abatement costs in developing countries suffers from the same limits as the ones underlined in the case of countries in transition. First, even if it should be underlined that the amount of existing material is not negligible and far higher than for these latter countries, studies cover a minority of developing countries. Second, the overwhelming majority that do exist are based on methodologies designed for use in developed nations; time, money or human means having lacking, these models were poorly adapted and tend to treat the dynamics of developing nations as a caricature of industrialized economies. Third, national climate-change emission reduction studies for developing countries carried out so far have been primarily bottom-up studies who have either assessed the emission reduction potential of individual technologies, or performed an integrated analysis for main emitting sectors mainly the energy system

4.4.1 A Review of Top-down Studies

Top-down models applied so far tend to describe the dynamics of each third world countries or each geographical region in a way that tend to mirror the market based economies of the OECD countries. The models are market driven and assume the existence of future markets, perfect information, competitive economic dynamics on the demand and supply side, and hardly consider the difficult issues of the linkages between endogenous development and international specialisation. Many exercises tend even to ignore the impact of financial constraints and the overindebtedness crisis who play such a decisive role on the development dynamics of these countries.

In addition, despite recent progress for including the informal sectors of developing economies in macroeconomic analysis by the way of social accounting matrices, the macroeconomic models applied so far tended to ignore or underestimate the contribution of these sectors. In many countries, these sectors account for the overwhelming proportion of agriculture and land use activities, household energy consumption. Activities in these sectors, such as traditional biomass use, deforestation, rice cultivation, animal husbandry, account for significant greenhouse gas emissions. Beyond, the existence of a huge informal sector in urban areas distorts may also greatly, say the impact of a carbon tax on employment, from the predictions of models describing the only one formal economy. As recalled in section 2, the models also have difficulty capturing the patterns of change whereby the development process transforms the traditional activities into modern activities through a myriad of simultaneous processes such as monetization, market development, technology penetration, institution building and education.

Despite these limitation, top-down models can still provide, useful insights into a number of important issues. These include taxes and subsidies, revenue recycling, international trade, allocations for research and development and "backstop" technologies. But until more effort is devoted to broadening the frameworks to better deal with the unique characteristics of developing countries, one must be especially cautious in interpreting their results such as in the case of countries in transition. With these caveats in mind, we now turn to a review of several recent applications.

4.4.1.1 The costs of emissions reduction in China

Of the developing countries, China has received the greatest attention from top-down modelers. This is not surprising since it is currently the third largest emitter of CO2 and there is every expectation that its share will continue to increase. Because of its importance, global models usually include China as a single geographical region. For example, the OECD Model Comparison Project divided the globe into five geopolitical regions: the US, other OECD countries, the former Soviet Union, China and ROW (the latter being a catchall for the rest of the world). This study provides some interesting perspective on how China's emissions are likely to evolve in the future and the potential costs of emissions reduction.

Besides business as usual (BAU), the following two scenarios were examined: Scenario I) a reduction in the rate of growth of emissions in each region by 2 percent per annum, and Scenario II) stabilization of emissions at 1990 levels in each region. Table 4.4.1 summarizes the percent growth rate of carbon emissions for BAU. In addition, it shows GDP losses for China and the world under the two control scenarios.

Note that all models report very large GDP losses for China under the stabilization scenario. This is because the emissions growth under business as usual is much higher for China compared to the world as a whole. Hence, China requires especially large emission cuts. In Scenario I, absolute cuts in emissions will be required in the industrialized countries, while a low growth in emissions is allowed for China. Hence, the GDP losses for China (in percentage terms) are somewhat lower. Although figures are not reported for ROW due to the heterogeneous nature of this region, the study indicates that the GDP losses are also very high for ROW under both scenarios. Among other things, the OECD study underscores the importance of the emissions allocation scheme in determining costs to individual countries. This issue will be addressed in greater detail in the section on global models.

4.4.1.2 The impacts of energy subsidy removal

One area where macroeconomic models are particularly useful relates to the removal of market imperfections. In a recent study, the OECD used the GREEN model to analyze the impact of subsidy removal in China and India (OECD, 1994). The "distortion removal" scenario assumes phasing out of subsidies on the sale price of oil by 2000 and on coal and gas by the year 2010. Under the "no-distortion removal" scenario, the energy subsidies observed in the base year continue.

The study finds that the removal of energy subsidies has a major impact in reducing energy consumption and carbon emissions. Under the no-distortion removal scenario, energy consumption and carbon emissions increase by a factor of fourteen between 1985 and 2050 in both countries. Under the distortion removal scenario, energy consumption and emissions in China and India are reduced to nearly forty and sixty percent, respectively, in 2050 (relative to the no distortion removal case). The reductions are due to higher energy efficiency and the use of Backstops promoted by higher market prices for carbon based fuels.

4.4.1.3 The impacts of carbon taxes on non-commercial energy consumption

But, even if this conclusion relies non contestable price mechanisms, it should be balanced by the consideration of the role of informal economy who could offset part of the expected gain. That was pointed out, among others by researchers from the OPEC Secretariat who used a macroeconomic model to investigate the impacts of OECD type carbon taxes on developing

Figure 4.3.3 Cost Studies: Emissions Reduction in Central Europe

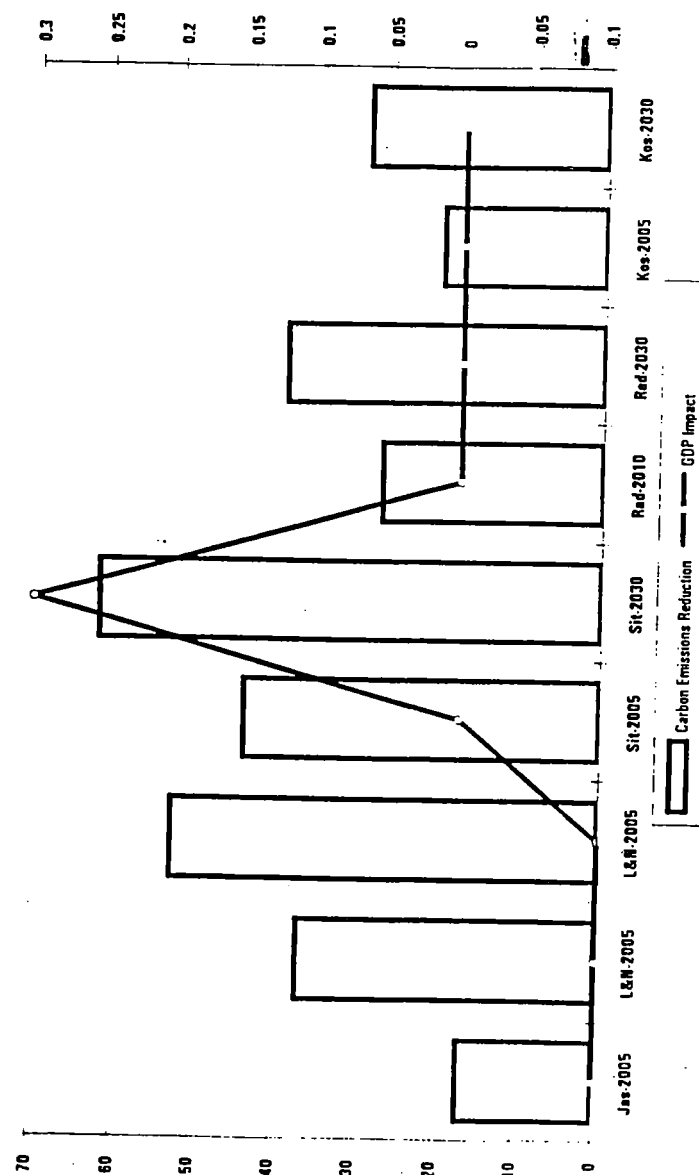


Table 4.3.2 Cost of Carbon Dioxide Emissions Reduction

Country	Study	Forecast Year	CO2 Reduction from Baseline (%)	Cost of reduction (% of GNP)
Former Soviet Union	Burniaux (1992)	Bur 2020	45	0.9
	Burniaux (1992)	Bur 2050	70	2.3
	Burniaux (1992)	Bur 2100	88	3.7
	Kononov (1993)	Kon-2005	50	0.3
	Makarov et al (1991)	Mak-2005	23	0.5
	Makarov et al (1991)	Mak-2020	44	1
	Manne (1992)	Man-2020	45	3.1
	Manne (1992)	Man-2050	70	6.4
	Manne (1992)	Man-2100	88	5.6
	Olivera Martins et al (1992)	OM-2020	45	1.7
Hungary	Olivera Martins et al (1992)	OM-2020	70	3.7
	Rutherford (1992)	Rut-2020	45	1.5
	Rutherford (1992)	Rut-2050	70	5.8
	Rutherford (1992)	Rut-2100	88	4.1
Poland	Jaszay (1990)	Jas-2005	17	-0.1
Czechoslovakia	Leach & Nowak (1991)	L&N-2005	37	-0.1
	Leach & Nowak (1991)	L&N-2005	53	-0.1
	Sitnicki et al (1991)	Sit-2005	44	0
	Sitnicki et al (1991)	Sit-2030	62	0.3
	Radwanski et al (1993)	Rad-2010	27	0
	Radwanski et al (1993)	Rad-2030	39	0
Czechoslovakia	Kostalova et al (1991)	Kos-2005	20	0
	Kostalova et al (1991)	Kos-2030	29	0

NOTE: Bold face denotes a bottom-up study.

Table 4.4.2

Energy & Environmental Division, LBL, 1991.
CO ₂ emissions from developing countries. India, Indonesia, China, Argentina, Brazil, Mexico, Venezuela.
High and low emission scenarios 1985-2025. Country specific reductions between 13% and 54% reduction in 2025.
Energy system model, STAIRS.
Asian Development Bank, 1993.
National Response Strategy for Global Climate Change: People's Republic of China.
Business as usual with high and low economic growth and policy scenario 1990-2050. CO ₂ reduction of 23% from baseline in 2050.
Energy system model combined with macroeconomic assessment.
UNEP Collaborating Centre on Energy and Environment, 1994.
UNEP Greenhouse Gas Abatement Costing Studies. Brazil, India, Egypt, Senegal, Thailand, Venezuela and Zimbabwe.
Reference and abatement scenario. Emission reduction targets for 2005/10 and 2020/30 covering 12.5% to 50% reductions from baseline.
Construction of abatement cost curves using energy system models.
Davidson, Ogunlade, 1993
Carbon Abatement Potential in Western Africa. Ghana, Sierra Leone and Nigeria.
High and low emission scenarios 1985-2025. Reductions from baseline in 2025: Ghana 38%, Sierra Leone 25%, Nigeria 24%.
Energy system model, STAIRS.
La Rovere, E., Legey, L. F. L. Míguez, J. D. G., 1994
Alternative Energy Strategies for Abatement of Carbon Emissions in Brazil.
Three alternative economic growth scenarios, abatement scenario using high economic growth scenario as baseline. Reductions in 2010 8% and 50%, reductions in 2025 5% and 50% from baseline.
Input-output model used to forecast energy requirements, scenarios taking Japan, Spain and Colombia as focal points. Energy system analysis.
Asian Energy Institute, 1992.
Collaborative Study on Strategies to limit CO ₂ emissions in Asia and Brazil. Brazil, China, India. The Islamic Republic of Iran, South Korea and Thailand.
Emission reduction scenarios for 1988/90 to 2000/2015.
Calculation of investment cost for individual abatement technologies.
Greenpeace, 1993.
Towards a Fossil Free Energy Future. Global study including regional assessment for Africa, Centrally Planned Asia, Latin America and South and East Asia.
Reduction scenario 1988-2100. Global reductions from 1988 level: 50% in 2030, 100% in 2100.
Energy system model and macroeconomic assessment of the impact of carbon taxes on final energy prices.

Table 4.4.3 Growth rates of population, GDP, primary energy consumption and CO₂ emissions in reference and abatement scenarios for 1990 to 2020/30.

COUNTRY	POPULATION	GDP	PRIMARY ENERGY		CO ₂ EMISSIONS	
			Reference	Abatement	Reference	Abatement
ARGENTINA (1)	1.1	2.0	1.8	1.1	1.8	1.1
BRAZIL	1.4	4.7	3.5	3.7	5.3	3.2
BRAZIL (1)	1.2	3.2	2.5	1.0	2.8	0.8
CHINA (6)	0.8	6.0	3.1	2.7	2.6	2.1
EGYPT	1.7	5.0	3.2	1.4	3.8	1.4
GHANA (5)	2.9	4.0	3.6	3.0	5.4	5.0
INDIA	1.8	6.3	4.2	3.8	3.8	2.9
INDIA (1)	2.0	5.0	4.6	4.3	4.6	4.3
INDONESIA (1)	1.2	3.0	3.6	3.2	4.0	3.5
SOUTH KOREA (4)	0.4	5.0		3.1		2.8
MEXICO (1)	1.7	4.4	2.7	2.1	2.8	1.9
NIGERIA (5)	3.0	4.0	2.6	1.9	4.6	3.8
SENEGAL	3.0	3.2	3.2	2.4	3.5	2.6
SIERRA LEONE (5)	2.3	3.0	2.2	1.7	3.5	3.0
THAILAND	0.9	4.8	4.8	4.2	5.5	4.6
THAILAND (4)	2.0	8.0		7.8		7.8
VENEZUELA	2.1	3.8	2.5	1.9	3.1	2.1
VENEZUELA (1)	1.7	4.0	3.4	3.2	2.5	1.9
ZIMBABWE	2.4	4.2	2.8	1.9	3.2	1.5
LATIN AMERICA (2)	1.5	3.3	2.7		3.2	
LATIN AMERICA (3)	1.3	3.2		0.9		-0.6
SOUTHEAST ASIA (2)	1.4	4.6	3.9		5.1	
SOUTHEAST ASIA (3)	1.6	4.1		1.5		-0.2

(1) Energy & Environmental Division, LBL; CO₂ Emissions from Developing Countries: Better Understanding the Role of Energy in the Long Term; July 1991.

(2) IPCC, 1992; Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment.

(3) Stockholm Environment Institute - Boston Centre Towards a Fossil Free Energy Future; April 1993.

(4) Asian Energy Institute; Collaborative Study on Strategies to Limit CO₂ Emissions in Asia and Brazil; 1992.

(5) Davidson Ogunlade; Carbon Abatement Potential in Western Africa; in P. Hayes, K. Smith, eds., The Global Greenhouse Regime: Who Pays?; 1993.

(6) Asian Development Bank; National Response Strategy for Global Climate Change: People's Republic of China; Nov. 1993.

Unnumbered studies were part of the UNEP GHG Abatement Costing project.

4.4.1
Table 4.4.1 Comparative Results from Five Models for Carbon Emission and GDP Losses for China and the World

Model*	% Av. Annual Carbon Emission Growth		% GDP Loss in Year 2100 over BAU				Major Policy Option for Carbon Emission Abatement
	BAU Scenario		Scenario I		Scenario II		
	World	China	World	China	World	China	
CRTM	1.6	2.5	4.0	3.5	3.5	5.0	-
ERM	1.2	2.5	7.0	6.0	4.5	13.0	Fuel substitution
GREEN	2.0	3.8	3.6	1.5	3.0	5.5	Energy conservation
IEA	2.0	3.2	-	-	-	-	Energy conservation
MR	1.7	2.2	5.2	5.0	4.5	5.0	Fuel substitution

* Terminal year for ERM, GREEN and IEA models are 2095, 2050, and 2005 respectively, and Year 2100 for other two models

octipcc07/10/94 17:50

1 countries (Walker and Birol, 1992), and explicitly considered the impact of income and price
2 levels on consumption of Non Commercial Energies.

3
4 The study finds that the income elasticity of NCE is negative, meaning that consumers shift
5 from NCE to commercial energy as income rises. But more importantly, the study also reports
6 an inverse relationship between non-commercial and commercial energy demand in response to
7 price changes. That is, consumers switch from commercial to NCE in the case of price hikes.
8 Both of these results point to the obvious and what is well known in the developing nations,
9 and yet most often forgotten or ignored in top-down analyses. Based on the above findings, the
10 study concludes that in the absence of effective controls on deforestation, carbon taxes would
11 create incentives to deplete forests for energy use.

14 4.4.2 A Review of Bottom-up Studies

15
16 Contrary to the top-down studies who, China excepted, divide the Third-World in large
17 regions, the bottom-up studies are systematically carried out in national country studies for a
18 scenario period from 1988/90 to 2020/30; some of the main studies are listed in Table 4.4.2.
19 The national studies for developing countries have focused on energy system analysis and CO₂
20 reductions. Only some studies however have evaluated the costs of achieving emission
21 reduction: the UNEP studies (UNEP 1994a), the LBL study for India (Mongia 1991), and the
22 ADB study for China (Asian Development Bank 1993).

23
24 Moreover, contrary to the most of the studies carried out for developed countries where
25 emission reductions targets are generally calculated, for each reference scenario in terms of
26 stabilisation or abatement from a given benchmark date, the targets are here more
27 systematically formulated in terms of percent from a baseline case which may be defined to
28 reflect reference economic development and energy requirements (UNEP 1994a), or as a high
29 emission case for the energy sector (Sathaye and Goldman 1991).

30
31 Two main coordinated country study efforts have been carried out by the Lawrence Berkeley
32 Laboratory (LBL) and by UNEP Collaborating Centre on Energy and Environment (UCCEE)
33 who facilitate comparative analysis, such as it was the case for the Energy Modelling Forum in
34 the USA. The results and methodological framework of these country studies were indeed
35 assessed in relation to similar country study activities for China, West Africa and South East
36 Asia in order to evaluate possible common conclusions. The UNEP studies for example have
37 estimated emission reduction costs for a range of target reductions spanning 12.5% to 25%
38 reduction in 2005/10 and 25% to 50% reduction in 2020/30; the levelised emission reduction
39 costs have been estimated following the same cost curve format, (UNEP 1994c).

41 4.4.2.1 Main assumptions and findings: trends and margins of freedom for curbing 42 GHGs emission

43
44 Growth rates of GDP, primary energy consumption and CO₂ emissions are shown in Table
45 4.4.3 for the reference and emission reduction scenarios of the country studies. The economic
46 growth rates range from 3.0% up to 8.0% annual growth, with the bulk of the projections
47 below 5.0%.

48
49 A variation is seen between economic growth rate forecasts in different studies for the same
50 country. Generally the growth rates of the UNEP studies are higher than for the LBL studies.
51 This are fully understandable given the uncertainties surrounding such long term forecasts.

current low level of energy consumption in these countries, there is no use to speculate about the ways to control emissions trends from these countries and that the tendencies are irrevocably dangerous in terms of climate risks.

This conclusion was also the outcome of a study by Asian Energy Institute for a number of Asian countries and Brazil. The study assessed a room for emission reduction in these countries through energy efficiency improvements and shifts to supply technologies with a lower carbon intensity. Studies for Bangladesh, Brazil, China, India, the Islamic Republic of Iran, Japan, South Korea and Thailand were included.

4.4.2.2 Emission reduction costs; a survey for some countries

The UNEP country studies include an estimation of emission reduction costs for emission reductions between 12.5% and 25% from baseline in the short-term (2005/10) and between 25% and 50% from baseline in the long-term (2020/30). Cost is defined as direct cost including investment, operation and maintenance, and fuel costs (UNEP 1994c). Cost curves containing a number of target reductions in one year should be regarded as snapshot pictures of the levelised cost of achieving a given reduction in that year. Figures 4.4.1 and 4.4.2 show the cost curves for a number of participating countries in the short-term and long-term target years, respectively.

The short-term cost curves for Brazil, Thailand and Zimbabwe exhibit a number of similarities. A particular feature is the large potential for negative cost emission reduction options up to 10% to 15% reductions from baseline. The curves are also similar in shape: the first part of the cost curves up to about 5% reductions indicates very low emission reduction costs, followed by a long interval up to about 25% reductions in which emission reduction costs fall within a relatively narrow range between - \$10 and + \$30 marginal cost per tonne CO₂ reduced. Few options were included in the analysis after this interval. The options that do occur tend to be expensive supply-side options, thus implying a steep increase in marginal costs.

The long-term marginal cost curves shown in Figure 4.4.2 show many similarities for the developing countries in line with the short term curves. Venezuela may be regarded as an exception due to entirely positive curve which arises from the inclusion of all "no-regret" options in the baseline.

Senegal has a negative marginal cost interval up to 8% reduction from baseline in 2020/30 followed by very low costs amounting to less than \$10 up to the maximum 50% reduction. The potential for negative marginal cost emission reduction is expanded to about 30% and 40% reduction for Egypt and Zimbabwe respectively.

As in the short-term curves, the long term marginal cost falls within an interval of - \$10 + \$25 per tonne CO₂ for a broad emission reduction interval from about 10% to 40% reduction

Table 4.4.5. shows marginal, average and total emission reduction costs for the short and long term reduction targets related to GDP of the countries. In the long term, the average emission reduction costs for reductions from baseline between 25% and 50% range between -\$5 and +\$37 per tonne CO₂. The total emission reduction costs are negative for Egypt and Senegal.

The range of variation of abatement costs is then far higher in developing countries than in the developed countries. The reason lies partly in the assumptions about technical options, but more interestingly in the definition of the reference scenario.

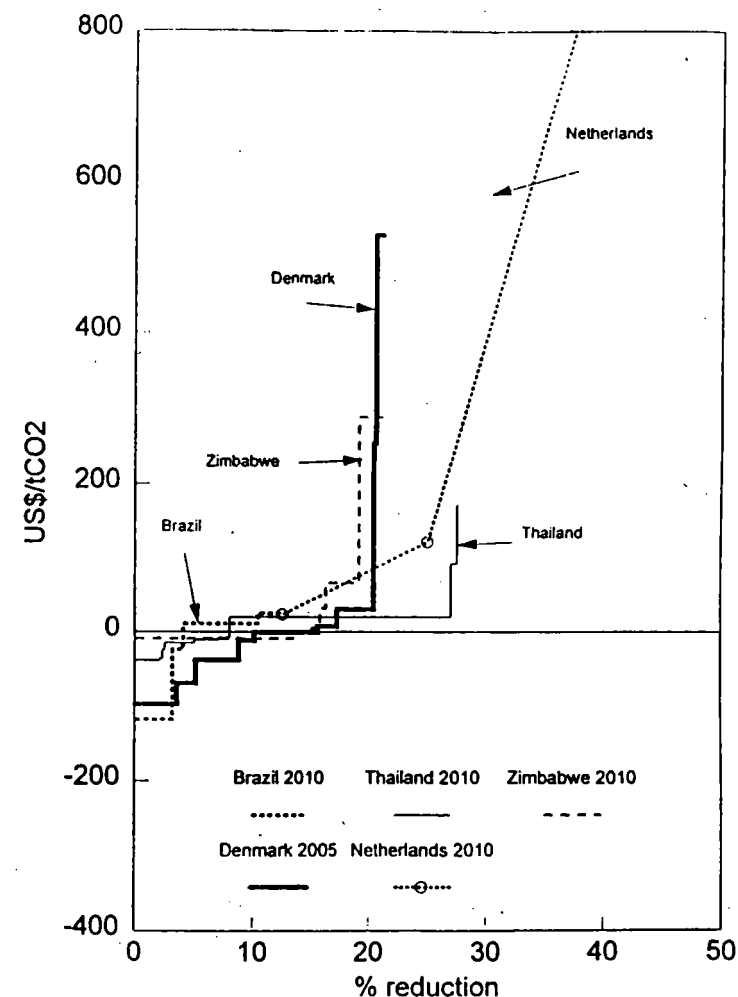


Figure 4.4.1 UNEP Studies: marginal abatement costs for 2005/10

These disparities may be a consequence of different approaches to the definition of national economic growth assumptions: either one retains critical evaluations of official national macroeconomic and energy system forecasts (UNEP studies) or one uses past international development trends as focal points to calibrate long run growth rates by comparative analysis.

The elasticities of primary energy to GDP, CO₂ emissions to primary energy and CO₂ emissions to GDP are shown in Table 4.4.4 for the reference scenarios. Many of the countries have a primary energy/GDP elasticity between 0.6 and 0.8, which is low for a developing country in one consider current trends. This is due to the fact that modellers account for structural changes expected in these countries over the long run and tendential improvements in the energy system. Despite this trend the CO₂/GDP elasticity is close to unity for most of the country studies, as a consequence of a high expected CO₂/energy elasticities. This reflects a development process where traditional local biomass and also hydropower resources amounts to a decreasing share of primary energy consumption while commercial fossil fuels is expected to play a larger role. A remarkably high CO₂/energy electricity is projected for the UNEP Brazil study and for Ghana, Nigeria and Sierra Leone where biomass very extensively are replaced by fossil fuels in the reference.

The combination of different assumptions on the development in GDP, primary energy and energy supply in the reference case result into large variations of the projected CO₂ ranging from a six to eight-fold projected increase in emissions, for Thailand and Brazil, to a two to three-fold increase for the other developing countries in the Unep study and from a high six-fold increase for India, five-fold increase for Indonesia and an increase of between two and three times for China, Argentina, Brazil, Mexico and Venezuela in the LBL study.

We will come back later on the meaning of such a wide range of results; despite these discrepancies, however there is a convergence about the prospect of a steep increase of CO₂ emissions from developing countries over the following decades. Another strong convergence is about the existence of important margins of freedom for reducing the CO₂ content of economic growth in these countries.

In the low emission scenarios of the LBL for example, emissions are projected to grow by only about 50% from present levels in Brazil after a 54% reduction, and in Argentina after about 25% reduction. China, Mexico and Venezuela project emission increases between a doubling and tripling of today's level after 20% to 30% baseline reductions. India and Indonesia project after the high reference emissions also a persistent high abatement emission level amounting to a four to five-fold increase from present after very small reductions of 13% and 18% from baseline, respectively. In the Unep study the main of the developing countries project emission increases up to a doubling in the emission reduction scenario after a 40%-50% reduction in 2020/30; the fact that Thailand still projects a six-fold increase in emissions after 30% reduction from baseline, and Brazil projects a three-fold increase after a 50% reduction does not contradict this overall picture⁶⁹.

These margins of freedom are indeed insufficient to offset the overall tendency to increased CO₂ emissions but they are wide enough to contradict the commonplace idea that, given

⁶⁹The high emission projections for Thailand and Brazil in the reference and emission reduction scenario can be explained by a large contribution of fossil fuels in the supply system. In addition the Thailand study includes very low expectations for energy efficiency improvements.

Table 4.4.4 Key elasticities in reference and abatement scenarios for 1990 to 2020/30.

Country	REFERENCE			ABATEMENT		
	Energy/GDP	C/Energy	C/GDP	Energy/GDP	C/Energy	C/GDP
ARGENTINA (1)	0.9	1.0	0.9	0.6	1.0	0.5
BRAZIL	0.8	1.5	1.1	0.8	0.9	0.7
BRAZIL (1)	0.8	1.1	0.9	0.3	0.8	0.3
CHINA (6)	0.5	0.8	0.4	0.5	0.8	0.4
EGYPT	0.6	1.2	0.8	0.3	1.0	0.3
GHANA (5)	0.9	1.5	1.4	0.8	1.7	1.3
INDIA	0.7	0.9	0.6	0.6	0.8	0.5
INDIA (1)	0.9	1.0	0.9	0.9	1.0	0.9
INDONESIA (1)	1.2	1.1	1.3	1.1	1.1	1.2
SOUTH KOREA (4)				0.6	0.9	0.6
MEXICO (1)	0.6	1.0	0.6	0.5	0.9	0.4
NIGERIA (5)	0.7	1.7	1.1	0.5	2.0	1.0
SENEGAL	1.0	1.1	1.1	0.8	1.1	0.8
SIERRA LEONE (5)	0.7	1.6	1.2	0.6	1.8	1.0
THAILAND	1.0	1.2	1.1	0.9	1.1	1.0
THAILAND (4)				1.0	1.0	1.0
VENEZUELA	0.7	1.3	0.8	0.5	1.1	0.6
VENEZUELA (1)	0.9	0.7	0.6	0.8	0.6	0.5
ZIMBABWE	0.7	1.2	0.8	0.4	0.8	0.4
LATIN AMERICA (2)	0.8	1.2	1.0			
LATIN AMERICA (3)				0.3	-0.7	-0.2
SOUTHEAST ASIA (2)	0.8	1.3	1.1			
SOUTHEAST ASIA (3)				0.4	-0.1	0.0

(1) Energy & Environmental Division, LBL; CO₂ Emissions from Developing Countries: Better Understanding the Role of Energy in the Long Term; July 1991.

(2) IPCC, 1992; Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment.

(3) Stockholm Environment Institute - Boston Centre Towards a Fossil Free Energy Future; April 1993.

(4) Asian Energy Institute; Collaborative Study on Strategies to Limit CO₂ Emissions in Asia and Brazil; 1992.

(5) Davidson Olungade; Carbon Abatement Potential in Western Africa; in P. Hayes, K. Smith, eds., The Global Greenhouse Regime: Who Pays?; 1993.

(6) Asian Development Bank; National Response Strategy for Global Climate Change: People's Republic of China; Nov. 1993.

4.4.2.3 the special case of China

Special attention needs to be given to China due to the magnitude of expected future emissions. The Asian Development Bank has in collaboration with the Chinese government conducted a comprehensive technology assessment study for the period 1990 to 2050 (ADB 1993).

The economic growth rate for the period as a whole is assumed to be 6.0%, primary energy growth is 3.1% and the CO₂ emission growth rate is 2.6%. The resulting elasticities are 0.5 for energy/GDP, 0.8 for CO₂/energy and 0.4 for CO₂/GDP. These very low elasticities are a consequence of assumptions in the baseline scenario of a decreasing coal share in the Chinese energy supply and large expected efficiency improvements, especially in power production.

The share of coal in the primary energy supply is projected to decrease from 75.5% in 1990 to 58.0% in 2050. Coal is replaced by an increasing amount of natural gas and nuclear power and to a minor degree hydropower.

It is assumed that 3.6% annual savings can be achieved until 2000, decreasing to 1.8% for the rest of the period to 2050. The high savings are related to the low present power production efficiency of 30% and to high expectations regarding efficiency improvements in industry related to a high investment level in that sector.

From this baseline total primary energy consumption decreases by 14% and total emissions are reduced by 23% from the baseline in 2050. The main emission reduction option relating to energy supply is nuclear power. The share of hydropower and natural gas is also increased slightly.

Total energy expenditures are assessed to amount to as much as 20% of the GDP in 1995, decreasing to below 15% in the baseline and below 10% in the policy scenario in 2050. The energy expenditures include investment costs as well as O.&M. and fuel costs. Energy investments amount to about 4% of GDP from 1990 to 2020, and this share is nearly constant between the business as usual- and the policy scenario.

4.4.2.4 Comparing numerical results: the assumptions on technical options

However the emission reduction costing studies for developing countries considered here exhibit similarities with regard to the assessed potential for negative or low-cost emission reduction.

As an example, a summary of the main technical emission reduction options in the UNEP country studies is presented in Table 4.4.6. The national options are listed in aggregated form and thus represent classes of options rather than individual technologies. The cost curve may in general be considered in three segments, starting from zero emission reduction and representing negative/low-cost options, intermediate- and high-cost options. One general similarity between the country studies is that the least expensive part of the cost curve contains energy end-use savings in households and/or industry. Another common result is that electricity supply options first appear in the second third of the reduction potential of the cost curves.

Table 4.4.6

Country	CO ₂ reduction option	reduction (%)	MAC (US\$)
Brazil	Electricity savings (industry, services and residential)	7	-66
	Solar uses in agriculture	1	22
	Fuelwood and charcoal for afforestation programmes	21	24
	Ethanol, bagasse and electricity generation from bagasse	19	29
	Total CO ₂ reduction	48	
Egypt	Fuel switching in households	6	-21
	Efficient industrial equipment and maintenance	10	-12
	Transportation	2	-12
	Heat recovery and new industrial processes	9	-8
	New raw materials	5	-3
	Efficient household appliances	5	-3
	Electricity generation	8	-1
	Efficient stoves	7	2
	Total CO ₂ reduction	52	
Senegal	Early hydropower implementation	0.1	-210
	Agriculture intensification	5	-28
	Energy conservation in industry	0.4	-4
	Dissemination of improved stoves	11	0
	Improved carbonisation efficiency	13	1
	LPG-charcoal substitution	15	2
	Biomass from afforestation	6	3
	Total CO ₂ reduction	50	
Thailand	Efficient airconditioners	2	-36
	Electronic ballast	1	-27
	Compact fluorescent lamps (service sector)	6	-14
	Compact fluorescent lamps (residential sector)	2	-9
	Nuclear electricity	18	20
	Highly efficient gasoline cars	1	92
	Total CO ₂ reduction	30	
Venezuela	Reduced flaring and leakage of methane	7	3
	Efficient boilers and kilns	10	10
	Freight transport	1	13
	Efficient electric motors in the industrial sector	2	17
	Passenger transport	4	21
	Electric sector	0.6	35
	Other energy savings in the industrial sector	2	39
	Efficient electric appliances	0.4	52
	Total CO ₂ reduction	27	
Zimbabwe	Efficient boilers	23	-9
	Energy savings in the industrial sector	4	-2
	Efficient motors and power factor correction	2	-2
	Increased hydropower	5	5
	Efficient furnaces	2	66
	Central photovoltaic power	1	153
	Coal for ammonia	1	289
	Total CO ₂ reduction	38	

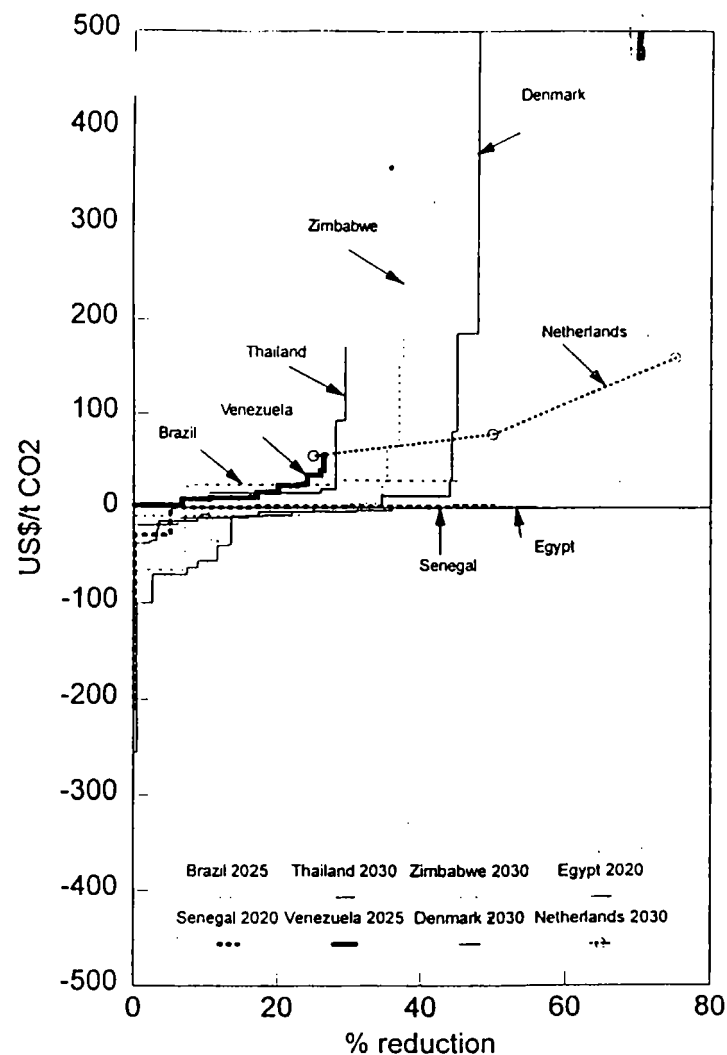


Figure 4.4.2 UNEP Studies: marginal abatement costs for 2020/30

Table 4.4.5 Marginal (MAC), Average (AAC) and Total Abatement Costs (TAC) for maximum reductions, comparison with GDP.

(a) Short term

country	year	baseline emission (mil. t CO ₂)	Reduction (mil. t CO ₂)	Reduction %	MAC (1) (\$/t CO ₂)	TAC (\$mil.)	AAC (\$/t CO ₂)	GDP (\$bn.)	TAC/GDP %
Brazil	2010	767.8	101.3	13.2	25	-1881	-18.6	848	-0.22
Thailand	2010	359.8	99.3	27.6	171	1027	10.3	250	0.41
Zimbabwe	2010	32.7	6.9	21.1	289	221	32.0	35	0.64
Denmark	2005	53.4	11.3	21.2	529	-70	-6.2	154	-0.05
France (2)	2005	407.0	50.9	12.5	-	9725	191.2	1463	0.66
Netherlands	2010	185.0	46.3	25.0	121	1440	31.1	379	0.38

(b) Long term

country	year	baseline emission (mil. t CO ₂)	Reduction (mil. t CO ₂)	Reduction %	MAC (1) (\$/t CO ₂)	TAC (\$mil.)	AAC (\$/t CO ₂)	GDP (\$bn.)	TAC/GDP %
Brazil	2025	1611.2	741.2	46.0	29	9339	12.6	1740	0.54
Egypt	2020	253.0	141.7	56.0	2	-732	-5.2	118	-0.62
Senegal	2020	15.4	7.7	50.0	3	-16	-2.0	14	-0.12
Thailand	2030	751.4	221.7	29.5	171	2089	9.4	538	0.39
Venezuela	2025	189.4	50.4	26.6	56	685	13.6	177	0.39
Zimbabwe	2030	57.4	22.2	38.7	289	205	9.3	72	0.28
Denmark	2030	59.3	29.0	48.9	614	168	5.8	211	0.08
France (2)	2030	615.0	153.8	25.0	-	11756	76.5	2400	0.49
Netherlands	2030	204.3	102.2	50.0	78	3775	36.9	548	0.69

¹ The Marginal Abatement Cost (MAC) here corresponds to the level at the maximum reduction achieved for the country.

² The Average Abatement Cost for France is set equal to the rate of carbon tax necessary to achieve the reductions.

4.5 Global Studies of the Costs of Reducing CO₂ Emissions

The review of existing studies up to this point has focused on country analyses. In addition, there are a number of studies which attempt to provide a global perspective in the assessment of emission reduction costs (see Table 4.5.1). These studies are important for several reasons. The greenhouse effect is inherently a global issue. It will be then helpful to have some sense of the overall costs before confronting the difficult issue of burden sharing and of the reductions of abatement costs likely to be met. Moreover, actions taken in one region are apt to have "spillover" effects into other regions and country based studies ignore (or handle in a very rough way potentially significant linkages (e.g., trade in oil, gas and carbon intensive basic materials) which could substantially alter the economic impacts of a carbon constraint. In other words, analysis at a global scale is needed in order to construct a "least-cost" global emission reduction cost curve.

However, all of the caveats expressed above about the limitations of country-specific or region-specific models should be borne in mind when evaluating the results of global studies. In particular, the very great differences between the different types of economies described above, and the need for global studies to aggregate across economies, technologies and response options, means that caution must be exercised in interpreting these studies. They are meaningful to give orders of magnitude of the importance of the international dimension but no direct information can be derived for policy making in specific sectors in specific countries.

The most of global studies are top-down in approach. Some bottom-up studies will be nevertheless reported here because they aim at illustrating the overall technical potential for curbing down greenhouse emissions at a world level.

4.5.1 A Review of Top-down Studies: the importance of international cooperation

The global top-down models typically divide the globe into five or more geopolitical groupings. By necessity, they are highly aggregate in their treatment of macro-economic and technology issues and many local economic detail must be sacrificed.

Figure 4.5.1 summarizes the results of recent studies using these models. Not surprisingly, there is considerable disagreement concerning the costs of emissions reduction. Consistent with the national studies who do not study in a very detailed manner the double-dividend expected from specific tax-recycling and who do not account for additional non-price induced exogenous progress in energy efficiency, the top-down global analyses indicate that emission reduction will involve positive costs, but the size of these costs varies from study to study.

4.5.1.1 The costs of stabilizing global emissions

A systematic comparison of global models was undertaken by the OECD in its 1992 Model Comparison Project (OECD, 1993). The study included all available global models with the capability of simulating regional carbon tax curves and output losses. The models were calibrated to the same set of input assumptions employed by the parallel study being conducted by the Energy Modeling Forum (see earlier discussion). Results were reported for a business as usual scenario and for four scenarios involving various levels of emissions reduction

For emissions stabilization, it was assumed that global emissions would be permanently held to 1990 levels. The costs of meeting such a target will depend, in part, upon how emission reductions are allocated among regions and whether there is scope for international

Table 4.5.1 Global CO₂ Abatement Cost Modelling Studies

Author (year)	Key	CO ₂ reduction from baseline	CO ₂ reduction from reference year ^a	GNP impact/cost (reduction) from baseline
Anderson & Bird (1992)	AB (2050)	68%	-17%	2.8%
Burniaux et al (1991)	B (2020)	37%	17%	1.8%
Burniaux et al (1992)	B (2050)	64%, 64%, 66%	-18%, -18%, -11%	2.1%, 1.0%, 0.3% ^b
Edmonds & Barns (1990)	EB (2025)	14%, 36%, 47%, 70%		0.1%, 0.5%, 0.7%, 2.2% ^c
Edmonds & Barns (1992)	EB (2020, 2050, 2095)	45%, 70%, 88%	22%, 41%, 53%	1.9%, 3.7%, 5.7%
Manne & Richels (1990b)	MR (2100)	75%	-16%	4.0%
Manne (1992)	M (2020, 2050, 2100)	45%, 70%, 88%	13%, 25%, 21%	2.9%, 2.7%, 4.7%
Mintzer (1987)	MI (2075)	88%	67%	3.0%
Oliveira Martins et al (1992)	OM (2020, 2050)	45%, 70%	-2%, 2%	1.9%, 2.6%
Perroni & Rutherford (1991)	PR (2010)	23%		1.0%
Rutherford (1992)	R (2020, 2050, 2100)	45%, 70%, 88%	15%, 28%, 43%	1.5%, 2.4%, 3.6%
Whalley & Wigle (1990)	WW (2030)	50%		4.4%, 4.4%, 4.2% ^d

^a Negative values imply an increase in CO₂.

^b Toronto-type agreement in all three cases, with tradeable permits in the second and third cases and removal of energy subsidies in the third case.

^c Costs as estimated from consumer + producer surplus.

^d The three numbers refer to three different tax forms: a national producer tax, a national consumer tax, and a global tax with per capita redistribution of revenues

The highest level of detail in the country studies generally occurs in the first part of the cost curve relating to end-use savings. Countries especially concentrated on one sector and one category of technologies, which were considered to be important for that country: for example industry in Egypt, Venezuela and Zimbabwe, and households in Senegal. The studies were not exhaustive and it is therefore likely that further work would lead to the identification of more low-cost options, and thus an extension of the first low-cost segment of the cost curves.

On the supply side, most of the studies assessed traditional energy-supply technologies and few included more advanced technologies and/or renewable energy technologies. Consequently the cost curve either increases very sharply or simply does not consider any further reduction after the exhaustion of these options.

4.4.2.5. Cost assessments and definition of reference scenario

Beyond the assumptions about technological alternatives, an important part of the differences in cost assessments stems from the way the reference baseline is calculated. This regard both the economic development scenario. There lies for example the major differences between the methodological approaches used in the UNEP and LBL studies.

The individual country studies are difficult to compare quantitatively with regard to detailed assessments of emission reduction potential and costs. This is a consequence of differences in methodological approach and in scenario assumptions on economic growth, energy requirements and emission reduction and costs. An important reason for these differences is the concepts of baseline scenarios used in the studies. This regard both the economic development scenario and the energy scenario. This seems for example to be the major differences between the methodological approaches used in the UNEP and LBL studies.

In the UNEP framework the national teams were recommended to take official macroeconomic forecasts as the starting point for energy demand projections. In contrast the LBL framework used international economic focal points to describe a possible economic structure and income distribution which could be achieved in a developing country within a given time horizon. It could for example be assumed that a country like Brazil would approach an economic structure like Spain in a given time frame.

The advantage of using national macroeconomic projections is obviously that it reflects national views on development. But the absence of formalised macroeconomic models and long-term economic projections making it difficult to make valid projections and national forecasts may therefore sometimes be only partially consistent and realistic. The use of international economic data may be of help in establishing an internally consistent set of data. Studies made on such a common well documented background can also be somewhat easier to compare than studies which uses different national forecasts. The use of international economic data to make national forecasts may, however, de-couple the emission reduction studies from national development and priorities, thus reducing the relevance of the study to application within the context of the Climate Convention.

Experience demonstrates that the degree of optimism of experts from different countries as regard to the tendential penetration of energy efficiency or of carbon free technics may differ very drastically. In the UNEP study for example where country teams were free to make judgements on the most likely hypothesis a country like Venezuela assumed all profitable efficiency improvements to be implemented, while other countries like Brazil and Thailand assumed a relatively inefficient reference scenario. The Indian country study (Mongia et al.

1991) estimated emission reduction costs for two emission reduction scenarios. One assumes a least cost supply system requiring foreign exchange and capital resources. Another emission reduction scenario assumes a more expensive supply solution with greater reliance on domestic renewable energy sources. The first (and cheapest) emission reduction case estimates average emission reduction costs to be -\$9.5 per tonne of CO₂ for a 45% reduction from an inefficient reference in 2025. Measured in relation to an efficient reference in the same year the average emission reduction costs for a 22% reduction is assessed to be +\$10.9 per tonne of CO₂. It should be noted that the absolute amount of CO₂ reduced in the two alternatives is the same.

Another difference in national definitions of reference scenarios relates more generally to assumptions on large structural changes in fuel supply and overall development. The striking difference between the UNEP and LBL in the case of Brazil is an enlightening example of the consequence of assumptions about development patterns and overall economic context and of the necessity to account for several baseline scenarios: part of the difference is indeed due to different assumptions on the GDP growth rate but another stems from the fact that a low fuel price increase is projected in the UNEP study during a period long enough to rule the existing pro-alcohol program out of the baseline and that a more energy intensive industrial development is accounted for. Here the reference case assumes replacement of present biomass use, including ethanol, with fossil fuels; conversely, the LBL studies defined the reference energy scenarios in order to reflect a continuation of historical trends assumed biomass to continue in Brazil and, in line with the business as usual approach used in many energy system analyses for industrialized countries and assume gradual changes in supply structure and a slow rate of implementation of efficiency improvements. A new Brazilian study (La Rovere et al. 1994) has been carried out as a compromise between the assumptions of the UNEP and LBL study.

Any comparison of national emission reduction potential and cost must therefore recognize that the results depends on the baseline. All other equal a given emission reduction from baseline must be expected to be more expensive and will imply the use of more costly and advanced technologies, if it is measured in relations to an "efficient" reference energy system than to an "inefficient" one.

4.4.2.6 Conclusion

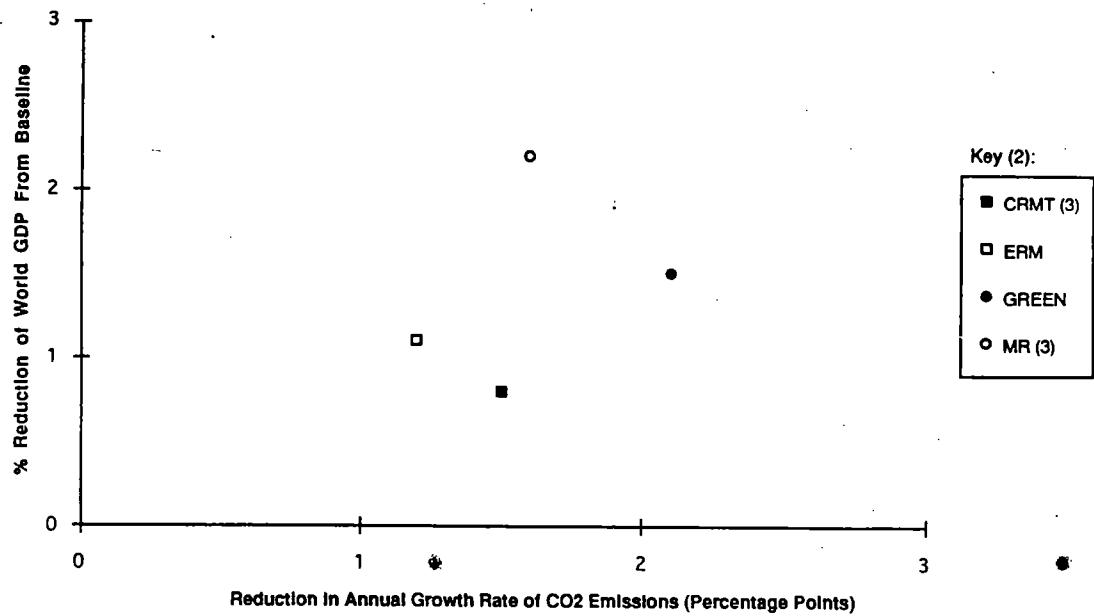
The climate change emission reduction costing studies carried out for the energy sector until now for developing countries exhibit, despite differences in methodological approach, some common empirical results:

- 30-40 years reference scenario projections show a tendency to decreasing energy/GDP intensity, but increasing carbon/energy intensity.

- potentially 30-40% emission reductions from baseline in 40 years time frame have been assessed. Even after such reduction, emissions will on average be two or three times more than present levels.

- a large potential for efficiency improvements in the energy system exists. This potential includes low/negative-cost options relating to end-use and conventional supply technologies. In the 30-40 years time frame the UNEP country studies have estimated average emission reduction costs to be below \$37 per tonne of CO₂.

Figure 4.5.3 Estimated CO2 Abatement Cost in 2020 (1)
(Stabilization of Emissions Relative to 1990 Levels)



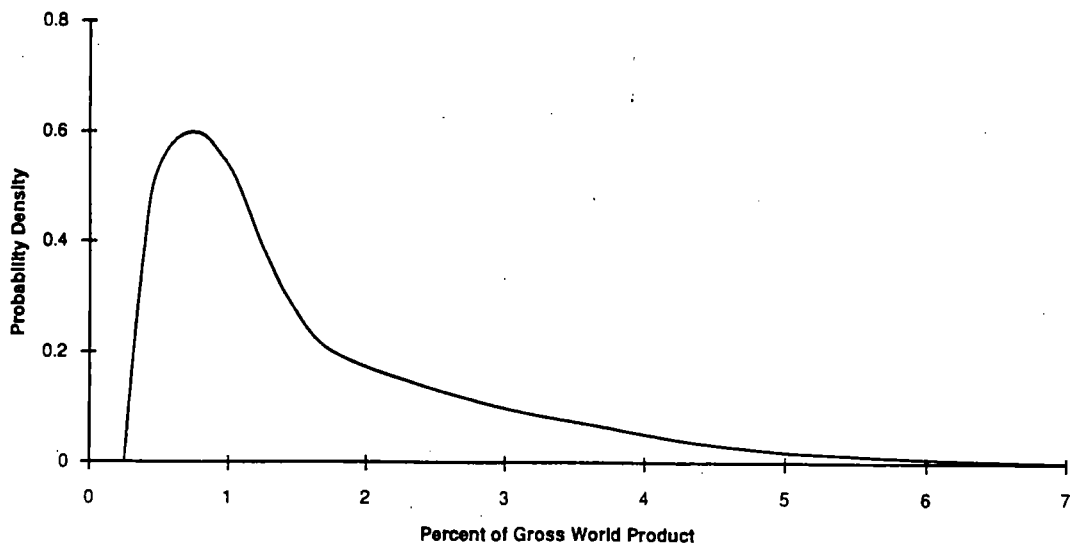
(1): No emission trading between regions.

(2): CRMT (Rutherford) model, ERM (Edmonds-Reilly) model, GREEN model and GLOBAL 2100 (Manne-Richels) model as described and referenced in OECD (1993).

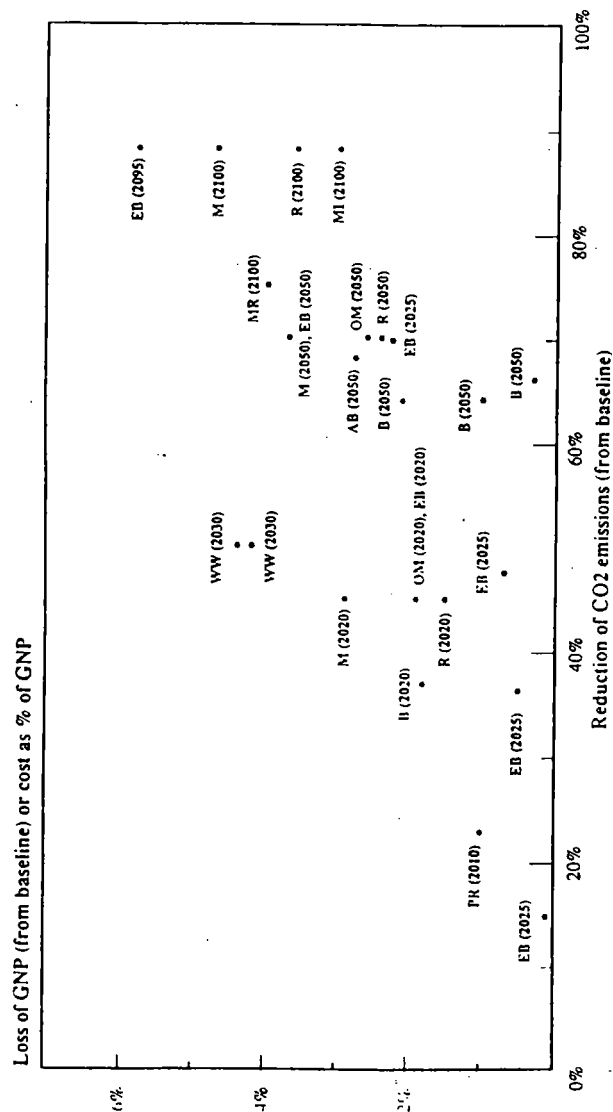
(3): World Totals are aggregated from regional GDP reductions using Baseline GDP as aggregation weights.

Source: OECD (1993).

Figure 4.5.3 The Costs of Stabilizing Global Carbon Emissions



4.5.1 Global Studies of CO₂ Abatement Costs Relative to Baseline Projection
(Labels are not attached to all points given danger of crowding. For key see Table 5.1)



Source: Grubb et al (1993).

octipcc07/10/94 17:50

1 cooperation. In a first step, each region is required to hold emissions to 1990 levels without the
2 opportunity of shifting emission reduction from high emission reduction cost to low emission
3 reduction cost regions. That is, there is no trade in carbon emission rights. Later on, we will
4 explore the potential benefits from relaxing this constraint.

5
6 Figure 4.5.2 compares losses in the year 2020. It also shows the reduction in the annual
7 growth rate of CO₂ emissions required to achieve the desired target. Note that losses vary
8 from 2 to 2.2 percent of gross world product.

9
10 The higher the baseline emissions path, the higher should be, ceteris paribus, the overall
11 emission reduction costs, but the comparison of the results confirms the role of backstop
12 technologies.

13
14 The GREEN model projects indeed the highest emissions for 2020, but does not lead to the
15 largest costs. This is because it is the most optimistic of the four models about the rate at
16 which "backstop" technologies can be introduced into the energy system. Conversely, ERM
17 projects the lowest baseline emissions for 2020. As a result, less carbon must be removed from
18 the energy system to achieve stabilization; economic losses are however still higher than those
19 projected by CRTM because it does not include backstop technologies.

20
21 In a separate experiment, it was determined that ERM and MR project essentially the same
22 baselines when employing identical rates of autonomous energy efficiency improvements. For
23 the OECD study, MR adopted an average annual rate of .5 percent whereas ERM assumed
24 that non-price induced efficiency improvements occur at twice this rate. Standardization for
25 this key parameter brings these two models much closer together in their projections of GDP
26 losses from emissions reduction.

27
28 The OECD Model Comparison Project suggests that the principal reason why studies differ is
29 alternative views about the future character of the energy system. In an attempt to place
30 greater reliance on knowledgeable experts, Manne and Richels (1994) polled a group of
31 individuals on their beliefs about key parameters to which emission reduction costs are
32 particularly sensitive.

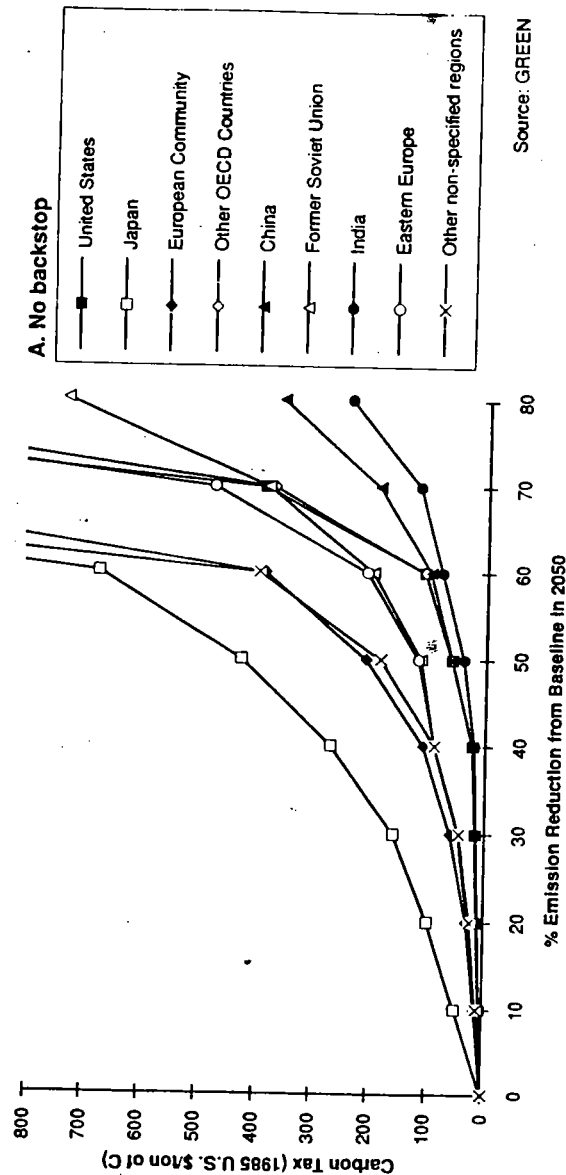
33
34 For each parameter, expert beliefs were encoded in the form of probability distributions which
35 were in turn combined to form a group probability distribution. Using the poll responses to
36 describe the uncertainty surrounding critical parameters, a probability distribution was then
37 constructed for the costs of stabilizing global CO₂ emissions at 1990 levels.

38
39 Figure 4.5.3 presents the results of the analysis. The spread of the distribution is quite broad,
40 ranging from .2 to 6.8 percent of gross world product (WP). The median (that is, the fiftieth
41 percentile) is approximately 1.0 percent of WP. The distribution is also quite skewed. Because
42 of the long right-hand tail, the mean value lies to the right of the median. It is approximately
43 1.5 percent of WP.

4.5.1.2 The costs of meeting alternative emission targets

44
45
46 In addition to stabilization, the OECD project examined scenarios in which the growth rate of
47 emissions in each region is reduced below the baseline by 1, 2 and 3 percentage points,
48 respectively. Figure 4.5.4 plots GDP losses as a function of worldwide emissions. Although
49 there are significant variations across models, the results yield some important insights who
50

4.5.5 Regional Carbon Tax Required for Equi-Proportional CO₂ Emission Reductions from Baseline



1 reduction are apt to vary widely among regions. Efficiency gains can be reaped from shifting
2 emission reductions from high to low marginal cost regions. If the resulting cost savings are
3 shared between participating regions, all can be made better off.

4
5 The potential gains through international cooperation can be demonstrated by comparing the
6 total costs of achieving a global emissions target — with and without trade in carbon emission
7 rights. Table 4.5.2 reports the results of such an experiment. From the viewpoint of economic
8 efficiency, trade in emission rights is clearly worthwhile. A reduction strategy in which each
9 region reduces its emissions by the same percentage will not be globally cost effective.

4.5.1.4 Allocation of emission rights

12
13 If we seek to establish international trade in carbon emission rights, a critical consideration will
14 be the allocation of permits. The decision on how emission rights are distributed among
15 regions does not affect global costs, but it will have a major impact on the distribution of net
16 gains and losses and hence on the perceived equity of the agreement. Unfortunately, for the
17 drafters of such an agreement, there is no unique definition of fairness (see section 3).

18
19 Edmonds et al (1993) studied a variety of schemes for allocating emission rights. At one end of
20 the spectrum they considered a "grandfathered" emissions principle. This is one in which future
21 emission rights are allocated on the basis of rates at the time of joining the protocol. At the
22 other end of the spectrum, they examined a "per capita emissions" principle where emissions
23 are allocated on the basis of adult population.

24
25 Figures 4.5.6 and 4.5.7 present results for a scenario in which global emissions are permanently
26 held at 1990 levels. The allocation of emission rights differ markedly under the two allocation
27 schemes. OECD countries hold on to approximately fifty percent of the emissions rights when
28 the status quo is maintained. With a shift to a per capita emissions principle, their share drops
29 to about twenty percent.

30
31 The implications for costs are as expected. The OECD is much better off with the status quo.
32 Indeed, they would be a seller of emission rights and the wealth transfers would be sufficient to
33 reduce GDP losses to a negligible level. Under such a scenario, the economic burden to
34 developing countries would be substantial.

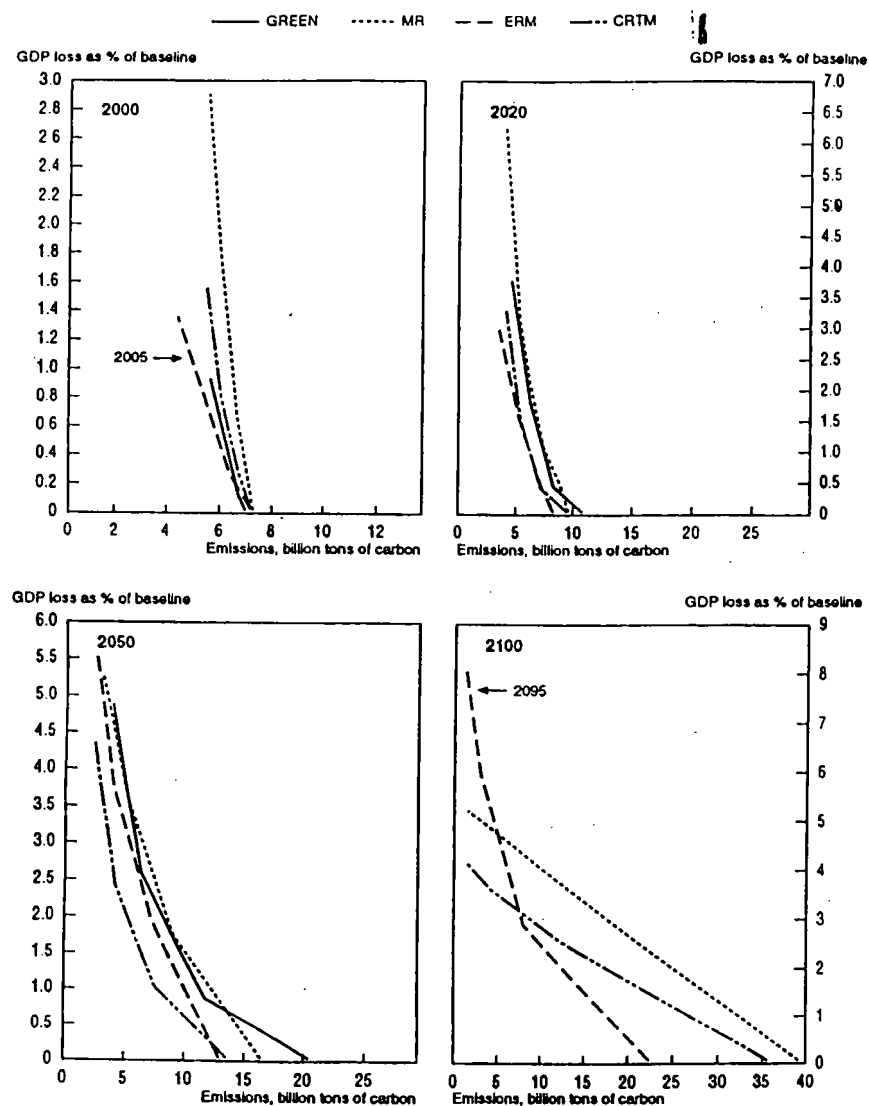
35
36 A per capita allocation scheme would substantially shift the distribution of net benefits and
37 losses. The OECD countries would incur significant GDP losses and the region labeled ROW
38 (rest of world) is now a winner. Under either scheme, China incurs substantial losses. Unless it
39 can greatly increase its energy efficiency, its huge demands for energy far outstrip its allocation
40 of emission rights.

41
42 In a third scenario, Edmonds et al explored what they refer to as a "no harm to developing
43 nations" principle. Here developing nations receive sufficient emission rights to cover their
44 own emissions and to generate sufficient revenue to cover the economic cost of participating in
45 the protocol. This leave developing countries no worse off in terms of GDP than had they not
46 participated in the agreement. The results are shown in Figure 4.5.8.

4.5.1.5 Carbon "leakage"

48
49
50 Some proposals for limiting CO₂ emissions call for high-income countries to take the lead in
51 reducing emissions. When actions are limited to a subset of regions, it is important to consider

Figure 4.5.4 World CO₂ Emissions and GDP Losses



Note: The scales on the different panels are not standardised.
Sources: Deen and Hoeller (1992) and OECD (1993).

octipcc07/10/94 17:50

confirm the critical role of hypothesis on backstop technologies and energy saving technical progress.

First, notice that the costs of stabilizing emissions at 1990 levels (approximately 6 billion tons) are lower in 2000 than in later years. The increase in emissions over the present decade is relatively small and there are ample quantities of low-cost substitutes (e.g., natural gas and demand-side management) to do the job. This does not continue as we move out in time. In these models technical progress is not high enough to offset totally the fact that more and more carbon must be removed from the energy system in order to maintain a particular target. As a result, annual losses are apt to increase.

As one would expect, macro-economic impacts rise with the stringency of the target, but it is important to note the non-linear nature of the loss function. Successive reductions are increasingly expensive. As cheaper options to reduce emissions are used up, it becomes increasingly difficult to substitute for, or to economize on, fossil fuels. For those models with backstop technologies, the marginal cost of emissions reduction will eventually level off. This accounts for the linear nature of the cost curves for CRTM and MR in the year 2100. ERM, on the other hand, excludes backstop technologies.

On the demand-side these models account for constant elasticity to prices; this means that the percent of energy reduction for a given percent of price increase remains constant whatever the energy price. For example passing the oil prices from 15\$/bl to 30\$/bl or from 40\$ to 80\$ will have the same effect. This means that the numerical value of required carbon tax from very stringent GHG emission targets should be interpreted very cautiously. On the one hand in effect some efficiency progress in given processes could be saturated and meet unremovable targets. On the other very high energy prices could trigger technical breakthroughs and drastic changes in consumption patterns. No available information being available about the non linearities in the responses to prices, it is impossible to decide if current results understate or overstate actual cost.

4.5.1.3 The potential gains from international cooperation

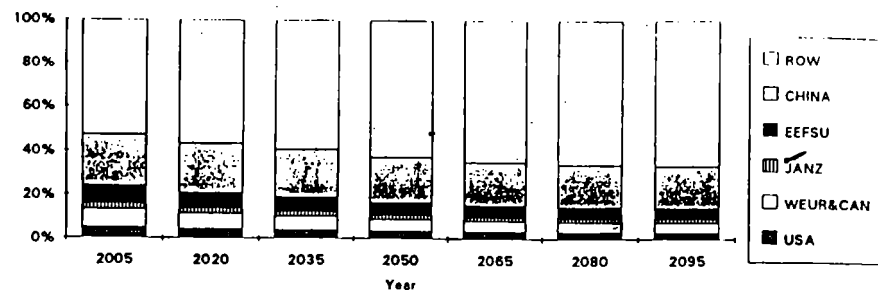
Emission reduction actions affect global emissions and atmospheric concentrations equally, irrespective of the geographical and sectoral origin of the emissions. The least-cost global solution entails reducing emissions where it is cheapest to do so. If the costs of reducing a ton of carbon were constant and the same in all regions, the location of the emissions reduction would have no effect on global costs. To the extent that marginal costs vary among regions, there are opportunities for efficiency gains through international cooperation.

These opportunities may be exploited through a system of international trade in carbon emission rights or a global carbon tax. Emission rights trading would allow for a more efficient allocation of emission reductions across regions by letting countries trade to the point where the marginal cost of emissions reduction is the same in all places. A global carbon tax would also result in the marginal cost of emission reduction being equal for all countries.⁷⁰

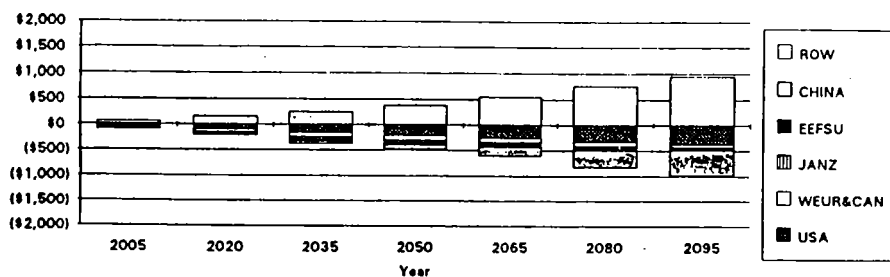
Figure 4.5.5 shows the carbon taxes that would be required, on a region-by-region basis, to achieve a given level of emission reduction (OECD, 1994). Although the emission reduction cost curves are from a single study, virtually all analysts agree that the costs of emissions

⁷⁰The unicity of the carbon tax or of the marginal cost of abatement in a tradable permit system has been contested at a theoretical level by Chichilnisky and Heal. We will not enter this discussion here.

a) Permit Allocation (Percentage of Global Total)



b) Income Received from Sales of Excess Emissions Rights (Billions of 1990 US\$)



c) Total Cost of Emissions Reductions plus Net Wealth Transfers from Sale of Emissions Rights (as Percentage of GDP)

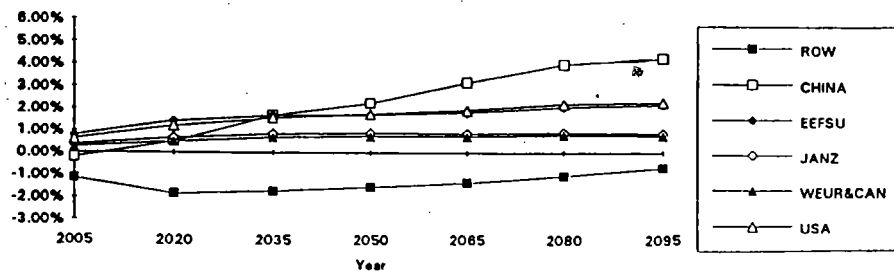
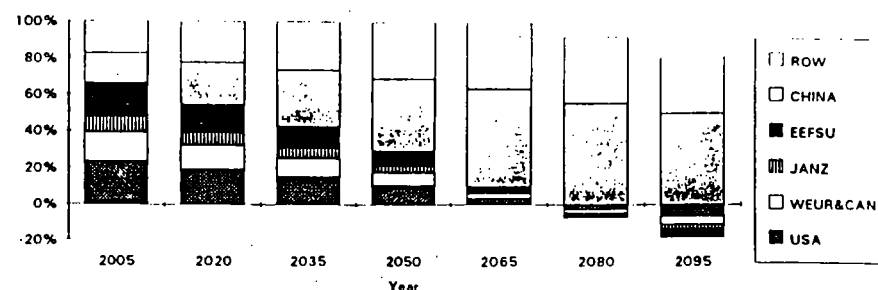
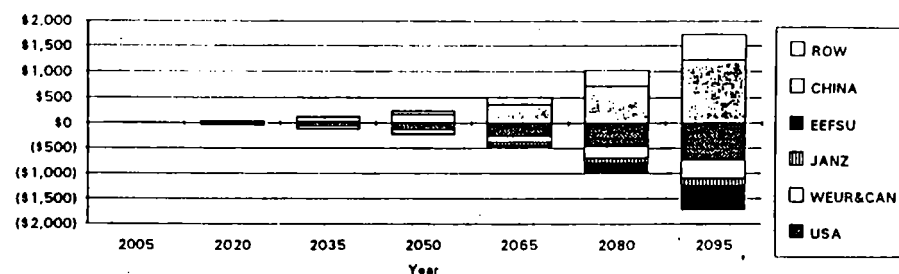


Figure 4.5.7 Equal per Capita Emissions Rights Principle

a) Permit Allocation (Percentage of Global Total)



b) Income Received from Sales of Excess Emissions Rights (Billions of 1990 US\$)



c) Total Cost of Emissions Reductions plus Net Wealth Transfers from Sales of Emissions Rights (as Percentage of GDP)

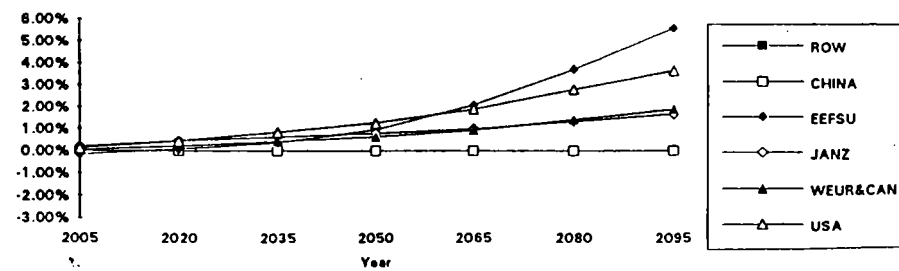


Figure 4.5.8 No Net Cost to Developing Nations Emissions Rights Principle

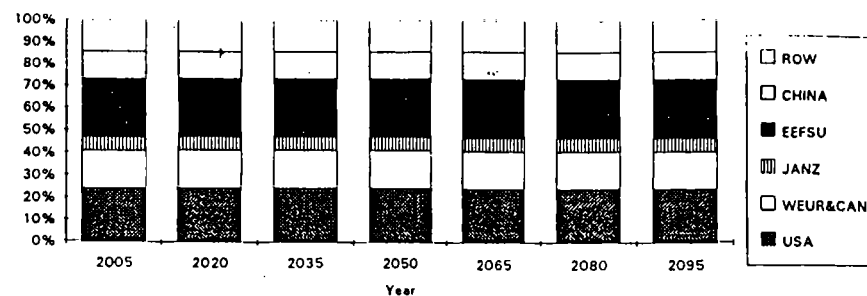
Table 4.5.2 Cost Differences for Emission Trading
Numbers refer to a 2 percentage point reduction in emissions from the base line and are global aggregates

		ERM (1)			GREEN			MR		
		Tax (\$/tC)	GDP loss (%)		Tax (\$/tC)	GDP loss (%)		Tax (\$/tC)	Welfare loss (2)	
2020	No Trade	283	1.9		149	1.9		325	-	
	Trade	238	1.6		106	1.0		308	-	
2050	No Trade	680	3.7		230	2.6		448	-	
	Trade	498	3.3		182	1.9		374	-	
2100	No Trade	1304	5.7		-	-		242	8.0	
	Trade	919	5.1		-	-		208	7.5	

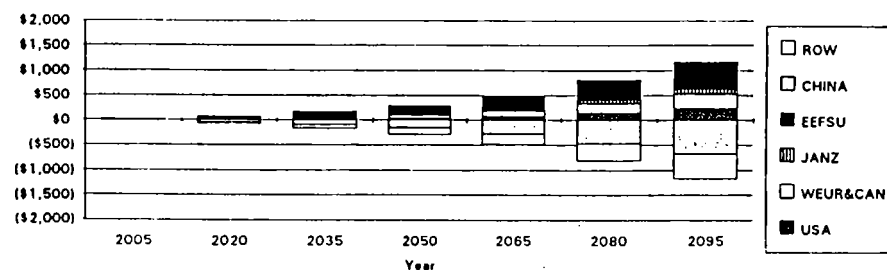
(1) End-year is 2095 for ERM.

(2) Consumption losses through 2100 – discounted to 1990 at 5 per cent per year – in trillions of 1990 dollars.

a) Permit Allocation (Percentage of Global Total)



b) Income Received from Sales of Excess Emissions Rights (Billions of 1990 US\$)



c) Total Cost of Emissions Reductions plus Net Wealth Transfers from Sales of Emissions Rights (as Percentage of GDP)

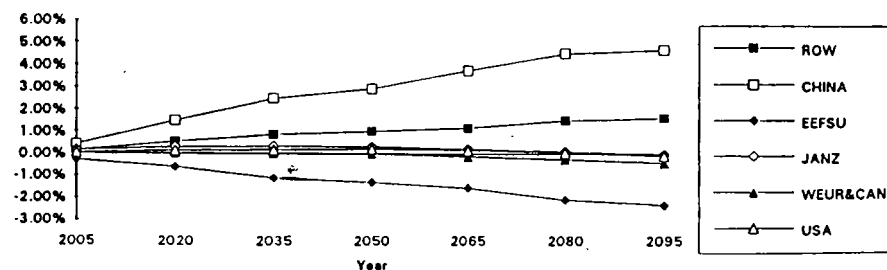


Figure 4.5.6 Grandfathered Emissions Rights Principle

In the bottom-up variant, the starting point is energy demand projections by world regions for 2025, 2050, 2075 and 2100 developed by the Response Strategies Working Group (RSWG, 1990) as part of the IPCC 1990 Assessment Report. A high economic growth variant of this scenario was used in order to stress the importance of technology assumptions in the LESS analysis. The main scenario assumptions for the base case are given in chapter II. Note that global GDP grows 8-fold by 2050 relatively to 1985 and 28-fold by 2100 when primary energy consumption grows from 323 EJ in 1985 to 559 EJ in 2050 and 664 EJ in 2100. Biomass, mostly for fuels used directly, plays a major role. It accounts for 31% of primary energy in 2025 rising to 50% in 2100 in the most far going scenario variant. This conclusion goes in the opposite direction than the one made by the Greenpeace scenario.

The result of the LESS scenario is that these emissions decrease from 5611 Mtc in 2100 and that the costs of the energy system are assessed to be non-increasing for the scenario variant with the lowest emissions and the highest biomass share compared with other cases, where more capital intensive technologies such as natural gas and nuclear electricity production plays a larger role.

To test the economic meaning of the bottom-up analysis, a top-down analysis was carried out (Edmonds et al. 1994) incorporating performance and cost parameters for some of the key energy technologies used in the construction of the low emission variant of the base case. The following six technology cases were modeled:

1. Reference scenario which is very similar to IPCC IS92a; the exogenous end-use energy intensity improvement rate is 0.5% by 2005, rising to 1.0% by 2035 and reaching 1.5% by year 2065.
2. Like 1 but emphasizes energy-efficient power generation from fossil fuels (efficiency reaches 66% by 2095)
3. Hydrogen, solar and wind power become more competitive
4. Like 3 but compressed hydrogen is used instead of liquefied
5. Like case 4 but biomass prices are more competitive
6. Like case 5 but the autonomous rate of energy efficiency improvements increases to 2.0% per year in 2050.

The results of the scenario analysis are shown in figure yy showing global annual fossil fuel CO₂ emissions and energy production and use.

Cases 5 and 6 show that if the assumed technological characteristics are realized, deep reductions in CO₂ emissions could be achieved without economic penalty in line with the facilitate the development and implementation of technologies embodied in the low emissions scenario so that they become competitive under market conditions with traditional fossil fuel technologies.

This confirms totally what was explained earlier in sub-section, namely the fact that the disagreement in the numerical outcomes of the models, in the very long run is less due to the modelling structure than to the exogenous hypothesis. A bottom-up exercise can be translated into a "top-down" framework conveying exogenous hypothesis on the progress in energy efficiency and on the costs of the backstop fossil free technologies. From a decision making point of view however the most sensitive issue which remains to be addressed is the plausibility of this long term transition if one accounts for all the general equilibrium effects to be included in (for example the implications of shifting massively agricultural activities to fuels production), and if one accounts for the transaction costs involved in the transition.

6. General Conclusions

- Estimates of the cost of GHG emission reduction are sensitive to assumptions about appropriate model structure, demographic and economic growth, the cost and availability of energy demand-side and supply-side options, the desired level and timing of abatement, and the choice of policy instruments. Different assumptions on these issues have led to a wide range of emission reduction cost estimates.
- The existence of a significant "no regrets" potential depends upon the existence of substantial market or institutional imperfections that prevent cost-effective emission reduction measures from occurring. The policy question is whether any such imperfections can be removed cost-effectively by policy measures. Despite significant differences in views, there is some agreement that some energy efficiency (perhaps 10-30% of current consumption, depending on baseline assumptions and the implementation time frame) can be realized at negative to slightly positive costs.
- Energy-related emissions can be reduced through both demand-side (energy efficiency) and supply-side (alternative sources of supply) options. In the short term, demand side options are cheapest in most countries.
- Estimates of the costs of stabilizing CO₂ emissions at 1990 levels in *OECD countries* vary widely. Most existing projections suggest that increasing amounts of carbon will have to be removed from the energy system over time to maintain stabilization. This means that costs will be lower (and possibly even negative) in the early years. But studies suggest that the annual costs of emissions reduction may ultimately exceed 1-2% of GDP.
- The costs of stabilizing emissions for *economies in transition* may be small relative to OECD countries. The potential for cost-effective reductions in energy use is apt to be considerable but the realizable potential may be a very different matter and will depend upon what economic and technological development path is chosen. A critical issue is the future of structural changes in these countries that are apt to change drastically the level of baseline emissions and the abatement costs.
- Analyses suggest that there may be substantial low-cost emission reduction opportunities for *developing countries*. However, these are likely to be insufficient to offset rapidly increasing emissions baselines, caused by increased demographic and economic growth. In the absence of a highly favourable allocation of carbon emission rights, any plan to stabilize global emissions will be particularly costly for developing countries.
- There has been much more analysis to date of emission reduction potentials and costs for industrialized countries than for other parts of the world. Moreover, many existing models are not well suited to study economies in transition or developing country economies. Much more work is needed to develop models and undertake work in these areas.
- In all the countries however costs are sensitive to the timing of a transition to a low carbon economy. The trade-off is between the possible costs of postponing emissions reduction decisions and the cost of prematurely retiring or retrofitting existing capital stock.
- The overall cost of abatement programs will ultimately be determined by the rate of capital replacement, the discount rate, and the effect of R&D. Appropriate long-run signals to encourage R&D will reduce long-run costs and the implementation of any "no regrets"

so-called carbon "leakage" effects. These represent the impacts of the emission policies of abating regions upon the emissions of non-abating regions.

Leakage can occur through a number of channels, including a) the location of the production of energy intensive products in non-abating regions, b) increased demand for energy and higher fossil lower substitution to energy in these regions due to lower fossil fuel world prices induced by the abatement policies of other regions could be positive or negative.) c) changes in the terms of trade. A case of "negative carbon leakage" is the reduced income of energy exporting regions.

There have been several attempts to estimate leakage (Barrett, 1994). Unfortunately, estimates have varied so widely that they provide little guidance to policy makers. Pezzey (1992), using the model of Walley and Wigle, examined a scenario in which the European Union acted alone to reduce emissions by 20 percent below baseline. He found that for every 10 tons of carbon abated, global emissions fell by only 2 tons. Leakage rates for the OECD as a whole were of the order of 70 percent.

Horton, Rollo and Ulph (1992) are even more pessimistic about leakage rates. They estimate that for some industries (e.g., fertilizer), unilateral action could lead to substantial relocation. They argue that if the shift is to countries where energy use is more carbon-intensive, leakage rates may exceed 100 percent.

In contrast, Oliveira-Martins, Burniaux and Martin (1992) using the OECD's GREEN model, estimate relatively small leakage rates. They examined a scenario in which emissions are held to 1990 levels and found leakage rates of 11.9 and 3.5 percent respectively, for the European Union and the OECD as a whole. In a subsequent study, Burniaux and Oliveira-Martins (1993) find that negative leakage effects nearly offset positive leakage effects.

Using still another model (12RT), Manne (1993) estimates leakage rates which fall between those of Pezzey (1992), and Oliveira-Martins, Burniaux and Martin (1992). He examines a case in which the OECD acts unilaterally to reduce emission by 20 percent below 1990 levels and finds that 25 percent of the OECD region's reductions could be offset indirectly through changes in international trade patterns.

The reasons why results differ so widely are not entirely clear. Manne and Oliveira-Martins (1994) have attempted a systematic model comparison of results from 12RT and GREEN. They find that much of the differences in leakage rates reported by the two models can be explained by alternative treatment of expectations and of international trade flows. The model comparison, needs to be extended to include other models, particularly those which show extremely high rates of leakage.

4.5.2. A review of bottom-up studies: the critical role of innovation

Many bottom-up studies have been carried out who aim at providing a normative view of very long term future and check their intrinsic consistency. After the Lovins' contribution in the seventies and early sixties, the study by Goldemberg et al.⁷¹ played a pioneer role to

emphasize the differences between the developed and developing countries. Many of them do not explicitly assess the overall costs entailed by these scenarios.⁷²

A typical global bottom-up analysis has been carried out for Greenpeace International by Stockholm Environment Institute, Boston (1993) for the period 1985-2100. The scenario "fossil-free energy future" has the following objectives and constraints:

- meeting far going global CO2 emission reductions targets
- phase-out of nuclear power by the year 2100 or by the year 2010
- considering alternative scenarios for infrastructure, population and GDP with the aim of achieving a greater degree of economic equity between different regions of the world.

Two reference scenarios were used as a high and low projection case for primary energy demand and CO2 emissions, namely the IPCC 1991 scenarios as the high alternative and an average of the US EPA's Rapidly and Slowly Changing World cases as the low alternative (IPCC 1990; Lashof and Tirpak, 1990). The range of these reference scenarios is shown in figure zz. The main results of the FFES are shown in table zz below together with the IPCC91 and the EPA scenarios.

The CO2 decreases to zero in the FFES in 2100, compared with 22.6 (Pg C) in IPCC 91 and 17.7 (Pg C) in EPA. Also the EPA policy scenario assess a large emission reduction possible in 2100, where global CO2 emissions decreases to 1.5 (Pg C). The total primary energy consumption is relatively similar in FFES and the EPA policy scenario.

The FFES and EPA policy scenarios differs significantly however in their assumptions on the energy supply system structure. The EPA policy scenario assumes a share of renewables of 77% in total primary energy consumption, while FFES assumes 100% renewables in 2100. Furthermore the EPA policy scenario assumes a higher share of biomass, amounting to 58% of primary energy consumption in 2100, compared with only 18% in FFES. FFES instead expect solar/wind resources to cover as much as 79% of primary energy consumption in 2100 compared with only 9% in the EPA policy scenario. FFES assesses the large biomass contribution in the EPA policy scenario to be uncertain and ecologically problematic.

The high expectations to the contribution of solar/wind in the FFES links to an assumption on a breakthrough in solar photovoltaic electricity production costs during 2010-2030. In the same way a breakthrough is expected for electricity production costs for wind power also in areas with poorer wind resources. Finally, the development of advanced storage facilities enable intermittent solar and wind resources to follow a greater part of electric system load. All these assumptions about technical progress explain why the FFES concludes, that the costs of implementing the scenario is small compared with the baseline.

The same result is given by the Low Emissions Supply System (LESS) scenarios of the IPCC WG II Second Assessment Report. These scenarios provide self-consistent estimates of the potential for GHG abatement whose background data were taken from detailed technology assessments as part of the WG IIa assessment process. The interesting point is that the energy supply systems were constructed using both a bottom-up approach (Lashof and Tirpak 1990; Johansson et al. 1993) and a top-down approach (Edmonds, 1994).

⁷² see for example the "Jérémie" and "Noé" scenarios by B.Dessus (1990)

⁷¹ Goldemberg et al. (1988) *Energy for a Sustainable World*. New Delhi: Wiley Eastern Ltd.

potential will increase the time available to learn about climate risks and for new technologies to enter the market-place.

- Infrastructure decisions are critical because they can allow or restrict future options, and different infrastructure decisions can lead to very different cost outcomes. This issue is of particular importance to developing countries, where major infrastructure decisions will be made over the next 25 years.
- If the climate issue is formulated in terms of stabilizing atmospheric concentrations, the choice of emissions time path is critical in determining the overall price-tag. It is important to identify those paths that minimize the costs of achieving a particular target.
- Minimizing the costs of the transition to a low-carbon world will require sustained investment in R&D combined with appropriate long-run signals to decision-makers. Such R&D can make a significant contribution to reducing costs.
- The overall impact of a carbon tax will depend not only on the size of the tax, but also on the uses to which the revenues are put. If carbon tax revenues are used to reduce more distortionary taxes, overall emission reduction costs will be reduced. Inefficient tax recycling could, however, increase costs.
- Whereas historically top-down and bottom-up methods have been associated with very different cost estimates, this need not be the case. Indeed widely differing methods can produce quite similar results when calibrated to the same set of input assumptions. Substantial disagreement still exists, however, over the existence and size of a significant "no regrets" potential for GHG emissions reduction.
- There is need for both detailed (bottom-up) analysis of technological options and also more aggregate (top-down) analysis of economic effects. Given differences in marginal emission reduction costs among countries, international cooperation can significantly reduce the global price-tag for emissions reduction. This would require that emissions reductions are carried out where it is cheapest to do so (i.e. that the practical problems of joint implementation are overcome).

CHAPTER 10

An assessment of greenhouse policy instruments

**B.S. FISHER, S. BARRETT, P. BOHM, M. KURODA, J.K.E. MUBAZI, A. SHAH
and R.N. STAVINS**

Contributors:

L. Goulder, M. Hinchy, A. Jaffe, R. Newell, R. Repetto and S. Thorpe

CONTENTS

10.1 Introduction

- 10.1.1 Guidelines from the FCCC
- 10.1.2 The Greenhouse Policy Problem
- 10.1.3 A Guide to the Chapter

10.2 Greenhouse Policy Instruments and Criteria for Policy Assessment

- 10.2.1 Domestic Policy Instruments
 - 10.2.1.1 Conventional Regulatory Instruments
 - 10.2.1.2 Market-based Instruments
 - 10.2.1.2.1 Taxes and Subsidies
 - 10.2.1.2.2 Tradable Permits
 - 10.2.1.2.3 Other Complementary Policies
- 10.2.2 International Policy Options
 - 10.2.2.1 Regulatory Instruments
 - 10.2.2.2 International Taxes and Harmonised Domestic Taxes
 - 10.2.2.3 Tradable Quotas
 - 10.2.2.4 Other Complementary Policies
- 10.2.3 Criteria for Policy Assessment
- 10.2.4 Coverage of Greenhouse Gases
 - 10.2.4.1 The Need for Comprehensive Targets
 - 10.2.4.2 Initial Coverage of CO₂ Sources and Sinks

10.3 The Domestic Policy Context

- 10.3.1 Pre-existing Market Distortions
 - 10.3.1.1 Energy Subsidies
 - 10.3.1.2 The 'Local' Environmental Benefits of Climate Change Policy
 - 10.3.1.3 Information and Energy Conservation
 - 10.3.1.4 Transport
 - 10.3.1.5 Agriculture and Forestry
- 10.3.2 Revenue Recycling
- 10.3.3 The Broader Context for Climate Change Policies
 - 10.3.3.1 'No Regrets' Policies
 - 10.3.3.2 Adaptation Policies

10.4 Regulations, Voluntary Agreements and other Non-Market-Based Instruments

- 10.4.1 Uniform Technology and Performance Standards
- 10.4.2 Government Investment
- 10.4.3 Voluntary Agreements
- 10.4.4 Demand Side Management
- 10.4.5 Distributional Impacts

10.5 Market-Based Policy Instruments

- 10.5.1 Introduction
- 10.5.2 Carbon Taxes
 - 10.5.2.1 Related Instruments – Deposit Refund Systems for Carbon Removal
- 10.5.3 Tradable Quotas and Permits
- 10.5.4 Joint Implementation
- 10.5.5 Distributional Impacts of Market-based Measures

10.6 Policy Implementation Issues

- 10.6.1 The 'Currency' of Regulation
- 10.6.2 Market Power
- 10.6.3 Transaction Costs
- 10.6.4 Participants in the System

10.6.5 Free-Riding and Emissions Leakage Problems

- 10.6.5.1 Policies to Reduce Free-riding
- 10.6.5.2 The Severity of Emissions Leakage
- 10.6.5.3 Policies to Reduce Leakage
- 10.6.6 Information Issues, the Role of Brokers and Risk Management
- 10.6.7 Implementation Issues for Economies in Transition

10.7 Comparative Assessment of Greenhouse Policy Instruments

- 10.7.1 Introduction
- 10.7.2 Comparing Regulatory Systems and Market-Based Instruments
- 10.7.3 Comparing International Tradable Quotas and Tax Systems
- 10.7.4 Comparing Domestic Tradable Permits and Domestic Tax Systems

10.8 Summary

10.9 References

Figures

- 10.1 Fuelwood stumpage fees as a percentage of replacement costs, late 1980s

Tables

- 10.1 A Taxonomy of costs of environmental regulation
- 10.2 A Summary of empirical evidence on the redistributive impacts of economic instruments
- 10.3 Carbon tax incidence in developing countries

An assessment of greenhouse policy instruments

10.1 Introduction

10.1.1 Guidelines from the FCCC

The aim in this chapter is to provide an economic assessment of possible policy instruments to manage greenhouse gas emissions under the FCCC. The Framework Convention contains several key guidelines for policy implementation. First is the emphasis given to developed countries demonstrating that they are taking the leading role in policies to control greenhouse emissions. In essence, developed country signatories (as listed in Annex 1) have accepted the goal, but not necessarily the requirement, of stabilising greenhouse gas emissions at 1990 levels by 2000 (Article 4.2). Developing country signatories (non-Annex countries) are under no such obligation. Rather, the economic needs and special circumstances of developing countries (Articles 4.8 and 4.10), and of countries that are highly dependent on incomes from fossil fuels (Article 4.10), will be taken into account in determining specific commitments to control emissions.

To achieve greenhouse emission reductions, Annex 1 countries have the option to implement greenhouse policy measures jointly with other Parties to the Convention (Article 4.2). This provision is consistent with another guiding principle in the Convention that all greenhouse policy measures should be cost effective — that is, achieve policy goals at least cost (Article 3). Other key principles in Article 3 include that Parties should promote sustainable development, that precautionary measures are taken to minimise the costs of greenhouse uncertainties and risks (noting that where there are risks of serious or irreversible damage, lack of scientific certainty should not be used to justify policy deferral), and that measures taken to combat climate change should not amount to unfair trade restrictions.

Prior to the development of the FCCC the most closely related international conventions were the Vienna Convention for Protection of the Ozone Layer (concluded in 1985) and the 1987 Protocol on Substances that Deplete the Ozone Layer (the text of which was revised in 1990 and again in 1992). The experience of the parties to that Protocol provides valuable information about implementation of policy approaches within the FCCC.¹

In this chapter, the factors affecting the policy mix for the control of greenhouse gas emissions are reviewed using these guiding principles and taking account of the general international legal framework in which the Convention must operate.

10.1.2 The Greenhouse Policy Problem

Two characteristics of the greenhouse problem are central to the design of policy responses. The first key feature is that it is a global problem. It is the total accumulation of greenhouse gases in the atmosphere which could cause global warming over the next century (IPCC 1990; 1992), regardless of the geographic source of emissions. Added to this, there is a long time lag, up to 50 years, between emission reductions and their impact on atmospheric concentrations. Thus the greenhouse problem is a pollution problem over space and time. Any benefits from controlling concentrations depend on long term global cooperation, and the costs of collective control will be incurred long before any potential benefits are realised.

The second key feature of the greenhouse problem is that both the extent of any climate change and the nature of its effects are uncertain. This means that potential greenhouse

policies must be assessed using a decision-making framework which explicitly incorporates risk, uncertainty and the capacity to learn about evolving climatic and economic conditions around the world.

A basic principle in public policy (as for any financial decision) is to time the introduction of the policy to maximise the expected discounted value of the stream of net benefits from the initiative. In this context, there may be significant gains from waiting to reduce uncertainties before implementing greenhouse policies². The value of the information gained from waiting could allow greenhouse policy to be properly tailored to the most likely damage scenario in order to avoid excessive control costs (Peck and Teisberg 1993; Leary and Scheraga 1994; Richels and Edmonds 1994). Conversely, there could be significant costs in waiting if waiting precludes greenhouse policy from being properly tailored to avoid excessive damage costs (Chichilnisky and Heal 1993) or if waiting results in the need for urgent action at some future time, with associated disproportionate adjustment costs.

Greenhouse policy assessment must therefore take into account the existence of opposing risks. Indeed, one important avenue for policy assessment is to examine the extent to which policy can be directed to reduce the costs of uncertainty and the costs of risk from natural damage caused by the enhanced greenhouse effect and from mitigation measures in response to climate change concerns. An immediate response to the greenhouse problem is to invest in research and development to reduce greenhouse uncertainties.

An efficient greenhouse policy will ensure that the costs of greenhouse uncertainties, and of associated risks, and the costs of emission reductions and adaptation strategies are balanced, at the margin, with the benefits from avoiding damage from global warming. One implication of this efficiency criterion is that optimal policy is least cost in achieving a global greenhouse target in the face of risk, uncertainty and learning about the causes and effects of climate change.

10.1.3 A Guide to the Chapter

The remainder of this chapter is organised as follows. In Section 10.2 the policy instruments under review are briefly described and criteria for their assessment outlined. This is done first in the domestic policy context and then in the international domain. The question of the need for comprehensive targets covering all greenhouse gases is also addressed.

In Section 10.3 changes in background policy settings which may have a positive impact on the efficiency of fossil fuel use, and therefore emissions, as well as be of benefit to the economy more generally are outlined. These approaches are important in that they constitute part of a number of countries' stated official policies on mitigating the effects of climate change.

In Sections 10.4 and 10.5 reviews of both conventional regulatory instruments and market-based policy instruments are provided, while issues of policy implementation are outlined in Section 10.6. This material is brought together in an assessment of greenhouse instruments in Section 10.7. Some concluding remarks are made in Section 10.8.

² For a general review of the literature on investment under uncertainty see Pindyck (1991).

¹ For a comprehensive legal review of the Convention see Bodansky (1993).

10.2 Greenhouse Policy Instruments and Criteria for Policy Assessment

The variety of instruments that are available to policy makers to control greenhouse gas emissions is outlined here. Such instruments include conventional regulatory instruments, market-based instruments such as taxes, subsidies and tradable quotas and permits, and other complementary policies. In this chapter the term 'tradable quota' is used to describe internationally traded emissions allowances. The term 'permit' is more commonly used in the literature to describe domestic trading schemes and that convention is adopted here. Existing global climate change research that has analysed a broad range of policy instruments includes Mintzer (1988); US Congress, Office of Technology Assessment (1991); IPCC (1992); National Academy of Sciences (1992); and McCann and Moss (1993).

10.2.1 Domestic Policy Instruments

10.2.1.1 Conventional Regulatory Instruments

One way of controlling activities which both directly and indirectly lead to greenhouse gas emissions is to set standards and to regulate the activities of firms or individuals. By mandating standards governments attempt to ban or alter the use of materials and equipment that is considered to be damaging. Standards are typically applied in areas such as buildings (energy efficiency, for example), fuel use by motor vehicles, energy efficiency of household durables and the content of fuels. Standards may be voluntary or mandatory. They may be fixed or set as targets, or 'rolling standards' might be adopted (Grubb 1991, p. 128).

10.2.1.2 Market-Based Instruments

In using market-based instruments governments attempt to alter price signals to ensure that emitters face direct cost incentives to control emissions. The primary market-based instruments for greenhouse management are emissions taxes and tradable emissions permits.

10.2.1.2.1 Taxes and subsidies

Under an emissions tax, those who produce emissions face a tax per unit of emissions. Subsidies might be offered for adopting particular technologies or practices. Such subsidies might be directed at fostering emissions abatement or the creation of additional sinks by, for example, subsidising tree planting.

10.2.1.2.2 Tradable permits

Under an emissions trading scheme emitters are given permits to emit (the total allocation is the aggregate emissions cap for the country) and have the option of buying or selling permits in the marketplace. While there are important and often subtle differences between taxes and tradable permits, under some restrictive circumstances, the outcome can be the same. Both may target full user cost pricing of the atmosphere to dispose of net greenhouse gas emissions from human activity. When traded on a national market, permit prices are established that show the costs of marginal emissions, just as an emissions tax does. The difference is that the tax is exogenous and its effects on emissions endogenous, while emissions are exogenously determined in the case of a permit system and hence, permit prices are endogenous.

10.2.1.2.3 Other complementary policies

A range of other complementary instruments exist which might be adopted to moderate greenhouse gas emissions. Education and provision of new information may be valuable in changing consumer behaviour with respect to energy consumption and the adoption of new technology. Family planning may play an indirect role in reducing total energy demand in the future as might more general education directed specifically at women in developing countries. Modifications of trade policy and reductions in energy production and consumption subsidies (and other market distortions) may also have indirect consequences for greenhouse gas emissions.

10.2.2 International Policy Options

10.2.2.1 Regulatory Instruments

Standards uniform among countries participating in an international emissions reduction agreement are conceivable. But it may be difficult to achieve wide agreement about any large set of specific instruments of this type. Moreover, this regulatory approach would limit individual countries' domestic policy choices and hence their flexibility in adjusting their emissions under an international greenhouse gas reduction agreement. What amounts to another regulatory approach is where countries agree on fixed national emission levels (a 'non-tradable emissions quota' system), essentially in the tradition of the European Union's Large Combustion Plants Directive. This agreement specifies reductions in the emissions of sulphur dioxide and oxides of nitrogen from plants with a thermal rating of 50MW or larger. Such an approach would mean that marginal emissions abatement costs among participating countries would tend to be different and, hence, total abatement costs, globally speaking, would be unnecessarily high.

10.2.2.2 International Taxes and Harmonised Domestic Taxes

If countries agree to apply the same level of domestic greenhouse or carbon taxes (harmonised domestic taxes), marginal abatement costs would tend to be equalised among countries. Such an agreement may have to include side payments from rich to poor countries if the latter are to be encouraged to participate.

An alternative type of international policy to reduce emissions could be an agreement to levy a uniform international tax on greenhouse or carbon emissions in each of the participating countries. The total international tax revenue would be shared among the participating countries according to rules established in the agreement.

If an international tax agreement did not cover all countries, world fossil fuel prices would decrease and fossil fuel use increase in non-participating countries (so-called carbon leakage). In addition, since carbon-intensive products would be less expensive in such countries, exports of them to the participating countries are likely to rise. A policy instrument might then be introduced by the latter countries to control carbon leakage. For example, a carbon tariff might be imposed at a rate corresponding to the tax rate on imported products on the basis of their estimated carbon contents.

10.2.2.3 Tradable Quotas

Another potentially cost effective international solution would be one where countries agree to an allocation of carbon emission quotas, perhaps reflecting an overall emissions target. International quota trade (Sandor et al. 1994) would establish a quota price — an implicit international tax rate — which would tend to equalise marginal abatement costs among countries. A carbon-leakage problem similar to that mentioned above would arise to the extent that such an agreement was not global.

In the case of an international tradable quota scheme, participating countries may use whatever domestic policies they prefer in order to stay within their ex-post-quota-trade quotas. For example, they might employ tradable permits, domestic taxes or regulations.

10.2.2.4 Other Complementary Policies

Technology transfer from industrialised to developing countries potentially has a large part to play in reducing future emissions. One mechanism to facilitate such transfers is through joint implementation, to the extent that joint implementation proves practically feasible. Joint implementation aims at minimising the joint costs of emissions reductions for a group of emitters. In the context of emitters who are committed to targets it could lead to the development of a tradable quota scheme.

10.2.3 Criteria for Policy Assessment

In this chapter a range of criteria is used to assess policy instruments to manage the greenhouse problem. Two important criteria are economic efficiency and distributive justice. The efficiency objective or benefit-cost principle is to maximise the global net benefits from the use of resources. Both the global greenhouse emissions target and the policy instrument to achieve it are choice variables in satisfying this criterion. However, there is considerable uncertainty regarding the causes and effects of unconstrained greenhouse gas emissions at this time. Hence, there is uncertainty regarding the benefit and cost functions, and as a consequence of this, there is considerable uncertainty regarding the optimal (economically efficient) level of control. One practical response is to employ a cost effectiveness objective — that is, to minimise the costs of achieving a given global greenhouse emissions target.

The cost effectiveness of achieving a given but potentially time varying target is a criterion that is employed in much of this chapter. Policies potentially differ in their ability to achieve an emissions target under changing conditions. A policy which consistently 'hits the target' (achieves environmental effectiveness) and remains cost effective is desirable.

As a practical matter it is also important to distinguish static from dynamic cost effectiveness. Static efficiency refers to a short term operating environment in which technology options and aggregate primary resource availabilities are fixed, while dynamic efficiency pertains to a long term operating environment in which technology options and primary resource availabilities can change. A policy which is cost effective in the short run may not be cost effective in the long run.

As well as applying the global least cost principle to policies for emissions control, the other main criterion for policy assessment is the objective of distributive justice. This requires that the total net benefits (costs) generated by the policy should be 'equitably' shared.

Central to the analysis of the performance of any greenhouse policy is the recognition that the real world operating environment involves major sources of greenhouse uncertainty and associated risk regarding future economic and ecological conditions. Decision makers will face the costs of uncertainty and risk from making incorrect decisions. But it is possible to reduce these costs by ensuring that policy is flexible and reversible in response to new information about the most cost effective future strategy. The ability to modify policy settings and introduce new policies without generating major costs of adjustment are key criteria for greenhouse management.

Potential net benefits from a policy initiative must also take into account the administrative costs of the program to both the public (implementation costs) and private agents (transactions costs). Two prerequisites for program efficiency may be distinguished. First, the administrative costs of implementing a policy must not exceed the potential net benefits from the policy inclusive of private transaction costs. In principle, policies that promote self-enforcement have the lowest implementation costs and are therefore most likely to realise potential efficiency gains, other things equal. In addition, besides the direct impact of the policy on the market prices of goods and services, the private opportunity cost of searching and assessing information, and obtaining any necessary approval, for a market transaction may be affected by policy. Hence, the second prerequisite is that the private transactions costs of implementing a policy must not exceed the potential net benefits from the policy inclusive of public administration costs. In practice, policies that facilitate the private provision of information services will have the lowest transaction costs and are therefore most likely to realise potential efficiency gains, other things equal.

Costs need to be measured correctly. A taxonomy of the costs of environmental regulation, beginning with the most obvious and moving towards the least direct, is provided in Table 10.1.³ First, many policy makers, and much of the general public, would identify the on-budget costs to government of administering (monitoring and enforcing) environmental laws and regulations as *the* cost of environmental regulation. However, most analysts would identify the capital and operating expenditures associated with regulatory compliance as the fundamental part of the overall costs of regulation, although a substantial share of compliance costs for some environmental regulations fall on government rather than private firms — one example being regulations of contaminants in drinking water. Additional direct costs include legal and other transaction costs, the effects of refocussed management attention, and the possibility of disrupted production.

Next, the potential 'negative costs' (in other words, non-environmental benefits) of environmental regulation, including the productivity impacts of a cleaner environment and the potential innovation-stimulating effects of regulation should also be considered. General equilibrium effects associated with product substitution, discouraged investment⁴, and retarded innovation constitute another important layer of costs, as do the transition costs of real-world economies responding over time to regulatory changes. Finally, there are a set of potential social impacts that are given substantial weight in political forums, including those on jobs and economic security.⁵

Finally, in assessing policy options in this chapter both spatial and temporal aspects of emissions coverage are considered. General design features of economic instruments are categorised by the coverage of net greenhouse gas emissions, the scope and level of participation and the point of application. That is, for example, an emissions control objective could involve a target on all or a subset of all human sources and sinks and all or a subset of all greenhouse gases. In addition, the scope of a policy instrument could involve all or a subset of countries. The level of participation in a scheme refers to the economic unit responsible for meeting a target. Options range from the level of the country to that of individuals and companies. The point of application of the policy simply refers to the point in the production or consumption chain of a good or service at which greenhouse gas emissions are to be counted or proxied.

10.2.4 Coverage of Greenhouse Gases

10.2.4.1 The Need for Comprehensive Targets

Should an initial international program include all greenhouse gases or focus on CO₂ alone? This question has received considerable debate in the literature (see, for example, Cristofaro and Scheraga 1990; Victor 1991; Stewart and Wiener 1992). The advantage of the more comprehensive approach is the additional flexibility it introduces into the system, and hence the potential it creates for even greater cost effectiveness. However, the sources and sinks of methane and nitrous oxide emissions are as yet poorly understood. Currently, important anthropogenic sources of emissions of methane appear to include domesticated ruminant animals, rice cultivation, landfills and mining;

³ For a very useful decomposition and analysis of the full costs of environmental regulations, see Schmalensee (1994). Conceptually, the cost of an environmental regulation is equal to 'the change in consumer and producer surpluses associated with the regulations and with any price and/or income changes that may result' (Cropper and Oates 1992, p. 721).

⁴ For example, if a firm chooses to close a plant because of a new regulation (rather than installing expensive control equipment), this would be counted as zero cost in typical compliance-cost estimates.

⁵ For a fuller explanation of these different categories of the costs of environmental protection, see Jaffe, Peterson, Portney and Stavins (1995).

and for nitrous oxide appear to include legume crops and nitrogen fertilisers (Howden and Munro 1994; Pearce and Warford 1993). Clearly, countries with a comparative advantage in agricultural industries could be significantly affected by either the exclusion or use of a multiple gas scheme. While CO₂ is the main source of past and present greenhouse concerns, methane and nitrous oxide are also significant in radiative forcing.

By including all the major greenhouse gases (sources and sinks) in setting global and any national greenhouse management targets policy makers would avoid throwing away valuable knowledge (Schmalensee 1993). Given a set of weights relating the radiative forcing potential of each greenhouse gas to a numeraire (say CO₂), a multiple gas market policy would only need to involve one quota market or one emissions tax scheme and one permit market or domestic tax scheme as well as one control obligation for each country. At this stage these weights are uncertain and may vary with both environmental and economic conditions (Hoel and Isaksen 1993).

If the administrative burden is deemed to be too great initially for the incorporation of (net) greenhouse gas emissions other than CO₂ in an international greenhouse management program, the program needs to be flexible enough to do so when implementation costs fall, and indeed could provide incentives to generate such an outcome. Care must be taken not to worsen problems for future greenhouse management. This means that the international target must be comprehensive as must targets for countries within the coalition which adopts any international market based policy regime. Coalition governments must manage those emissions outside the international market based policy regime.

10.2.4.2 Initial Coverage of CO₂ Sources and Sinks

Any international greenhouse gas reduction policy presumes some agreed aggregate goal for management of greenhouse gas emissions into the atmosphere. This is because it is aggregate emissions rather than individual country emissions which affects atmospheric concentrations and hence climate change itself. Such a goal may be expressed as either a quantity or a price rule. If a quantity rule is preferred then the goal may be specified as a fixed level of ambient greenhouse gas concentrations, perhaps translated into an aggregate emissions profile. If a price rule is preferred then the goal may be thought of as an 'insurance premium', a payment per unit of emissions to avoid greenhouse damage.

Specifying an aggregate goal is hard enough, but disaggregating to provide nation-specific goals is even more difficult, for equity issues loom particularly large in this transformation. As well, there is the problem of how a coalition of countries should adjust its aggregate goal in the event that the size of the coalition either shrinks or expands. It is perhaps because of this last reason that the Montreal Protocol defined individual country targets but not an aggregate target.

The coverage issue in the case of CO₂ has been widely discussed (see, for example, UNCTAD 1992; OECD 1992a,b). Should consideration be limited to only changes in emissions of CO₂ or also include changes in CO₂ sinks, such as expanding forests? One question is whether and how an international agreement might help retard deforestation and promote reforestation (Dudek and LeBlanc 1992). Deforestation could be treated as equivalent to emissions, while afforestation activities could be a source of emissions abatement credits.

Whether one is considering net CO₂ emissions from fossil fuel burning or net deforestation, it is necessary to have a net emissions target (baseline which applies in the absence of policy) from which to assess the effectiveness of the greenhouse policy in place. This baseline has yet to be determined for the forestry sectors of the world's economies, and cost effective monitoring techniques have not yet been proven. One of

the major difficulties is that many trees exist outside forests as such and measuring their contribution to carbon sequestration with remote sensing devices is extremely difficult. A further and more pervasive issue is associated with specifying ex ante a 'status quo' time path, against which 'improvements' can be measured.

The coverage of the scheme may have a major impact on the incentive of different countries to participate. With an international market program for CO₂, countries like Brazil and Indonesia might find it economically attractive, as well as environmentally sound, to retard the depletion of their forests or to implement reforestation programs. Under an international tradable quota regime, CO₂ emissions credits would amount to a valuable export commodity from the seller's viewpoint and would be an equally valuable import from the buyer's viewpoint (a country which would otherwise be in CO₂ emissions deficit). Under an international CO₂ emissions tax, net emissions would also be treated symmetrically.

Currently, there are significant difficulties in measuring the carbon stored in trees and how it varies over time (Houghton 1992). Current estimates of the costs of carbon sequestration through tree planting vary widely (ranging from US\$1 to US\$50 per ton of carbon abated), reflecting the opportunity costs of alternative land use (Stavins 1994b) as well as uncertainty (see Sedjo 1994 and the references cited there). However, estimates at the low end of the range refer to developing countries and, aside from uncertainty, appear promising in terms of shifting any long term need for high cost carbon free backstops further into the future. According to current estimates such backstops become economic when the marginal cost of emissions is around US\$250 per ton of carbon (Manne and Richels 1991).

Satellite imagery is a critical tool in monitoring forestry systems. Given the potential stimulus of global net CO₂ emissions trading, this tool could be tailored to ensure that coverage is complete and backed by verification (OECD 1992b). Further, such a price stimulus for reduced deforestation (and increased afforestation) could yield complementary gains in terms of sustainable land management practices and global gains in biodiversity values. Indeed, the global nature of biodiversity values has prompted one suggestion for an international tradable quota system in global forestry management (see Sedjo 1994).

Hence, an important option value would be preserved by including in any international agreement to control CO₂ sources that the adoption of sinks would be reviewed, at fixed points in time, by all Parties. However, it would be important to ensure that the integrity of the existing policy regime was preserved as new sinks were included.

10.3 The Domestic Policy Context

From the basic theorems of welfare economics it can be deduced that if an economy is perfectly competitive, there is a full set of markets and information is perfect, then the resulting equilibrium (if it exists) is efficient in the sense that no one could be made better off without making someone else worse off. The real world does not satisfy these conditions. There exist many externalities, of which climate change is only one. Competition is not perfect; increasing returns to scale characterise many industries. Information is often not perfect and markets are not complete. Moral hazard and adverse selection partly explain why a full set of insurance markets does not exist. What is more, even if all the conditions of perfect competition were satisfied, the resulting Pareto efficient outcome may not accord with society's view of a distribution of resources that is equitable or 'fair'. If certain other conditions hold, then an alternative, feasible, Pareto efficient allocation can be sustained as a competitive equilibrium with appropriate lump-sum taxes and transfers, and so the objectives of efficiency and equity

need not necessarily clash. But lump-sum taxes and transfers are typically infeasible, and as a consequence distorting taxes and transfers are employed virtually everywhere.⁶

The above observations about distortions are important because many analyses of climate change policy assume that the externality of climate change is the only distortion which exists. In fact, climate change policy must be considered in the context of real economies, already rife with distortions. A market economy can function effectively only if government defines property rights and provides for the enforcement of contracts, and yet in some countries even these basic requirements are not met. The extent to which government can provide these basic requirements and correct market failures will in part determine GNP. The importance of GNP in determining future emissions is highlighted in Chapter 10.

Further, it is necessary to take into account the distortions introduced by governments. Government interventions can undermine net national income and cause environmental damage (see Binswanger 1989). Another important determinant of future emissions, as discussed in Chapter 10, is population. Here, too, both market and government failures play a role. For example, high rates of fertility have been linked to the absence of effective capital markets, which make it difficult or impossible for people to obtain social security (see Dasgupta 1993).

One purpose in this Section is to draw attention to the importance of this policy context in evaluating climate change policy proposals. The merits of any given proposal depend on this context. Equally, changes in the context have implications for emissions. Sometimes these two different observations are confused, and another purpose here is to clarify the distinction between them. Obviously, the types of policies that might warrant discussion here are many. However, the discussion is restricted to a few areas that seem particularly important and on which some research has already been done.

10.3.1 Pre-existing Market Distortions

10.3.1.1 Energy Subsidies

The emissions abated by a climate change policy will depend not only on the policy itself but also on whether the consumption of energy is subsidised, and the magnitude of such subsidies. It is the combination of the climate change policy and these subsidies (and indeed other policies) which will determine relative prices and hence the incentives for substituting away from the carbon-intensive fuels.

In some regions such subsidies are significant (Larsen and Shah 1994a). Using border prices as a benchmark, Larsen and Shah (1992) calculated that primary fossil fuel subsidies worldwide are equivalent to a negative carbon tax of US\$40 a ton. Larsen and Shah (1994a) estimate that global CO₂ emissions would be reduced by between 4 and 5 per cent if all energy subsidies were removed.⁷ At the same time, eliminating such subsidies would increase real incomes. The reason is that the subsidies distort prices; users pay less for fossil fuels than it actually costs to supply them. Removal of the subsidies would improve efficiency, and thereby increase incomes.

An OECD study using the GREEN model arrives at a similar result. The OECD estimates that the removal of energy subsidies would reduce global emissions by 18 per cent compared with the level that would otherwise be attained by 2050 (Burniaux,

⁶ Although lump sum taxes and transfers are typically infeasible in a single economy, market based instruments such as a tradable quota scheme or a carbon tax can be designed to achieve transfers of goods and services between countries to implement the equity criteria described in Section 8.2.3.

⁷ They estimate that a carbon tax of US\$60-70 per tonne of carbon would be required in OECD countries to achieve an equivalent reduction in global emissions.

Martin and Oliveira-Matins 1992a). Elimination of subsidies could increase global real incomes by 0.7 per cent annually and real incomes in non-OECD countries could rise by 1.6 per cent annually.

Fossil fuels may also receive indirect subsidies from electricity generation. Electricity is typically subsidised in both developed and developing countries. In the United States, for example, government regulation frequently restricts electricity prices from privately owned utilities to equal long run average costs, which are often below marginal costs. Power is sold by the federal government at approximately 25 per cent below even these levels, because of interest and tax subsidies (DCEIA 1992). In developing countries, electricity prices declined in real terms by 25 per cent over the 1980s, and by 1988 were at an average level just over half as large as the average level in OECD countries, even though long run marginal costs in real terms were higher in developing countries (Schramm 1992). In 80 per cent of developing countries, electricity prices are below long run marginal costs — on average 30 per cent below (World Bank 1990, 1992a). Such distortions lead to excessive expenditure on new capacity, failure to generate sufficient internal funds to maintain or expand service, excessive energy consumption and excessive environmental impacts from power generation.

10.3.1.2 The 'Local' Environmental Benefits of Climate Change Policy

So far, the effect that the removal of energy subsidies can have on income, as conventionally measured by GNP, has been stressed. But the effects are likely to be felt more widely. One consequence of actions to reduce CO₂ emissions will be a reduction in other pollution. For example, Bye, Bye and Lorentsen (1989) estimate that a policy which reduced CO₂ emissions in Norway by 20 per cent would have the incidental effect of reducing SO₂ emissions by 21 per cent and NO_x emissions by 14 per cent. Larsen and Shah (1994b) calculate that, for Pakistan, a carbon tax could be justified taking only the benefits of reductions in local pollutants into account, despite the fact that Pakistan already has high energy-related taxes.

10.3.1.3 Information and Energy Conservation

There has long been concern that apparently cost-effective energy conservation technologies were being adopted and diffused only very gradually. One possible reason, identified by Jaffe and Stavins (1994a), is the failure of the market to supply appropriate and credible information about these technologies. These technologies are 'experience goods' in the sense that one can only learn about the true quality of the good by purchasing and using it. Yet energy-saving technologies are typically more costly to purchase, even if they are less costly to run. Unless consumers can ascertain their advantage in reduced running costs, they will have no reason to purchase the technology. But, because they cannot ascertain this advantage (unless they have available detailed technical information) until after they have purchased and used the good, there exists little incentive for them to purchase the good.

One means of avoiding this dilemma is for the company manufacturing the technology to offer a warranty on the product's performance. But there is a problem in that the performance of the good may depend on how it is used by the consumer, as well as its intrinsic qualities (the moral hazard problem). A full warranty would therefore create an incentive for the consumer to misuse the good. Another problem is that there may be a tendency for the users most likely to purchase a more expensive good with a full warranty also to be those most likely to misuse the good (the adverse selection problem). For both these reasons, warranties may not be able to convey the information that would benefit both consumers and the firms manufacturing the technology.

Empirical work dating back to Hausman (1979) shows that purchases of energy-saving technologies often reflect high rates of discount (see Treadwell, Thorpe and Fisher 1994). In other words, purchasers of such technologies may insist on earning a higher rate of return on this investment than on alternative investments. One explanation for

this may be inadequate information, or the availability of credible information, on the return on the investment (Hassett and Metcalf 1992).

Empirical evidence in the United States (Horowitz and Haeri 1990; Sutherland 1991) indicates that when information on energy efficiency is widely available, the real estate market functions efficiently — consumers show a willingness to pay more for houses with energy-saving features, all else being equal. However, Jaffe and Stavins (1994a,c) demonstrate that information problems can directly inhibit the diffusion of energy efficient technologies in new housing. They also show that decisions on such investments depend on expectations about the future. If the price of such technologies is expected to fall, or the availability of information about the performance of such technologies is expected to increase, then consumers may delay making such purchases. Though individually rational, such behaviour can lead to less investment than is socially desirable, depending on whether true market failures are involved (Jaffe and Stavins 1994b). This creates a potential role for public policy.

A number of projects designed to convey information to rural people exist in developing countries. One such project is the Mount Elgon Conservation and Development Project in Uganda which is designed to provide new information to local people to enhance the cost effective use of local resources and minimise damage to forest reserves.

10.3.1.4 Transport

A large and growing fraction of CO₂ emissions arise from transport fuel use. Full social (user cost) pricing can promote greater efficiency in transport while reducing these emissions substantially. Most countries tax gasoline (petrol) to finance highways and other public automotive transport services. However, few countries collect enough from drivers to pay the full social costs of automotive travel.

Appropriately designed road user charges should also reflect the peak-period costs of using congested road capacity (Cameron 1994). Congestion costs, in the form of time delays, accidents, excess fuel costs and pollution, are an increasingly serious urban problem in developed and developing countries. In the United States, the costs of time delays alone has been estimated to be \$50 billion a year (Repetto, Dower, Jenkins and Geoghegan 1992). User charges set at an appropriate level could lead to a change in the allocation of resources to the transport task and coincidentally could also likely lead to a reduction in greenhouse gas emissions assuming that such charges could be collected cost effectively.

10.3.1.5 Agriculture and Forestry

Distortions in agriculture and forestry are common. As already noted, government subsidies and tax policies have encouraged deforestation in the Amazon (see Binswanger 1989; Mahar 1988). But the distortions in agriculture go further than this. The external environmental costs of wood harvesting, including loss of soil cover and fertility, are substantial (Newcombe 1989), and yet user charges for rights to harvest timber on public lands typically do not even cover the replacement costs of the wood (Figure 10.1). In many countries, land must be cleared to gain land rights (Pearce and Warford 1993). In sub-Saharan Africa, farmers and nomads carry extra cattle as an insurance against droughts and as an asset. Herds are therefore larger than they would be if capital and insurance markets were fully developed (Dasgupta and Mäler 1994).

Underpricing of water in agriculture leads to inefficiency in water use, excessive expenditure on irrigation, and a variety of local environmental and social costs, including soil waterlogging and salinisation and the degradation of riverine and estuarine environments. Irrigation charges in a sample of six developing countries covered only 1–23 per cent of storage and conveyance costs during the 1980s. Charges for federally supplied irrigation water in the United States cover only 5–20 per cent of these costs (Repetto 1986). These charges fail to reflect the marginal opportunity cost of

water in alternative urban and industrial uses, which is typically an order of magnitude higher than its value in agriculture (Stavins 1983). When irrigation water is underpriced, farmers grow more rice than they otherwise would, even in the semi-arid areas of Egypt, India, Pakistan, China and the United States. These practices increase methane emissions (Ranganathan, Neue and Pingali 1994). Proper pricing for water could well generate global benefits as well as significant domestic gains.

10.3.2 Revenue Recycling

The abatement achieved by a carbon tax, and the effect of the tax on an economy, will depend on what is done with the tax revenue. Likewise, a tradable permit scheme can raise the same government revenue as a carbon tax if the government auctions the permits and the impact of such a scheme on the economy will depend on what is done with the revenue. The direct impact on government revenue of the two policies can be made equivalent across a variety of cases. No direct impact on government revenue would occur if permits were grandfathered (that is, allocated on the basis of some historical record) or tax revenue redistributed to emitters. Intermediate cases would be represented by partial grandfathering or partial redistribution of revenue to emitters. Thus, in principle, the same revenue recycling issues apply regardless of whether a tax or tradable permit scheme is used (Bohm 1994b), although taxes have been studied in more detail in the literature.

Jorgenson and Wilcoxon (1994) estimate that real GNP in the United States would rise if revenues from a carbon tax were used to reduce marginal tax rates on capital (see also Schackleton et al. 1992). Similarly, the European Commission (1994) estimates that, if carbon tax revenues were used to reduce employers' social security contributions, both GDP and employment could be 1 per cent higher in the long run than would otherwise be the case.

There is widespread agreement that revenue recycling can significantly lower the costs of a carbon tax (Koopmans, Mors, and Scherp 1992; Schackleton et al. 1992; Goulder 1992, 1993, 1995; Bovenberg and de Mooij 1994; Jorgenson and Wilcoxon 1994). Some of this research suggests, further, that all of the abatement costs associated with a carbon tax can be eliminated through revenue recycling in the form of cuts in income taxes. However, research by Goulder (1992, 1993, 1995) and related theoretical work by Bovenberg and de Mooij (1994) rejects this stronger claim. Their work indicates that recycling revenues through income tax cuts only partly offsets the total general equilibrium abatement costs implied by a carbon tax.

None of the above research denies the possibility that a carbon tax or revenue from a permit scheme may increase national income when combined with reductions in a particularly burdensome existing tax. In any event, such a result is an argument for reform of the taxation system rather than for the introduction of a carbon tax or permit scheme. It may be that some tax other than a carbon tax could result in a greater efficiency gain in raising public revenue. If there are efficiency arguments for a carbon tax or tradable permit scheme and reform of the tax system, then both changes should be introduced.

It is clear that the possible gains from (and, hence, appropriate level of) a carbon tax will depend on whether it is assessed against an efficient or inefficient public finance regime. It will be important to consider how the impact of the tax on the level of emissions and economic activity will vary with the public finance regime and distortions in energy pricing.

10.3.3 The Broad Context for Climate Change Policies

10.3.3.1 'No Regrets' Policies

Policies or policy reforms which improve the efficiency of an economy while also reducing greenhouse gas emissions have sometimes been described as 'no regrets' policies because their adoption could not be 'regretted' even if climate change were later shown not to be detrimental.

Of course, the reduction of virtually any distortion is to be encouraged, provided equity concerns can be safeguarded. Policy reforms which help in this regard are therefore also to be welcomed, whatever the consequences for climate change. If greenhouse gas emissions are reduced in addition then extra potential gains exist. But even where this is not so, the removal of distortions can lead to greater economic welfare. In general, such policies should not be linked directly to climate change policy. However, their significance for climate change policy needs to be recognised. These policies will influence both the 'business-as-usual' emissions scenario and the effectiveness of any climate change policy.

While there may be political advantages in linking so-called 'no regrets' policies to climate change policy, such linkage serves to confuse the policy debate. For example, the observation that a carbon tax (or auctioned tradable permits) may increase national income when combined with a tax reform is really an observation that the structure of taxation could be improved. A carbon tax is not the only device available for improving public finance, and indeed it may not be the best device available; it is possible that a different tax could improve the efficiency of raising public finance by more than a carbon tax. What this means is that the merits of a carbon tax will depend on whether the tax is evaluated taking all other existing policies as given, or whether it is instead evaluated against the background of a (second-best) efficient tax regime.

It is not, however, obvious how a carbon tax should be evaluated. If the tax is evaluated against the background of a (second-best) efficient tax regime, and yet the actual tax regime is different, then the evaluation could lead to inappropriate public policy. A better approach would be to demonstrate how the performance of a carbon tax (reflecting both the emissions and level of economic activity associated with the tax) depends on the policy context, including the regime for raising public finance and the presence of distortions in energy pricing.

10.3.3.2 Adaptation Policies

It is important to draw a clear distinction between the impacts of climate change itself and the impacts of any policies that might be adopted to mitigate climate change. The impacts are uncertain because our scientific understanding is imperfect. In addition, both ecosystems and economic systems are changing all the time and will adapt, to some extent, to climate change. Policies designed to assist economic systems to adapt to climate change will affect the economic environment in which mitigation policies must operate. In general it will be important to design adaptation and mitigation policies such that they complement each other.

Adaptation policies are incentive schemes to defend activities against expected damage from environmental degradation or to enhance the ability of the economic system to cope with change. The only incentive required for 'defence' under ideal conditions—competitive markets and certainty and the absence of any market distortions, aside from the environmental pollution itself—is to internalise the source of the externality. The right amount of private defensive action will follow through the automatic working of the market place by making polluters face the full social cost of their actions using an emissions tax or the equivalent quantity control (Cropper and Oates 1992).

Damages may be avoided by reducing net emissions sources (abatement control) and/or by taking defensive measures to prevent climate change from net emissions resulting in

damages (Fankhauser 1993). If an environmental change is gradual then, as it affects supply and demand for traded goods and services (such as food and energy), resources will move to their most productive uses as signalled by changes in relative prices. In this case damaged parties may receive lump sum compensation—which is, by definition, independent of the level of their private defensive actions as otherwise incentives will be distorted and the moral hazard problem in insurance will arise.

However, where defensive action is a public good then additional incentives will be required. Public infrastructure projects such as building dykes or funding resettlement programs are cases in point as is the funding of public research and development of carbon free technologies where there would otherwise be strong free riding incentives. Furthermore, if there are risks of increased environmental hazards (drought, flood, fire, famine, pests) then greater hazards insurance is an appropriate defensive action. Another type of 'insurance' could be purchased by increasing public research expenditure. For example, increasing efforts in plant breeding in order to develop plant cultivars better adapted to new climatic conditions is one possible response.

10.4 Regulations, Voluntary Agreements and other Non-Market-Based Instruments

The conventional approach to environmental policy in many countries has employed policy instruments in the form of uniform standards (based on technology or performance) and direct government expenditures on projects that are designed to improve the environment (Baumol and Oates 1979; OECD 1989; Hahn and Stavins 1991). As with market-based incentives, the first of these strategies requires that polluters undertake pollution abatement activities, while under the second strategy the government itself expends resources on environmental quality. Both of these strategies figure prominently in current and proposed policy measures to address global climate change.⁸

10.4.1 Uniform Technology and Performance Standards

Uniform regulatory standards (often described as 'command and control' regulations) can be loosely categorised as being either *technology-based* or *performance-based*, although the distinction between these two categories of instruments is often unclear. Technology-based (or design) standards typically require the use of specified equipment, processes or procedures. In the context of climate change policy, there could be requirements that particular types of energy efficient motors, combustion processes, or landfill gas collection technologies be utilised by firms.

Performance-based standards are relatively more flexible than technology-based standards, specifying allowable levels of pollutant emissions or polluting activities, but leaving the specific methods of achieving those levels up to the regulated entities. Examples of performance standards for greenhouse gas abatement include minimum levels of energy efficiency for appliances, maximum allowable levels of carbon dioxide emissions from combustion, or maximum levels of methane emissions from landfills.

Uniform standards can also take the form of outright bans of certain products or processes, such as the banning of aerosol sprays containing ozone-depleting substances. Although bans may appear to be the strictest form of regulation, if low-cost substitutes for targeted products are available, bans may actually be a relatively cost-effective policy instrument. Moreover, bans or other more proactive design standards may make economies of scale in the production of substitutes materialise faster than through market mechanisms by themselves (Bohm and Russell 1985).

⁸ In the case of the United States, for example, see: US Environmental Protection Agency (1989); National Academy of Sciences (1992); Clinton and Gore (1993).

Although uniform technology and performance standards may be effective in achieving established environmental goals and standards, they typically tend to lead to economically inefficient outcomes in which firms use unduly expensive means to control pollution (Tietenberg 1985; Hahn 1989; Hahn and Stavins 1991). Because the costs of controlling pollution vary greatly among and even within firms, any given aggregate pollution control level can be met at minimum aggregate control cost only if pollution sources control at the same *marginal cost*, as opposed to the same *emission level*. Indeed, depending on the age and location of emission sources and available technologies, the cost of controlling a unit of a given pollutant may vary by a factor of a 100 or more among sources (Crandall 1984). Nonetheless, because performance standards give economic agents additional flexibility to make choices based on economic criteria, performance-based standards will generally be more cost effective than technology-based standards. On the other hand, if there is essentially only a single means of achieving a particular performance standard, a technology-based standard may conserve on information and administration costs.

In theory, the government could achieve a cost-effective allocation of pollution control responsibility among sources if it assigned source-specific control levels that equated the marginal costs of control across sources. This approach would, however, require detailed information on the pollution control cost functions of individual firms and sources — data that governments usually lack and could obtain only at great cost, if at all. Although they are not typically designed to address the cost-effectiveness issue, source-specific or firm-specific permit programs are one approach traditionally taken to adjust regulatory standards to individual circumstances. If pollutants exhibit highly localised effects, such an approach may have distinct advantages over a tax or permit system. Global climate change is not, however, a localised problem; a unit of greenhouse gas emission will have roughly the same impacts regardless of where it is emitted.

Even if the government were able to use conventional technology and uniform performance standards to achieve a cost-effective allocation of pollution control at present, such standards do not provide continuous *dynamic* incentives for the development, adoption and diffusion of environmentally and economically superior control technologies (Bohm and Russell 1985; Jaffe and Stavins 1994d).

All forms of intervention have the potential for inducing or forcing some amount of technological change, because by their very nature they induce or require firms to do things they would not otherwise do. Performance and technology standards can be explicitly designed to be 'technology forcing', mandating performance levels that are not currently viewed as technologically feasible or mandating technologies that are not fully developed (Jochem and Gruber 1990). The problem with this approach, however, is that while regulators can typically assume that *some* amount of improvement over existing technology will always be feasible, it is impossible to know how much. Standards must either be made unambitious, or else run the risk of being ultimately unachievable, leading to political and economic disruption (Freeman and Haveman 1971).

Once a performance standard has been satisfied, there is little benefit to the individual firm from developing and/or adopting even cleaner technology. In addition, regulated firms may fear that if they do develop a cleaner technology, the performance standard will be tightened. Technology standards are even worse than performance standards in inhibiting innovation, since, by their very nature, they constrain the technological choices available, and may thereby remove all incentives to develop new technologies that are environmentally beneficial (Magat 1979). As an example, when vehicle emission standards requiring the use of catalytic converters were adopted by the European Community, incentives to develop lean burn engines were reduced. This is because these technologies are presently incompatible; a lean burn engine cannot be

fitted with a three-way catalytic converter. Lean burn technology is not presently able to meet the emission standards which can be satisfied by the catalytic converter technology, but lean burn has the potential advantage of reducing CO₂ emissions significantly, and even reducing other emissions more effectively over the lifetime of an automobile. Under some circumstances, however, a performance standard may provide greater incentives for technological adoption than a marketable permit system (Malueg 1990).

There are better and worse ways of establishing performance standards. To take an example, the Corporate Average Fuel Economy (CAFE) standards in the United States are applied to the fleet *average* of every manufacturer and importer. CAFE may thus be binding on a manufacturer which sells many larger cars as well as some small cars, but not on a manufacturer which sells only small cars. The problem here is that the former manufacturer may sell small cars which are more energy efficient than the latter manufacturer. In other words, the innovation and manufacture of more efficient automobiles may not be rewarded by these standards. If CAFE differentiated the standards according to the market segment of each vehicle (sub-compact, compact, mid-size, etc), then firms which sold vehicles which were more efficient for their class than required by the standard would be rewarded by not having to pay the penalty for which the manufacturers of less efficient cars were liable. Better still, if manufacturers were allowed to trade in energy efficiency credits, then even the manufacturer of the most efficient cars would have a continuous incentive to develop even more energy efficient cars. Finally, a tax on petrol/gasoline would not only provide incentives for the manufacture of more fuel-efficient cars, but would also provide incentives for vehicle owners to reduce their fuel consumption.

As with virtually all policy instruments, the administration of uniform standards typically includes programs for compliance monitoring and enforcement. Although technology-based standards may seem to be the least cost-effective of the policy instruments, if monitoring costs are high they may have an advantage because they are relatively easy to monitor and enforce. An inspector can simply check whether a particular piece of equipment has been installed, rather than continuously monitoring information on emission levels. Performance standards, in general, and pollution charges and marketable permits for non-carbon greenhouse gas emissions all require more detailed monitoring systems, which can suffer from the following problems: (a) once emissions leave the source they are usually lost to measurement; (b) emissions may be random, rather than fixed values, and may vary depending on equipment breakdowns, shifts in product mix and input quality, or changes in production levels; (c) monitoring instruments may be imprecise; and (d) unless monitoring is continuous, polluters may adjust emissions up or down according to the likelihood of inspections (Beavis and Walker 1983).⁹

10.4.2 Government Investment

Direct government expenditures also play a major role in both current and prospective environmental programs in many countries. Such government activities include projects to: (a) prevent, mitigate, or adapt to changes in environmental quality; (b) disseminate information; (c) conduct research; and (d) educate specialists and the general public (Baumol and Oates 1975). Many environmental ends that could be achieved through incentive-based policy instruments or uniform standards can also be met directly through government-funded projects or programs.

The two primary economic rationales for the inclusion of direct government investment in an effective overall government policy are the public good character of many

⁹ For discussions of relevant enforcement issues see, for example: Harford (1978); Shibata and Winrich (1983); Polinsky and Shavell (1979).

environmental services and the possibility of economies of scale. Public goods arguments for direct government expenditure to disseminate information, conduct research and sponsor education programs are common in debates about climate change policy. Indeed, the potential role for government research and information provision regarding energy efficient technologies is particularly prominent in the climate change context (Jaffe and Stavins 1994d). Finally, proposed methods for addressing climate change through climatic engineering or 'geoengineering' options are also likely to require direct government involvement.

One such potential approach is changing the albedo (reflectivity) of the earth by sending tiny reflective particles into the atmosphere to create a sunscreen or placing minute particles of iron in the upper atmosphere (Nordhaus 1991). Another proposal being studied would place minute iron particles in the North Atlantic and Antarctic oceans, thereby increasing photosynthesis and the rate of carbon precipitation to the ocean floor (National Academy of Sciences 1992). Efforts to reduce electricity use by lowering urban temperatures through an increase in the reflectivity of urban surfaces (for example, buildings and roads) and by planting shade trees also figure prominently in some climate change policy proposals (US Environmental Protection Agency 1992; National Academy of Sciences 1992; Clinton and Gore 1993).

10.4.3 Voluntary Agreements

Beyond mandatory policy instruments, voluntary agreements can also play a role in an overall greenhouse gas reduction strategy. The threat of mandatory government intervention may be enough to encourage voluntary agreements. Forward-looking firms may undertake some, albeit limited, steps in controlling greenhouse gas emissions if they fear more costly mandatory controls in the absence of these voluntary reductions. This could explain why voluntary agreements have arisen in some cases in domestic energy management.¹⁰ The vast majority of greenhouse gas reductions from the actions announced or expanded through the US *Climate Change Action Plan* (Clinton and Gore 1993) come from voluntary initiatives aimed at increasing the energy efficiency of the industrial, commercial, residential and transport sectors.

10.4.4 Demand Side Management

Demand side management may be defined as an attempt by an electricity utility to alter the characteristics of its demand profile. Demand side management may alter the quantity of electricity supplied, the timing of the use and the quality of supply (voltage variability and the interruptibility of supply). There is an extensive literature on demand management (Katz 1992; Kahn 1992; Hirst 1993; Joskow and Marron 1993) as a means of reducing capital costs for utilities. The impact of demand side management on operating costs and emissions has not been studied as closely. The most widely recognised form of demand side management is where utilities attempt to limit the growth in demand for electricity.

It is difficult to offer an economic rationale for why electricity utilities would want to limit the growth in demand without taking account of the regulatory environment in many countries. It would be in the self-interest of a utility to slow the growth in demand if, at the margin, the cost of reducing demand by an additional kilowatt (a so-called 'negawatt') was less than the net profit from selling an additional kilowatt. It is clear that such a relationship could hold only if the net profit from selling an additional kilowatt were negative. The simplest and most efficient way to reduce the growth in demand would be to raise price but this may be difficult because of regulatory or political obstacles. An economic rationale for involvement of utilities in the types of

programs regarded as demand-side management can be made only if price is regulated to a level below marginal cost. Some of the regulatory pressures applied to utilities to adopt such programs can also be regarded as disguised environmental impact taxes (Sioshansi 1992).

The types of programs regarded as demand-side management include provision of information about energy efficiency and subsidies for the adoption of energy efficient equipment. Thus, utilities sometimes attempt to promote the types of policies that might be regarded as no regrets as discussed earlier in the chapter. It was also noted earlier that electricity prices in some countries are regulated to be below long run marginal costs. It may be more cost-effective to increase electricity prices up to long run marginal cost than have utilities involved in demand-side management programs. Higher electricity prices would increase the incentive for consumers to search for and adopt more energy efficient technologies, perhaps reducing the scope for apparent no regrets options.

Load smoothing is also usually defined by utilities as demand-side management. It is well known that there are distinct daily and seasonal peaks and troughs in the pattern of electricity demand. Time varying prices are used by utilities to attempt to shift demand to clip peaks and fill troughs. Such time varying prices are a straightforward application of marginal cost pricing since marginal generating and distribution costs increase with load. Transactions costs mainly in the form of metering and billing costs limit the extent to which time varying prices can be applied to residential consumers. Emissions from a generating plant, once it is started, are largely independent of load. Since load smoothing improves utilisation of generating capacity, load smoothing reduces emissions required to produce a given electricity output over a day.

10.4.5 Distributional Impacts

Any greenhouse policy will have distributional effects on firms and households. Regulations impose quantity limits on the use of particular inputs or outputs in production and consumption activities. The direct cost of regulation is the reduction in profits and consumer welfare due to the regulatory constraint on choice. The distribution of this cost is often hidden, but that does not make it unimportant. For example, poorer households tend to own appliances which are cheaper to purchase but more costly to run. That is, poorer households tend to make appliance purchasing decisions reflecting higher effective individual discount rates (Hausman, 1979). A regulation which required that all households purchase more efficient appliances would thus fall disproportionately on the poor, even though by outward appearances it might seem not to. To the extent that regulation is not a least cost option to control greenhouse emissions, the excess burden it implies must also be distributed. Notably, though, in contrast with a system that taxes all emissions, with quantity limits – whether in the form of conventional regulations or tradable permits systems – individual emitters do not face an environmental cost for emissions which are less than the limit.

While the initial incidence of a greenhouse regulation will fall on greenhouse-intensive energy users, the final incidence will depend on the ability of firms to pass the costs of the regulation to others through higher prices for goods and services, and these distributive impacts are likely to differ over time. For example, the long run incidence of greenhouse pollution controls applied progressively to newer cars might be regressive as low income earners face substantial increases in used car costs, although in the short run low income earners might gain a relatively larger capital reward on selling their cars (Tietenberg 1992). Where the costs of regulation are regressive (costs fall disproportionately on the poor), compensatory transfers may be used, funded from a specific tax or general government finances, or the regulation might be modified, exempting some individuals from the regulatory net.

¹⁰ See, for example, the experience of the Netherlands cited in Lenstra and Bonney (1994).

To date, most applied economics research on potential greenhouse policy responses has concentrated on analysing the overall costs and incidence of market based instruments. Multicountry and national studies on the economic impacts of regulatory measures are needed. Researchers may need to give more emphasis to incorporating real world conditions in these models, such as uncertainty and asymmetric information in energy markets. This would allow for any differences in the informational role of price and quantity controls (and policy mixes) in determining the size and distribution of greenhouse control costs.

10.5 Market-Based Policy Instruments

10.5.1 Introduction

Because of the considerable potential costs of meeting greenhouse gas emission targets, one of the central issues for Parties to the Framework Convention is to identify least cost measures, that is, policies which minimise the costs of achieving a given greenhouse gas emissions target. In this section attention is focused on emissions taxes and tradable quotas and permits, the two core market-based instruments which directly target least cost measures to meet greenhouse gas emissions targets. Mention is also made of joint implementation, an instrument which can facilitate technology transfer and amounts to bilateral 'trades' in emissions.

There is an extensive discussion of the principles behind the use of market based policy instruments for greenhouse management—for example, see Bohm and Russell (1985); Baumol and Oates (1988); Stavins (1988); OECD (1989, 1993); Tietenberg (1990); Epstein and Gupta (1990); Dornbush and Poterba (1991); Stavins (1991); Bureau of Industry Economics (1992); Cropper and Oates (1992); IIASA (1992a,b); Pillet, Hediger, Kypreas and Corbuz 1993; Hahn and Stavins (1993). For a summary and assessment of the cost and environmental effectiveness of emissions taxes and tradable quotas in national applications see Howe (1994).

In a perfectly competitive market place, under an emissions tax or tradable quota scheme emitters would reduce emissions up to the point where the marginal cost of control equals the emissions tax rate or the equilibrium price of an emissions quota. Both instruments would promote dynamic efficiency (cost minimisation over the long term when factors of production are variable and technological change may be stimulated) as each provides a continuous incentive for research and development in emissions abatement technologies to avoid the tax or quota purchases. Under competitive markets and certainty, an emissions tax is identical to a tradable emissions quota scheme in which quota rights are auctioned and revenues are redistributed in the same way (Rajah and Smith 1993).

The use of taxes and/or tradable quotas (or a range of other instruments for that matter) will only lead to a cost-effective global outcome if certain conditions are met. First, unless individual countries undertake cost effective domestic greenhouse policy measures compatible with global efficiency, the policy instruments adopted internationally will not lead to global efficiency. Each individual country is free to choose its own instrument or combination of instruments to meet its international obligations but the choice of international instruments will, to some extent, dictate the choice of policy instrument at the domestic level. This is clearly so in the case of the harmonised carbon/energy tax proposed by the European Commission for member states of the European Union. Under this regime, every member of the Union would impose the same tax rate, although states would be free to decide for themselves what to do with the revenues from the tax. If nations themselves were taxed by an international agency, then it would not necessarily follow that nations would choose to impose the same tax domestically. For example, they might instead choose to reduce emissions domestically by means of a tradable permit scheme. Similarly, in the case of a system of internationally tradable quotas, individual countries might choose to implement their

obligations by means of a domestic tradable permit scheme or through a domestic emissions tax.

Second, given that information is not perfect and that distortions already exist in both international and domestic markets, the actual market outcomes from the implementation of particular greenhouse policies will not necessarily be efficient. The importance of the policy environment has already been discussed in Section 10.3 and implementation issues surrounding the adoption of market-based instruments are outlined below. For purposes of discussion, it will be assumed that a given ceiling on emissions as its target has been identified, and that governments seek to minimise the costs of meeting this target. The concern here is thus with cost-effectiveness rather than efficiency as such. As noted earlier, when there is uncertainty in the benefits and costs of abatement, efficiency may prescribe use of either price or quantity (or, more generally, non-linear price) instruments. To focus on the more narrow question of cost-effectiveness, such considerations will be ignored in the discussion which follows.

10.5.2 Carbon Taxes

With market-based policies, there can be incentives to reduce greenhouse emissions through the development and use of new technologies and by making changes to existing production and consumption practises. The aim in using an emissions tax (a tax per unit of emissions) is to minimise the total economic costs of achieving a given emissions target. In principle, both static and dynamic efficiency gains can be fostered under an emissions tax. Static (dynamic) efficiency gains arise where emitters face different opportunities for emission control (have different marginal abatement cost curves) in the short (long) run when factors of production and technological opportunities are largely fixed (vary endogenously).

Most research has focused on a tax on the carbon content of primary fossil fuels consumed as the most practicable base for greenhouse emissions (Pearce 1991; Boero, Clark and Winters 1991; Jorgenson and Wilcoxon 1992; Repetto, Dower, Jenkins and Geoghegan 1992; Dower and Zimmerman 1992; OECD 1992a, 1993; Jones and Tobler 1993; Pillet et al. 1993; Boyd, Krutilla and Viscusi 1994). A carbon tax is a tax on the carbon content of fossil fuels consumed. A carbon tax is not a perfect proxy for a tax on CO₂ emissions. For example, a carbon tax on fossil fuels provides an incentive to reduce the use of carbon based fuels, but not to reduce CO₂ emissions by such means as capture (fixation) and disposal of the emissions at source (on carbon removal see Section 10.5.2.1). There may also be, due to leakage or incomplete combustion, emissions of other carbon compounds which differ from CO₂ in their greenhouse effects (notably methane). In addition, domestic fuel consumption used for non-energy purposes (such as petrochemical manufacture) would need to be exempt from the proxy CO₂ emissions policy, and consistent accounting would need to apply to domestic emissions resulting from the processing of fuels from one energy form to another (such as in electricity generation).

There is a variety of points in the 'product cycle' for fossil fuels at which a carbon tax policy could be applied from production of fuels to their end use. End use is obviously the point at which emissions occur; but monitoring points covered under the policy would be fewest, and hence implementation costs lowest, if carbon contents were measured and policy applied to wholesale use. In addition, the application of a carbon tax to different points in the product cycle could generate differences in the international incidence of impacts and could also affect the overall global cost effectiveness of an international carbon tax scheme.

However, a carbon tax is a more efficient instrument for reducing energy sector CO₂ emissions than taxes levied on some other basis, such as energy content of fuels or the value of energy products (ad valorem energy tax). For example, model simulations of the US economy indicate that an energy tax could be between 20 and 40 per cent more

costly, and an *ad valorem* tax two to three times more costly, than a carbon tax for equivalent reductions in emissions (Scheraga and Leary 1992; Jorgenson and Wilcoxon 1992). The reason for this is that an energy tax raises the price of all forms of energy, whether or not they contribute to CO₂ emissions, and would make it more costly to substitute lower emitting or non-emitting energy sources for high emitting energy sources. As a corollary, a combined carbon/energy tax would be less efficient and more costly than a pure carbon tax, due to its energy tax component.

International action would be required to meet a global emissions target. One possibility is that the carbon tax would be imposed on nation states themselves by an international agency. In this case, the agreement would not only specify tax rate(s) but also a formula for reallocating the revenues from the tax. Cost-effectiveness would demand that the tax rate be uniform across all countries (assuming full participation), but the reallocation of revenues would not have a direct bearing on cost-effectiveness. As an alternative, the agreement could stipulate that all countries should levy the same domestic carbon tax, so-called harmonised domestic carbon taxes. In both cases, some experimentation would be required with the tax rate because it would only be by trial and error that the tax rate that achieved the coalition's emissions target was struck. The tax rate would also need to be adjusted over time as economic conditions changed and as more scientific information became available.

Requiring that tax rates be uniform is required for reasons of cost-effectiveness. But the resulting distribution of costs may not conform to principles of equity and justice. For this reason, transfers of resources may be required. In principle, the two versions of an international tax agreement could involve the same actual financial transfers, although the transfer principles may differ. Under the harmonised tax system, the agreement could involve fixed lump-sum payments from rich to poor countries, whereas under the first-mentioned international tax system, the agreement could specify what shares of the total international tax revenues would go to each participating country (Hoel 1993c). (In a tradable quota system, the financial transfers could again, in principle, be the same, but would then be represented by sales of time-limited quotas by poor countries and quota purchases by rich countries.)

10.5.2.1 Related Instruments – Deposit Refund Systems for Carbon Removal

A deposit refund system can take one of several forms: a tax (deposit) on a commodity followed by a subsidy of the socially least-cost disposal option (a refund); mandated deposits requiring private sellers of a commodity to add to the price a deposit that will be refunded under certain conditions; or a performance bond requiring an agent that engages in certain (production) activities to avoid certain negative consequences of these activities. For surveys of current use of deposit refund systems and descriptions of potential new areas of applications, see: Bohm (1981); Hahn (1988); Russell (1988); Stavins (1988); OECD (1989); Anderson, Hofmann and Rusin (1990); Hahn and Stavins (1991); Sigman (1991); Stavins (1991); US Environmental Protection Agency (1991).

For a deposit refund system to be a feasible means of encouraging carbon fixation, there must exist alternative actions that decision makers can take to avoid creating the environmental externality in question. This could be a choice between controlling emissions at source and 'end of pipe' emissions removal.

Currently, potential emitters of CO₂ — purchasers of fossil fuels for combustion, for example — do not have available to them the option of choosing to remove the carbon from the emissions.¹¹ On the other hand, new techniques for carbon removal (from

¹¹ It is precisely for this reason that a carbon tax (with relatively low monitoring costs) is feasible, by contrast with a true CO₂ emissions tax, which would obviously be extremely costly to monitor and enforce. (Compare this with the case of sulphur dioxide

stack gases, in particular) may eventually become economically feasible. (In 1993 Japan's Ministry of Trade and Industry launched a project on CO₂ fixation — see MITI 1993.) When and if this happens, incentives will exist to choose carbon removal when this is less expensive than reducing fossil fuel combustion through improvements in energy generation or use efficiency. This would open up the possibility of applying the deposit refund concept to CO₂ emission reduction.

This suggests that it is important, in the meantime, to maintain appropriate incentives for research and development of technologies that can eventually provide cost effective options for carbon removal. The appropriate incentive will exist if (future) carbon removal is known to be subsidised at a level equal to the (tax, tradable quota, or shadow) cost of carbon emissions.¹²

Thus, it may be possible to introduce clauses into a future climate change protocol that would validate subtractions of carbon removal from emissions. This would, in effect, be equivalent to creating an international deposit refund system — a tax/subsidy scheme — where nations would be credited for certified carbon removal (estimated carbon emission avoided) by equally large additions to their emission quotas. These quotas would be measured by the carbon contents of fossil fuel use, equal to production plus imports minus exports. Moreover, if fossil fuel use is taxed domestically (directly or indirectly through a tradable permit system), and carbon removed is subsidised (credited by a refund of the deposit, equal to the tax), the resulting policy package will be an international deposit refund system.¹³

Other greenhouse gases, such as CFCs, that could be recovered when servicing cooling equipment such as refrigerators or air conditioners, could be made subject to a system with general deposits (taxes) on CFCs and a refund when and if CFCs are recovered, provided that the transactions costs of such a system are not prohibitively high (Stavins 1988; Miller and Mintzer 1986). Obviously, if CFCs are successfully phased out in the near future, the role of policy instruments such as deposit refund systems to control CFC emissions will be very limited. Still, the problem mentioned above concerning CFC contents in discarded cooling equipment, which may be present for some twenty years after the phase-out of new production using CFCs, may be significant enough to justify the use of a CFC deposit refund system (Bohm 1981, 1982, 1988, 1990). Note, however, that for products containing CFCs that already have been purchased by final users, the deposit refund system will be one with zero deposits and a positive subsidy. In other words, it will collapse into a pure subsidy system. Then, one of the advantages of deposit refund systems, that ordinary taxes are not required for financing the refund/subsidy incentive, would no longer hold.

10.5.3 Tradable Quotas and Permits

Under an international tradable emissions quota scheme all coalition countries are allocated a quota for emissions (whatever emission is being controlled) per period for

(SO₂), for which a sulphur content tax on coal would be problematic, since it would fail to provide incentives for flue gas desulphurisation (scrubbing) even when this would be the cost effective route to reducing SO₂ emissions.)

¹² An option of this kind was used to some extent in the Montreal Protocol (Article 1.5). For an analysis of the cost-effective attributes of the Protocol see Bohm (1990).

¹³ In addition, uses of fossil fuels for purposes other than combustion, for example as chemical feedstocks, could be subjected to similar deposit refund treatment to 'keep the prices right'. Likewise, products such as lubrication oil could be subjected to the carbon tax while waste lubrication oil would be entitled to a tax refund if returned for oil recovery or other form of proper disposal instead of being disposed of by incineration (Bohm 1981).

some limited set of periods. For later periods, the targeted total level of emissions as well as the initial quota distribution among countries may vary. On the spot or forward market, each period countries would be free to buy and sell quotas on an international exchange in order that neither buyer or seller need be identified. Time limiting the quotas would probably be necessary not only to account for uncertainty about the extent of the enhanced greenhouse problem but also to give credibility to the system and, specifically, to avoid a situation where some present government sells quotas, that is, part of the nation's wealth, to an extent that would not be honoured by future governments in the country. Time-limited quotas would also reduce the risk of large countries gaining market power on the quota trade market or the need for measures to ensure that such market imperfections were avoided (such as limits to quota holdings).

An efficient international tradable quota system presupposes a market organisation for quota trade, possibly including forward as well as spot transactions (see Sandor et al. 1994). In the case of a system for the control of emissions of CO₂, quotas would have to be denominated according to the carbon content of the fossil fuel used. If quotas were to be established for the full suite of greenhouse gases, it would be necessary to weight gases according to their estimated (and agreed) global warming potential. For any such scheme to be effective in controlling emissions, it is clear that there must be a reasonable probability of detecting and penalising those responsible for unauthorised emissions. This, however, does not distinguish a tradable quota system from any other international agreement on emission reductions. In what follows, the focus is on quota systems for carbon emissions only.

Negotiations on initial quota allocation are likely to be facilitated by reference to some criteria such as, GNP, real GNP, total population, adult population, land area, 'basic needs' defined by industry structure and/or local climate, dependence on fossil fuel production, etc. (for an overview, see UNCTAD 1992; also see Grubb and Sebenius 1991; Bertram 1992; Bohm and Larsen 1993; Hinchy, Thorpe and Fisher 1993). There are numerous other possibilities. Evaluations of proposed rules would need to take account of their international trade repercussions.

Each of the criteria will have adherents, largely those with larger allocations under that criterion.¹⁴ Several criteria may need to be blended to create international consensus on emission allocations.¹⁵ For example, it is clear that the developing countries have relatively little incentive to participate unless they see clear economic benefits from an agreement. At the same time, the wealthy countries will want to make sure their burdens are divided in ways that are perceived as equitable. Whatever the initial allocation, subsequent trading can lead to a cost-effective outcome.¹⁶ This potential for pursuing distributional objectives while assuring cost-effectiveness is an important attribute of the tradable quota approach.¹⁷

¹⁴ For example, under an allocation system related to population levels, the big players in the market would likely be India and China, as permit sellers, and the United States and perhaps the former Soviet Union, as buyers. (See Epstein and Gupta 1990.)

¹⁵ For example, the Canadians proposed using population and GNP combined as allocation criteria when CFC reduction obligations were being considered in the development of the Montreal Protocol.

¹⁶ This is abstracting from the potential consequences of significant transactions costs. See discussion of this above.

¹⁷ See, in general: Bohm (1992). 'Appropriate' initial allocations can serve as an effective device to draw countries — particularly, developing countries — into an international agreement. On this, see: Barrett (1992c); Hinchy, Hanslow and Fisher (1994a,b). Most proposals for allocating control obligations among nations call for proportionately higher rates of reduction in emissions by the industrialised countries

However, as compared with an international tax agreement, where the effect on emissions is uncertain while transfer payments (if lump sum) are known, the tradable quota system has a known effect on emissions but uncertain quota prices and, hence, uncertain distributional effects through quota trade. (This is true for fully global agreements; if only a limited set of countries is involved, carbon leakage must be taken into account in both cases.) This means that the benefits of known effects on emissions in a tradable quota system must be bought at the price of distributional uncertainty. Thus, if a decision is taken that a poor country should be offered some minimum compensation, then initial quota allocations to that country would have to be increased as compared with the case under certainty. Alternatively, the agreement would have to include some co-insurance system.

Countries allocated quotas surplus to their requirements would be able to use the revenue from quota sales to increase their imports relative to their exports (Chichilnisky, Heal and Starrett 1993). Countries allocated quotas less than their requirements would have to reduce imports relative to exports to pay for additional quotas. In this way a tradable quota scheme would tend to reallocate world production. The allocation of tax revenue from an international carbon tax scheme would have similar effects.

Providing large initial quotas to poor countries for compensatory reasons implies that they would be selling quotas primarily to rich countries. Since quota permit prices represent an implicit or explicit tax on all participating countries, the terms of trade within the coalition for countries with the same carbon intensities in production would remain unaffected. Given some tariff or other protection from competition from non-participating countries, when the agreement does not involve all countries, means that industrialisation in poor countries would not have been made more difficult, relatively speaking and aside from the inevitable consequences of reduced global fossil fuel use. In addition, reducing fossil fuel use would emerge as a potentially important 'export industry' for the poor countries. From a distributional point of view, the end result would be that poor countries would be perhaps fully compensated, whereas rich countries would have to pay, first, for their own emission reductions as called for by the quota price and, second, for carbon reductions imported through quota purchases from abroad.

A powerful theoretical feature of a perfectly competitive tradable quota or domestic permit scheme is that, no matter what the initial quota/permit allocations, equilibrium quota/permit prices will be the same and the final allocation after international/domestic trade will be the one that minimises the cost of reducing emissions. Countries/firms will want to buy quotas/permits if abatement costs exceed the quota/permit price and sell quotas/permits in the opposite case. In this way, trade will continue until all countries/firms are indifferent between buying and selling quotas/permit — that is, between marginal abatement and additional fossil fuel use. When this state is reached, an ex post allocation of quotas/permits that minimises the costs of reducing emissions has also been reached.¹⁸

(and, among the industrialised countries, by the United States) and substantial reductions in the predicted rates of increase in CO₂ emissions by most developing countries. See, for example: Krause (1989); Flavin (1989); Wirth and Lashof (1990).

¹⁸ In a static model with fixed prices and neglecting the public goods aspect of abatement, transfers have purely distributional effects. However, this is not the case where economies are growing and production technology differs across countries in the sense that different quantities of capital and emissions are required to produce a given output of consumption or capital goods. In this case transfers make it possible to raise the growth rate of an economy above the maximum determined by its original

An international tradable quota scheme could coexist with domestic permit schemes within each country or particular countries may choose to meet their emission targets by some other means, such as using taxes or command and control systems. In the case of a domestic tradable permit scheme, a national government would issue (time-limited) emissions permits to wholesale dealers in fossil fuel or producers and importers of fossil fuel and allow them to trade on a domestic permit market. The government could also allow permit holders to trade directly on an existing international market. Alternatively, to the extent that both international quota and domestic permit markets existed for a particular country, the government could trade on the international market and set a definite or preliminary domestic limit on the volume of domestic permits for some period ahead.

A government may choose one of two main ways to distribute permits to individual firms. In the first case firms would be given shares of the total permit volume based on some historical record ('grandfathering') such as their recent fossil fuel sales. The second alternative would be for the government to auction permits. Some combination of these two approaches may also be feasible.

The two approaches differ in primarily two respects. First, grandfathering implies a 'transfer' of wealth, equal to the value of the permits, to existing firms, whereas, in the latter case, it is this wealth that is transferred to the government. The government would then collect revenue similar to that from a domestic tax producing the same volume of emissions. As with tax receipts, auction revenues could be used to reduce pre-existing distorting taxes as outlined in Section 10.3. In addition, grandfathering may slow technological change by impeding the entry of new firms (Bohm 1994a).

By contrast with international tradable quota systems which have so far been applied on a small scale only (for example, under the Montreal Protocol for international CFC production quota trade and for CFC consumption quota trade within the European Union), there is considerable experience with the use of tradable permit schemes within countries (see OECD 1992b; UNCTAD 1992). In most of these applications, permits have been allocated by grandfathering. Many of these applications have been designed to deal with local air pollution problems and, as a consequence, the permit markets have often been relatively small and far from perfect. This contrasts with the case of a tradable carbon permit system which would be nationwide. The contrast would be even more stark for an international scheme involving many governments and possibly large firms as well.

10.5.4 Joint Implementation

Joint implementation, provided for by Article 4.2 (a) of the FCCC, involves cooperation between two countries, with one funding emission reduction in the other to help the first meet its reduction commitments.¹⁹ The potential economic merits and demerits of joint implementation proposals have been widely discussed (Hanisch 1991; Hanisch, Pachauri, Schmitt and Vellinga 1992; Hanisch, Selrod, Torvanger and Aaheim 1993; Anderson 1993; Barrett 1993a,b; Jones 1993; Johnson 1993; Parikh 1993; Reddy 1993; Bohm 1993b, 1994a). In essence, there are three potential roles for joint implementation: (a) as the first step toward establishing an international tradable quota system for greenhouse management among Parties that have made a firm commitment to limit their emissions; (b) as a cost-effective option for Annex-I Parties to fund emission reductions projects in non-Annex-I Parties (developing countries) that have

productive capacity. This is illustrated by Hinchy and Hanslow (1994) using an *n*-country generalisation of a model studied by Tahvonen and Kuuluvainen (1993).

¹⁹ For a comprehensive review of the legal and practical aspects of joint implementation see Kuik, Peters and Schrijver (1994).

made no such commitments; and (c) as an activity for exploring when it is cost effective to bring new emissions sources or sinks into an existing international greenhouse management scheme.

A system of joint implementation trades in carbon reduction projects could develop automatically into an international tradable carbon quota system for countries which have carbon targets (Bohm 1994a). Where aggregate targets exist, the joint level of aggregate carbon emissions reported is a sufficient monitoring statistic for the actual aggregate abatement levels undertaken by each country under a joint carbon reduction policy. Cost incentives are such that emission reductions below the target in one country, when less costly than in another country, would be purchased by, and credited to, the latter. In particular, when several countries, committed to carbon targets, trade in this fashion the incremental costs of emissions reductions will tend to be equalised across economies. As a result, an international tradable quota scheme could be established once countries commit to binding targets, which would in effect then become their tradable quotas.

The literature on joint implementation has focused mainly on low-cost emission reduction projects in developing countries. Bohm (1994a) also considers the case of joint implementation between developed and developing countries, where only the former commit to binding targets while the latter do not. In the absence of binding targets in developing countries it would be difficult to determine the net emission reduction effects due to a specific joint implementation project, since nationwide indirect and direct effects on emissions must be counted. The net emission reduction effects of low-cost abatement projects are particularly uncertain since such projects may be close to being profitable and hence may be carried out by the market itself in the near future. In addition to these systematic risks, there are incentives to misrepresent the effectiveness of projects. Parties to a joint implementation project may exaggerate the project's nationwide net emission reduction effects. A clearinghouse version of joint implementation trades between developed and developing countries would eliminate these incentives on the part of the buyer countries. The role of the clearinghouse would be to screen and aggregate all projects from potential sellers before they are offered as anonymous carbon credits to buyers at a market clearing price.

Another potential role for joint implementation is as a complementary exploratory tool for information gathering to expand an existing international regime which initially involves only international carbon trading resulting from fossil fuel emissions. Participating nations could agree to revisit the coverage issue at fixed intervals, modifying strategies to accord with the underlying science and economics of climate change. Successful joint implementation programs are those which provide the necessary information to incorporate a truly cost effective new emissions source or sink into an international market base policy. However, this application of joint implementation raises problems of project emissions baseline estimation similar to those mentioned in the preceding case, and hence difficulties in ascertaining the nationwide net emission reduction effects of individual non-carbon projects. Current and future joint implementation demonstration projects could provide additional insight into these estimation problems provided there are sufficient incentives for developed countries to finance such projects.

The potential driving force behind joint implementation is that both buyer and seller countries, developed as well as developing, would benefit from this particular trade as they do from other forms of voluntary transactions. So far, monitoring problems seem to stand in the way of using joint implementation as an instrument for significant cost-effective operations, except for the limited case where Parties to the FCCC have committed themselves to emissions targets, primarily for carbon emissions. This type of joint implementation amounts to an international tradable quota system, the cost-effectiveness properties of which is determined by the number of countries that have made such commitments and want to engage in operations under such a system.

10.5.5 Distributional Impacts of Market-Based Measures

The literature on industrialised countries typically portrays carbon taxes and other market-based instruments such as emissions taxes, gasoline or BTU taxes as regressive because outlays on fossil fuel consumption as a proportion of current annual income tend to fall as incomes rise. But recent studies (see Table 10.2) using US and European data show that carbon taxes are considerably less regressive relative to life-time income or annual consumption expenditures than to annual income (see Poterba 1991, 1993; Jorgenson, Slesnick and Wilcoxon 1992; Smith 1992a,b).

Jorgenson et al. (1992) provide the most detailed assessment to date for the United States. They decompose the simulated equity and efficiency impacts of a carbon tax using an explicit national social welfare function. In this decomposition, when the carbon tax revenue is rebated lump sum, the negative efficiency effect dominates and the much smaller equity effect is either mildly progressive or regressive depending on assumptions regarding the nation's aversion to income inequality and the measure of progressivity used.

There is evidence that the same holds true for the rest of the world, although for quite a different reason. In developing countries institutional factors play an important role (see Shah and Larsen 1992). In the developing world, progressivity, or at least low regressivity, could be fostered by: (a) where there is a significant degree of foreign direct investment from countries where investors are allowed foreign tax credits against domestic liabilities, a significant tax burden could be passed on to foreign treasuries, producers and consumer; (b) if price controls apply, producers often cannot pass the tax on to consumers in terms of higher prices; and (c) with binding import quotas or rationed foreign exchange, a tax would reduce the excess profits made by the privileged class.

The existence of factors such as market power are likely to lead to regressivity. In this situation, producers could increase product prices in order to pass on a carbon tax to consumers. As it turns out, in most developing countries, there is some combination of the above elements, creating a situation where taxes can be only partially shifted to consumers. This means that a carbon tax would either be progressive or much less regressive than often suggested (see Table 10.3). Further, it is likely to be regressive only for the lowest income groups, which could be protected through direct subsidies or alternative measures. In addition, the overall tax structure could be made even less regressive by using a carbon tax to reduce more regressive taxes.

In principle, if a policy is introduced in order to achieve a particular outcome and it is found to be regressive then the theoretically appropriate policy instrument to deal with the equity issue is a lump sum transfer to the affected parties. This rests on the assumption that there are no non-greenhouse market distortions. If such distortions exist then non-lump sum transfers can improve welfare (Jorgenson et al. 1992). As Schillo et al. (1992) explain, if carbon tax revenue is used to reduce labour, or a blend of labour and capital, taxes then simulated household welfare improves as the adverse efficiency effect is reversed by the rebate, but at the cost of reducing the equality of wealth. A capital rebate is simulated to neutralise the efficiency effect but has uneven distributional effects.

10.6 Policy Implementation Issues

In assessing any of the wide range of instruments as potential devices for addressing global climate change, it is imperative to give due consideration to the implementation issues that can so severely affect real world outcomes. Such issues need to be considered in the design of practical policies, whether at the national, multinational or global level.

In the case of tradable permit systems, as applied to local air pollution problems in the United States, the claims made for their cost-effectiveness have often exceeded what can reasonably be anticipated. Tietenberg (1980) assimilated the results from ten analyses of the costs of air pollution control, and in a frequently cited table, indicated the ratio of cost of actual regulatory programs to least-cost benchmarks. Unfortunately, the resulting ratios (which ranged from 22.0 to 1.1) have sometimes been taken by others to be directly indicative of the potential gains from adopting specific ('cost effective') mechanisms such as tradable emission permits. A more realistic and appropriate comparison would be between actual regulatory policies and either actual trading programs or *reasonably constrained* theoretical permit programs (Hahn and Stavins 1992).

A number of factors can adversely affect the performance of tradable permit systems: concentration in the permit market (Hahn 1984; Misiolek and Elder 1989); concentration in the output market (Malueg 1990); transaction costs (Stavins 1994); non-profit-maximising behaviour, such as sales or staff maximisation (Tschirhart 1984); the pre-existing regulatory environment (Bohi and Burtraw 1992); and the degree of monitoring and enforcement (Keeler 1991). In the case of taxes, research on implementation issues has focused on: administrative costs (Polinsky and Shavell 1982), monitoring (Russell 1990), and enforcement (Harford 1978; Russell, Harrington and Vaughan 1986).

In the following sections a review is undertaken of what is known about some prominent issues regarding the implementation of (carbon) taxes and/or tradable permit systems. Where appropriate, reference is also made to regulatory systems. It is important to note that most of the research on tradable permit schemes is based on experience in the United States where such schemes were superimposed on regulatory policies. These schemes typically involve a limited number of participants, eternal permits and initial allocation by grandfathering. To control global emissions, tradable permit schemes may often operate where there was no former regulation, they will involve a larger number of participants, permits may be time limited and initial allocation eventually may be by auction. Thus, experience in the United States may not generalise to such schemes with rather different characteristics.

10.6.1 The 'Currency' of Regulation

Due to the awesome monitoring and enforcement burden associated with regulating actual carbon dioxide emissions, the most practical 'currency' for a tax or tradable permit system would presumably be the carbon content of fossil fuels. Given the proportional relationship between carbon content and CO₂ emissions and the lack of practical means of sequestering these stack gases, this is a highly appropriate approach. Monitoring could rely partly on self-reporting supplemented by international access to national fossil fuel inventories. Under an international carbon tax or tradable permit scheme, implementation costs may be least where incentives to comply are self-enforcing. An effective enforcement system makes ultimate sanctions credible so that penalties would rarely need to be imposed.

10.6.2 Market Power

There are two aspects of the market power problem for tradable permit systems (Bureau of Industry Economics 1992). The first is the potential for some economic agents to influence the permit price. The second is the potential for some economic agents to use permits to exercise market power in the output market for the product that 'generates' emissions. Market power in the permit market is sufficient but not necessary for market power in the output market (BIE 1992). Malueg (1990) argues that market power in the output market may reduce economic welfare under a tradable permit scheme even if tradable permits are fully cost effective.

The degree of competition in the tradable permit market will affect the extent to which potential control cost savings are likely to be realised. Hahn (1984) considers the case of a monopsonist (a price setting buyer) who forces down the real permit price below the competitive level. This behaviour is not cost effective since the monopsonist buys too few permits (spends too much on abatement) while the competitive agents will buy too many (spend too little on abatement). Misiolek and Elder (1989) consider the converse case of a monopolist (a price setting seller) who forces up the real permit price above the competitive level. That is, the monopolist spends too little on abatement while competitive agents spend too much. To the extent that market power derives from the initial allocation of permits, one solution may be to limit the amount of permit held by any player (Tietenberg 1985). This may be achieved by widening the market to many players, including by limiting the temporal duration of permits.

An emissions tax designed to make emitters face the full costs of production will tend to result in a cost-effective allocation of the control burden, provided that emitters are cost minimising/price takers. But this outcome does not necessarily occur where emitters have some degree of monopoly power in emission-intensive output markets (Buchanan 1969). In principle, a monopolist in an output market for an emissions-intensive commodity will tend to reduce output below the competitive level in order to raise its profits. Hence, the welfare gains from reduced emissions must more than offset the losses from reduced output of the monopolist for an emissions tax to be worthwhile (Cropper and Oates 1992). Which effect dominates is an empirical issue.²⁰ For example, Oates and Strassman (1984) find that monopoly power in the output market is unlikely to be a key concern in their select study of US industries.

In the case of a scheme to reduce global emissions, there typically will be more participants than under the schemes operating in the United States which may reduce the problem of market power. In an international scheme, firms that are large domestic emitters may be required to hold permits as a means of broadening the market. In domestic schemes, if market power posed a problem, government intervention may be required or a tax scheme may be a preferable option.

The issue of market power warrants further consideration in the context of either tax or permit schemes. Whether or not OPEC is involved in a scheme, the potential oligopolistic response of oil producers could interfere with the effectiveness of attempts to control global emissions (Sinclair 1992).

10.6.3 Transaction Costs

Transaction costs can potentially be of importance in the performance of tradable permit markets (Baumol and Oates 1988; Tripp and Dudek 1989; Hahn and Hester 1989a). Stavins (1994a) identifies three potential sources of transaction costs in tradable permit markets: (a) search and information; (b) bargaining and decision; and (c) monitoring and enforcement. The first source, search and information, may be the most obvious. Due to the public-good nature of some information, it can be underprovided by markets. Brokers step in, provide information about firms' pollution-control options and potential trading partners, and thus reduce transaction costs, while absorbing some as fees. Although less obvious, the second source of transaction costs, bargaining and decision, is potentially as important. There are real resource costs to a firm involved in entering into negotiations (Kohn 1991), including time and/or fees for brokerage, legal,

²⁰ Although there is no cutoff point, it is unlikely that firms or nations could engage in price-setting behavior if they controlled less than 10 per cent of the market (see Scherer 1980). Ultimately, the question is whether other firms present credible threats of entry to the market — that is, whether the market is 'contestable'. If so, it is less likely that anti-competitive behaviour can thrive (see Baumol, Panzar and Willig 1982).

and insurance services (Hahn and Noll 1982). The third source of transactions costs — monitoring and enforcement — can also be significant, but these costs are typically borne by the responsible government authority and not by trading partners, and hence do not fall within the notion of transaction costs incurred by firms as defined here.

There is abundant anecdotal evidence indicating the prevalence of significant transaction costs in tradable permit markets. Atkinson and Tietenberg (1991) survey six empirical studies that found trading levels — and hence cost savings — in permit markets to be lower than anticipated by theoretical models. Liroff (1989, p. 2) suggests that this experience with permit systems 'demonstrates the need for ... recognition of the administrative and related transaction costs associated with transfer systems.'²¹ For example, under the US Environmental Protection Agency's emissions trading program for 'criteria air pollutants', there is no ready means for buyers and sellers to identify one another, and — as a result — buyers frequently pay substantial fees to consultants who assist in the search for available permits (Hahn 1989). At the other extreme, the high level of trading that took place under the program of lead rights trading among refineries as part of the USEPA's leaded gasoline phasedown has been attributed to the program's minimal administrative requirements and the fact that the potential trading partners (refineries) were already experienced at striking deals with one another (Hahn and Hester 1989a). Hence, transaction costs were kept to a minimum and there was little need for intermediaries.

Another source of indirect evidence of the prevalence of transaction costs in permit markets comes from the well-known bias in actual trading toward 'internal trading' within firms, as opposed to 'external trading' among firms. It has been hypothesised that the crucial difference favouring the internal trades and discouraging the external trades is the existence of significant transaction costs that arise once trades are between one firm and another (Hahn and Hester 1989b). Finally, the existence of commercial brokers charging significant fees to facilitate transactions is another body of evidence.

Stavins (1994a) considers a market for emission permits in which costs are associated with the exchange of permits, and models several alternative types of transaction cost functions. He finds that transaction costs reduce trading levels and increase abatement costs and, most importantly, that in some cases, equilibrium permit allocations and hence aggregate control costs are sensitive to initial permit distributions. Thus, in the presence of transaction costs, the initial distribution of permits can matter in terms of efficiency, not only in terms of equity.

The effects of transaction costs should be ameliorated somewhat in markets with relatively large numbers of potential trading sources where permits may be of limited time duration. Such is likely to be the case in schemes intended to reduce global emissions. As the pool of potential trading partners increases, it should be easier for sources to identify potential trading partners, thereby lowering transaction costs. A larger number of firms can mean more frequent transactions, generating more information, and thereby reducing uncertainty.

Economists have tended to give greater emphasis to the symmetry between tradable permits and pollution charges, than to their differences, although the two approaches are not symmetric under conditions of uncertainty (Weitzman 1974), in the presence of

²¹ Alternative explanations of low observed trading levels have also been advanced: lumpy investment in pollution-control technology; concentration in permit or product markets; the sequential and bilateral nature of the trading process (in the context of a non-uniformly mixed pollutant) leading to some initial trades that then preclude better trades from being carried out subsequently (Atkinson and Tietenberg 1991); and the regulatory environment. Some of these 'alternative explanations' of low trading levels can be viewed as special cases of transaction costs, broadly defined.

transaction costs (Stavins 1994a), or under a number of other conditions (Stavins and Whitehead 1992). Analyses that have compared taxes and permits have assumed zero transaction costs. Systems of pollution taxes, of course, can also involve substantial administrative costs, both fixed (per firm) and variable (Polinsky and Shavell 1982).

In a newly established tradable permit scheme, transactions costs may be significant, especially initially. If a country already has a system of taxing fossil fuels, a tax system may have advantages, at least in terms of initial relative transactions costs.

10.6.4 Participants in the System

Who should participate in a trading system? This question can be divided into two parts: domestic trading and international trading. For domestic trading, any individual, business or public entity could be allowed to participate in programs, subject to constraints related to administrative feasibility. For example, it would obviously be impractical to have individuals accountable for their carbon dioxide emissions. The question of how to draw the line to make the regulatory scheme manageable is an important one. Some have advocated starting off with a simple scheme, even if it does not encompass a large part of the problem (Dudek and LeBlanc 1990).

The problem of international trading is more subtle (Green and Sands 1992). If international trading takes place among nations, there would be advantages of allowing firms within those nations to trade internationally. But depending on the nature of domestic greenhouse regulations, this can raise serious problems of departures from cost-minimising allocations of the control burden.²² In any event, limitations on trading may be necessary because of potentially high administrative costs. A large part of the decision to allow various kinds of international trading will hinge on the differential ability and willingness of nations to enforce an agreement.

10.6.5 Free-Riding and Emissions Leakage Problems

Can a unilateral policy by one country alone or by a group of cooperating countries prove effective in abating global greenhouse gas emissions? This is an important question, for it is total emissions, and not individual country emissions by themselves, that determine global concentrations of greenhouse gases, and yet some countries seem more willing to adopt abatement policies than others. The answer depends on how the other ('non-cooperating') countries respond to the unilateral policies adopted by the 'cooperating' countries. These responses in turn reflect two phenomena: 'leakage' and 'free-riding'.

As Barrett (1994a) explains, free-riding and leakage can undermine any international greenhouse management initiatives, whether they be market based or rely on regulatory measures. Free-riding arises when countries which benefit from global abatement do not contribute toward its provision. Leakage arises when abatement by the cooperating countries alters world relative prices (including shadow prices) in a way which leads to non-cooperating countries increasing their emissions.

10.6.5.1 Policies to Reduce Free-Riding

As long as participation in an international greenhouse management policy is voluntary, countries will have incentives to free ride, sharing in the benefits from such a policy without sharing in the costs. Even if there were no leakage, free-riding would result in abatement being less than would be globally optimal, in the sense that the benefit of a small increase in global abatement would exceed the associated cost. This issue has

been examined in a number of studies including Barrett (1992a); Hoel (1992); and Parson and Zeckhauser (1992). None of the existing empirical models have been used to estimate the magnitude of potential free-riding, although some insights into the gains from full cooperation are provided by Barrett (1992a,b,c), Bohm and Larsen (1993), Hinchey et al. (1994a,b) and Hoel (1992).

As Hoel (1992), Carraro and Siniscalco (1993), and Barrett (1994c) have shown, in spite of free-rider incentives, a stable coalition of cooperating countries may exist. The size of this coalition will depend on the ability of the cooperating countries to punish countries which might withdraw from the coalition, and to reward countries which might accede to the coalition. However, to be effective, such punishments/rewards must be both substantial and credible, and these requirements often clash. As a result, the size of the stable coalition may be quite small. In fact, these analyses do not consider international trade, and where there is trade, free-riding will be exacerbated by leakage. On the other hand, trade may also provide a vehicle for deterring free-riding.

For example, Barrett (1994a,b) explains how the threat of a complete ban on trade between cooperating and non-cooperating countries in carbon-based fuels and products could work to support full participation in a greenhouse management scheme. The key to this agreement, as with the Montreal Protocol on Substances that Deplete the Ozone Layer, is that the threatened trade ban would come into effect once a threshold level of countries agreed to participate in the scheme; but the threshold is determined such that all countries would gain from participation once it is reached. In other words, it is not necessary that trade be restricted, but rather that the threat to impose trade restrictions be credible.

An actual ban on trade introduces a distortion in the global economy, and is in this sense undesirable. However, free-riding is itself a distortion, and if trade restrictions reduce free-riding, they may be beneficial overall. The implication for climate change policy is that trade restrictions should not be prohibited. Whether they should ever be allowed, and under what circumstances, is a different matter, and one requiring additional research.

Finally, Heal (1992) argues that the free-riding problem can be exaggerated. He notes that in repeated games it is more likely that players will cooperate than in one-shot games. There may be reinforcing effects that strengthen the chances of forming a stable coalition. An example would be if countries share in the costs of developing abatement technology. Developing countries may benefit from abatement technology created in developed countries and this may increase their incentive to abate.

10.6.5.2 The Severity of Emissions Leakage

There are two main channels through which emissions leakage may be transmitted. First, a carbon abatement policy by the cooperating countries would shift comparative advantage in carbon-intensive goods toward the non-cooperating countries. As a result, production of such goods, and emissions, would rise outside the coalition. Second, the unilateral policy would have the effect of lowering world demand for carbon-intensive fuels, and thereby reduce the world price for such fuels traded in international markets. As a result (and ignoring income effects), demand for such fuels, and emissions, are likely to rise outside of the coalition. It should be emphasised that these two responses by non-cooperating countries do not result from any deliberate policy to increase emissions, but rather result from the absence of a policy to reduce emissions.

Barrett (1994a) surveys several global simulation studies which provide positive leakage estimates, including GREEN, 12RT, Global 2100 and the Whalley-Wigle model. The leakage rate is defined as the increase in emissions by non-cooperating countries divided by the reduction in emissions by cooperating countries. The evidence of positive emissions leakage varies widely and is strongly dependent on the model

²² The combination of domestic greenhouse taxes and a system whereby individual (taxed) firms could trade internationally could lead to significant departures from the cost-effective allocation of responsibility among firms.

used. For example, positive leakage rates are low in GREEN (Oliveira-Martins, Burniaux and Martin 1992) and high in the Whalley-Wigle model (Pezzey 1992).

In particular, Pezzey estimates that a 20 per cent reduction in carbon emissions within the European Union alone (relative to a baseline trend in emissions) would be associated with a leakage rate of 80 per cent. In other words, for every 10 tonnes of carbon abated by the EU, global emissions would fall by only 2 tonnes. Pezzey also calculates that a 20 per cent reduction in OECD emissions would be associated with a leakage rate of 70 per cent. These leakage rates suggest that unilateral policy would be largely ineffective. On the other hand, Oliveira-Martins et al. estimate much lower leakage rates for policies aimed at stabilising carbon emissions at their 1990 levels. They estimate leakage rates for a unilateral EU policy of 11.9 per cent in 1995 and 2.2 per cent in 2050, and for a unilateral OECD policy of 3.5 per cent in 1995 and 1.4 per cent in 2050. These leakage rates suggest that leakage does not render unilateral policy ineffective. These rates are more in accord with those reported by Hanslow, Hinchey, Small, Fisher and Gunasekera (1994, p. 16) who estimate that a policy induced 20 per cent reduction in CO₂ in Annex I countries would be associated with a leakage rate of 3.8 per cent.

One reason for the difference in these leakage estimates is that emissions leakage is greater where a country's fossil-fuel-intensive products and fossil fuels have close substitutes. Trade flows in GREEN are based on the Armington assumption that goods produced from different countries are imperfect substitutes (implying an exporter has some degree of market power). By contrast, in the Whalley-Wigle model goods from different countries are assumed to be perfect substitutes, thus making trade flows more sensitive to relative price changes. In MEGABARE, the model reported in Hanslow et al. (1994), imported goods from different sources are imperfect substitutes. An important distinguishing feature of the model is the way in which technology in the energy intensive industries is modelled.

As already noted, other studies estimate leakage rates somewhere between these two sets of estimates. As well, Oliveira-Martins et al. estimate negative leakage rates for some regions in some years, and Horton, Rollo and Ulph (1992) argue that leakage may exceed 100 per cent in some cases. Currently, there is no consensus among economists about the magnitude of leakage. More research is needed, and it would be particularly helpful if leakage rates were calculated for identical simulations employing a consistent set of assumptions, as has already been done in estimating the costs of climate change policies (see Dean and Hoeller 1992). What can now be said is that leakage is a potentially serious problem for unilateral policies.

The above studies ignore a possible third channel for leakage transmission. One consequence of a unilateral policy to reduce emissions is that non-cooperating countries may expect to benefit from the resulting reduction in global emissions; and, if so, these non-cooperating countries may respond by relaxing their own abatement policies. Unlike the other leakage channels, this form of leakage is not transmitted by trade. Rather, it arises because non-cooperating countries cannot be excluded from enjoying a reduction in atmospheric concentrations of greenhouse gases. The magnitude of this last form of leakage will depend on the nature of the marginal damage schedule facing non-cooperating countries, as well as the unilateral policy itself. None of the above studies takes note of this potential leakage, and hence may understate the leakage problem overall.

10.6.5.3 Policies to Reduce Leakage

What can be done to reduce emissions leakage? What is currently known stems from the basic general equilibrium model of trade so commonly used. As background, take the somewhat simpler case of the international incidence of a global carbon tax. Most of the results from greenhouse modelling studies to date are based on the simplifying assumption that the global cost-effectiveness of a common carbon tax (tradable quota

system) does not depend on the distribution of incomes between or within countries, that is, only relative prices matter for this cost effectiveness result. (This is not to say that the international distribution of the impacts from these policies does not depend critically on what is done with tax revenues or initial quota allocations.)

Hence, consistent with basic trade theory, a uniform global production tax (quota) on greenhouse emissions is equivalent to a uniform global consumption tax (quota) on these emissions. Both minimise the cost to global economic welfare of achieving a given global emissions target where there is perfect foresight. There are terms of trade gains (losses) to net fossil fuel exporters (importers) under a production tax, and the converse holds for a consumption tax. That is, fossil fuel exporters are less worse off under a production than a consumption tax on emissions, and the converse is true for net importers. Precisely such results are illustrated in the Whalley-Wigle model (Dean and Hoeller 1992).

What happens in this standard framework when coalition membership is less than global? This issue has been examined by Markusen (1975); Krutilla (1991); Bohm (1993c); Hoel (1993a,b); and Barrett (1994a). Treating the coalition as a single entity, and the rest of the world similarly, if the coalition is a net importer (exporter) of carbon intensive products in the absence of the carbon tax then a tariff (subsidy) sufficient to prevent positive emissions leakage through the terms of trade should be imposed on these net imports (exports). This response minimises the coalition cost of meeting the greenhouse constraint. Precisely the same argument holds for leakage through trade in carbon based fossil fuels. In addition, instead of using an import tariff (export subsidy) the equivalent production subsidy (tax) and consumption tax (subsidy) could be applied in the coalition. Hoel (1993b) shows that if an optimal tariff (subsidy) or its equivalent can be employed, then the carbon tax should be uniform across all sectors in all coalition countries, but if not then differential tax rates and exemptions may be required.

In summary, all the results from basic trade theory hold in analysing emissions leakage from a carbon tax or quota (see, for example, Woodland 1982; Voudsen 1990). However, as with a customs union, determining the optimal tariff (subsidy) to minimise positive emissions leakage from the carbon tax will be a complicated calculation given the extensive but differential use of carbon based fuels in all economies and the differential ability of some countries to exercise market power. Trade compliance with GATT rules will also need to be considered. In addition, further research on the leakage problem is warranted to consider strategic interactions between greenhouse policies in coalition and non-coalition countries.

10.6.6 Information Issues, the Role of Brokers and Risk Management

Policy instruments should be designed to provide needed information. In the case of tradable permit systems there are three ways this can be done: (a) government can take actions that directly reduce regulatory uncertainty; (b) barriers to private brokerage services can be reduced; and (c) allowance can be made for the development of futures markets. In the first case, at a minimum, government authorities can avoid creating regulatory barriers (such as requirements for government pre-approval of trades) that drive up transaction costs and discourage trading.

Private provision of brokerage services can also play an important role in information provision. Thus, although commercial brokers can certainly be recipients of transaction costs, their activities reduce transaction costs below what they would otherwise be (Stavins 1994a). Intermediaries, in general, can contribute to social welfare by helping parties economise on transaction costs. Brokers can play the role of consultants, adding value by understanding the regulatory process and by maintaining information about prospective suppliers and demanders of permits. Under the more conventional function of bringing together buyers and sellers ('brokering deals' by matching buy orders and

sell orders), these firms both absorb and reduce transaction costs. Finally, brokers may assume risk by buying, holding, and selling permits.

An important merit of an international tradable quota system (compared with any scheme including an emissions tax scheme) is that it can be used as a risk management tool to reduce the costs of greenhouse risks. An optimal international tradable quota system will not contain eternal quotas as this would fail to preserve the full worth of the option value to modify policy with future knowledge. Indeed, the costs to nations, and therefore to the world as a whole, of the uncertainties and of the risks attached to greenhouse management may be reduced if nations can adopt an optimal portfolio of tradable quotas.²³

A forward market for quotas could develop if there are a sufficient number of hedgers and speculators none of whom can significantly congest price signals. The latter requirement could be met by a rule fixing the maximum share of total net emissions entitlements held by any one country. By reducing the costs of risk and uncertainty, time limited quotas would tend to reduce any nation's incentive to pursue strategic behaviour (such as through quota hoarding) and could also reduce validity-forecasting problems.

Once the parties to the agreement know the basis on which quotas will be allocated over time, a futures market could develop. Provided contracts are standardised, one of the main difference between the above forward contracts market and a futures market is that the latter offers greater liquidity if contracts can be settled by the monetary equivalent of quota transactions as opposed to the delivery of the quota itself. As a consequence, more transactions are likely in the futures market and this should lead to greater information flows, reducing uncertainty and risk and transactions costs. As a consequence, spikes in the quota price would tend to be rapidly smoothed out as market players took up speculative and hedging positions.

Hence a major factor favouring a tradable quota scheme is that a forward and or futures market based on (net) emissions quota contracts would provide a way of efficiently reducing greenhouse costs of uncertainty and of risk. This will reduce the costs of control and stimulate investment in the research, development and use of least cost net emissions control mechanisms. For example, suppose a country invests in a risky technology transfer project as part of a strategy to meet a national greenhouse target. It could hedge against the risk of project failure by buying futures. Any profit on the futures market transaction could partly compensate for any rise in the spot price if it needs to buy quotas.

An auction system for forward sales in emissions quotas exists in the United States as part of provisions, controlling domestic sulphur dioxide (SO₂) emissions from fossil fuel fired power plants, in the 1990 amendment to the Clean Air Act. As Howe (1994) notes, under the amended legislation, by the year 2000, total SO₂ emissions from the

²³ One proposal is to time limit quotas to say ten years with one year overlapping for banking and for practical 'end of period' reasons (see Bertram 1992; OECD 1992b). In particular, one-tenth of quotas could expire each year and could be replaced by a new issue according to a procedure which could be modified say every five years. This would reduce the costs of uncertainty by providing flexibility to adapt to new information including the entry of new sources and sinks into the system. It also establishes a market in forward contracts to reduce the costs of greenhouse risks. Quotas of different duration would co-exist in the market to cover both short and long term risks, and the quota price would reflect the costs of risk.

United States electricity power sector are required to be around 50 per cent below the 1980 level. By January 1, 1995, of the 111 power plants directly affected in the first phase of measures, each must hold tradable quotas covering its total annual emissions target (its quota allocation), capped at about 50 per cent of the 1980 level. Currently, allowances may be traded to any party or credited ('banked') for future use. In the second phase, most electric power utilities will be brought within the system, beginning January 1, 2000. In addition to receiving an annual target allowance, quotas for excess emissions may be bought directly from other plants or through auctions held by the Chicago Board of Trade for the United States Environmental Protection Agency.

The temporal component of any pollution problem can be important, but this is particularly so in the case of 'stock pollutants' which tend to accumulate in the environment at a rate which significantly exceeds their natural rate of decay. Accumulations of greenhouse gases are of this nature and thus raise a set of time-related issues. If the overall goal of some public policy were to limit the rate or degree of climate change, then significant tradeoffs would exist with regard to the timing of any proposed reductions in greenhouse gas emissions. Earlier reductions would have the effect of slowing the potential onset of climate change.

Within the context of a tradable permit system, these temporal considerations can be addressed, to some degree, through provisions for (or restrictions on) 'banking', a mechanism that enables firms or nations to make early emission reductions in exchange for the right to emit a comparable amount at some later date. This notion could be extended to sinks as well as sources. It could be advantageous to allow nations to engage in banking of greenhouse gas allowances, since this would allow for inter temporally efficient market exchanges and could tend to delay the onset of global climate change.

10.6.7 Implementation Issues for Economies in Transition

Nations with economies in transition from centrally-planned to market-based systems are likely to exhibit certain characteristics that are relevant to the choice, design, implementation of greenhouse policy instruments. A small, but rapidly growing literature has begun to investigate issues of particular concern for implementation of environmental policy in transition economies, including matters such as: the adaptation of existing environmental tax systems to changing conditions (OECD 1994; Semenienc and Kundrotas 1994; Markandya 1994); historical, institutional, and fiscal factors (Ylicz 1994a; 1994b); the use of economic instruments to raise revenue for highly constrained government budgets (Ylicz 1994c, OECD 1994); the environmental impacts and cost-effectiveness of instruments for air pollution control in specific regions (London Economics 1993; Csermely, Kaderjak, and Lehoczki 1994; Dudek, Kulczynski, and Ylicz 1993); and environmental liability (Bell and Kolaja 1993).

High rates of economic growth and price inflation could affect the attractiveness of alternative policy instruments over time, due, for example, to the rapid inflation of relative permit prices or the erosion of unit-based taxes (Stavins and Whitehead 1992). Situations in which a large portion of the economy is state-owned or the private sector is in its infancy suggest the need to validate the usual assumption that emission sources (firms and individuals) are cost-minimisers and that markets are relatively complete (Stavins and Ylicz 1994). Enterprises may be protected from bankruptcy, facing only 'soft budget constraints' or have the ability to avoid environmental requirements through negotiation (OECD 1994).

Concentration of product or emission permit markets due to inherited industry mixes and possible barriers to entry (for example, imperfect capital markets) may also impede the efficient operation of a tradable permit system (Hahn 1984). Significant structural adjustment, including privatisation, shifts in industrial sector shares in the economy, and disruptions in international trading relationships could also affect the stability and

predictability of greenhouse gas emissions resulting from alternative policy instruments. Effective taxes may, for example, increase enterprise bankruptcies in a period of severe economic problems (OECD 1994). Even after privatisation, many enterprises may lack information on technological options for pollution control and their cost-effectiveness, hindering efficient responses to policy (OECD 1994).

Other non-economic characteristics of transition economies may also be relevant to the implementation of policy instruments to manage greenhouse gas emissions. Problems may arise from the legal and administrative constraints inherited from central planning, making monitoring and enforcement difficult. A relatively undeveloped sense of corporate responsibility and a lack of public awareness of environmental issues and a lack of pressure from non-government organisations could further impede effective implementation. Government personnel may lack the necessary administrative skills due to a shortage of economic, financial, and accounting skills and an inability of government agencies to offer competitive salaries (OECD 1994). Finally, high *ex ante* levels of pollution, high levels of desired reduction, and a concentrated pattern of pollution exposure may present environmental conditions that are more extreme than in many advanced industrialised countries, but may also provide abundant opportunities for low-cost abatement.

10.7 Comparative Assessment of Greenhouse Policy Instruments

10.7.1 Introduction

In this section an attempt is made to outline the issues that need to be considered in determining any greenhouse policy mix. Countries differ in their institutional structures, their resource endowments and their levels of industrialisation. Differences in economic and technical capacities among countries offer the potential for emissions abatement cost saving under a harmonised international greenhouse management scheme but, at the same time, add complexities in terms of reaching final agreement about appropriate policy approaches and burden sharing.

Economic instruments are considered by policy makers in a political environment. This has several important implications for the nature of the instruments finally adopted, as well as for the potential for reaching an international agreement on climate change.

First, to some extent the choice of instrument will be dictated by existing institutional infrastructure and experience. For example, market-based instruments are likely to be seen as less appropriate in an economy with a high level of central planning than in one with a long history of free enterprise.

Second, the ability to enforce the different instruments is likely to vary across nations. In addition, nations are unlikely to grant significant authority to a supranational body that would allow for consistent enforcement across countries. *

Third, to the extent that domestic policy is affected, the choice of policy instruments at the international level could itself affect the likelihood that an agreement will be reached.²⁴ For example, some countries may be unwilling to accept an agreement involving the use of international taxes or harmonised domestic taxes. On the other hand, as pointed out earlier, a tradable quota scheme leaves open the choice of domestic instruments.

Fourth, any approach that is implemented to control greenhouse gases may vary from the textbook application of these concepts. There are many reasons why both market-

based and regulatory approaches deviate from their ideal. Departure of actual instruments from their theoretical ideal, however, is not sufficient cause for rejection of an approach.

Fifth, the adoption of any international (domestic) instruments will have some impact on the distribution of wealth between (within) countries. Negotiations about distributional issues are likely to be crucial in determining the final policy mix that is chosen. In the case of domestic taxes and tradable permits some of the government revenue may be returned to the affected parties. Thus, for example, many charging systems in Europe designed to limit pollution recycle revenues to the participants or earmark the revenue for specific tasks. Similarly, in the United States, tradable permits for protecting the environment are distributed based on the historical pattern of emissions (grandfathering). While the precise nature of the distribution will be the subject of vigorous political discussions, countries and special interest groups (including environmental groups) are unlikely to accept an agreement that substantially shifts the distribution of wealth or political power. Since all instruments probably will have to, and also can, be connected with compensatory measures — side payments or specific quota/permit allocations — no difference between them would arise in this regard. For example, an international tax or tradable quota scheme might be designed in such a way as to encourage developing countries to join a coalition in order that they benefit from international transfers of income.

Sixth, governments are likely to attach more stringent monitoring and enforcement requirements to a market-based approach for limiting non-carbon greenhouse gas emissions than to a regulatory system. For example, environmentalists bargained successfully for the installation of continuous emission monitors as a condition for allowing a tradable allowance system for reducing SO₂ emissions in the United States. A similar strategy is likely to be applied if market-based approaches are implemented for limiting non-carbon greenhouse gases or for controlling carbon sequestration. One notable difference between the two control problems is that technology for accurately monitoring many sources and sinks of greenhouse gases has not yet been developed.

And finally, there are several reasons why politicians have traditionally taken a 'regulatory' approach, rather than an economic incentive-based approach to environmental policy (Bohm and Russell 1985; Hahn and Stavins 1991). First, industry tends to favour direct regulation over incentive mechanisms because: (a) if a tax instrument is used, the polluter must pay fees in addition to control costs, although the acceptance of this will be influenced by any revenue recycling as mentioned above; and (b) firms may have greater influence over the specifics of uniform standards. Second, the effects of quantity regulation are likely to be perceived to be more certain than pollution charges, whose effect will depend on abatement cost functions which are typically unknown. Third, economic efficiency arguments often rely on a relatively sophisticated understanding of market operation and price effects which seem 'indirect' compared with direct 'regulation' of the polluting activity. Finally, in many countries, economists play a minor role in the development of environmental policy, compared with the number of decision makers with backgrounds in law, natural science, or engineering.

10.7.2 Comparing Regulatory Systems and Market-Based Instruments

Regulatory policies may be defined as those where the authorities determine the level of permissible emissions from an emission source. Market-based policies may be defined as those where firms are free to determine their level of emissions but must pay some penalty (such as a tax or buy an emission permit) determined by the authorities for their level of emissions. For given output and input prices, to minimise the total costs of abatement, the level of abatement at each source needs to be chosen to equalise the marginal costs of abatement. If the authorities had complete information about the marginal costs of abatement at each source, regulatory policies could be determined to

²⁴ The likelihood of reaching an international environmental agreement will be affected by several factors. See: Sebenius (1991); and Hahn and Richards (1989).

1 minimise the total costs of abatement. Given that the authorities will not have such
2 complete information and typically cannot acquire it at a reasonable cost, regulatory
3 approaches tend not to be cost minimising.

4
5 On the other hand, it is necessary to consider the public as well as the private costs of
6 control (Stavins 1994a). In other words, the total costs to be minimised by a truly cost-
7 effective environmental policy instrument include both the costs of abatement (typically
8 borne by private industry, and including transaction costs) and the costs of
9 administration (typically borne by government in the form of monitoring and
10 enforcement costs). When monitoring and enforcement needs are particularly
11 burdensome, performance-based standards in general may not be cost effective. On the
12 other hand, certain forms of technology standards, which are typically relatively high
13 cost in terms of abatement, can involve only relatively minimal needs for adequate
14 monitoring and enforcement. Finally, in addition to such concerns about static or
15 allocative cost-effectiveness, it is important to consider the relative effects of alternative
16 policy instruments on the invention, innovation and diffusion of new technologies. That
17 is, in the long term, it is the dynamic efficiency properties of environmental policy
18 instruments that are likely to be most important.

19
20 In the international context, monitoring and enforcement requirements would hardly
21 differ with respect to fossil fuel use, since fossil fuel output plus imports minus exports
22 would have to be reported for each participating country under all systems.

23
24 Tradable permits (for emissions during a given time period) and taxes are the two major
25 domestic market-based policies. With tradable permits a national permit exchange
26 would develop among permit-liable fossil fuel producers and importers (or wholesale
27 dealers in fossil fuels) after the initial allocation of permits through recurring
28 government permit auctions or (temporary) grandfathering. In this connection
29 transaction costs would arise. Under a tax scheme administrative costs would be
30 incurred in payment and collection of the tax. The issue of how enforcement costs
31 would differ between policies to detect violation with a given probability has not been
32 studied and there does not appear to be any empirical evidence.

33
34 There have been a number of empirical studies that suggest significant potential cost
35 savings from the adoption of truly cost-effective instruments compared with regulatory
36 approaches (Tietenberg 1985), although most of these studies have contrasted actual
37 regulatory instrument costs with a theoretical cost-minimising alternative, not an actual
38 market-based policy instrument (Hahn and Stavins 1992).

39
40 In economies without well-developed market systems, there may be net efficiency gains
41 from applying regulatory approaches over a wider range of emission sources. On the
42 other hand, the adoption of a market-based approach may speed the development of the
43 market system. Net efficiency gains may favour market-based systems at an earlier date
44 than otherwise would be the case.

45
46 At the international level, there is little scope for using direct regulation of emissions
47 over and above using non-tradable emission quotas. Such a quota system would clearly
48 entail extra costs to the extent that marginal abatement costs will differ among
49 countries. Cost effective candidates for an international agreement are tradable quotas
50 and international or harmonised domestic carbon taxes.

51 10.7.3 Comparing International Tradable Quotas and Tax Systems

52
53 As outlined above, in many situations economic-incentive policies can lead to lower
54 total pollution control costs and spur greater technological innovation than conventional
55 regulatory approaches. Which incentive-based instrument is most effective, however,
56 will depend on a number of specific factors. The broadest set of possible international
57 applications is considered below.

1
2 A system of harmonised domestic carbon taxes would involve an agreement about
3 compensatory international financial transfers as well as the pre-carbon-tax net tax rates
4 on fossil fuels. These taxes would represent (at least) what amounts to an estimate of the
5 domestic environmental effects of fossil fuel combustion. Internationally acceptable
6 estimates of these basic tax levels, which would tend to differ between countries, would
7 be difficult to establish. Moreover, no design seems feasible and generally acceptable
8 where participants are not allowed to undertake policies on their own which indirectly
9 affect fossil fuel use, such as levying a tax on substitutes to carbon and subsidising
10 complements to carbon (Hoel 1993c). Thus, there are significant risks that a tax
11 harmonisation agreement would either never be adopted or fail after implementation
12 (Bohm 1993b).

13
14 A system of international taxes, where all participating countries were liable to pay a
15 given carbon tax, could include an agreement on how tax receipts would be shared
16 among the participants. Under such a system countries might retain all or part of the
17 taxes raised domestically and some participants (low income countries) might receive a
18 transfer (Hoel 1993c). Each country would have a good knowledge of the amount of tax
19 revenue likely to be raised internally. However, less information would be available
20 about other countries' tax revenues and hence there would be uncertainty about the size
21 of the net transfers to and from each country.

22
23 A tradable quota scheme, moreover, leaves each participant to decide what domestic
24 policy to use. Such a scheme does not require any ongoing side payments. Here, the
25 initial allocation of quota entitlements among countries reflects distributional
26 considerations. A disadvantage of a tradable quota scheme is that the (endogenous)
27 future prices in international quota trade are unknown when an agreement on the quota
28 allocation is reached. Hence, the exact distributional implications cannot be known
29 beforehand. This is the price paid for the main advantage of such a scheme, namely that
30 the resulting global emissions will be known with certainty for a global agreement and,
31 net of carbon leakage, for a non-global agreement.

32 10.7.4 Comparing Domestic Tradable Permits and Domestic Tax Systems

33
34 Both taxes and tradable permits impose costs on industry and consumers.²⁵ Both taxes
35 and tradable permits force firms to internalise the costs of their pollution. Practically
36 speaking, this means that firms will experience financial outlays, either through
37 expenditures on pollution controls or through cash payments (buying permits or paying
38 taxes). Taxes and permit prices (especially when permits are auctioned by the
39 government) tend to make these costs more visible to industry and the public. This may
40 be problematic for political reasons, although in the long run it has the advantage of
41 clearly signalling and educating the public about the costs and tradeoffs associated with
42 various levels of environmental control.

43
44 In principle, there need be no difference between domestic carbon taxes and tradable
45 carbon permits from a distributional point of view. Moreover, what was earlier called
46 tax recycling and a 'double dividend' for carbon taxes can exist to the same extent for a
47 permit system. Tradable permits may be grandfathered, in the short run, to (partly)
48 compensate existing firms that may have not been sufficiently forewarned about the
49 new policy. This choice corresponds to a tax scheme where, in a period of transition, all
50 carbon tax revenues are redistributed to the firms that would have received free permits
51 under a permit scheme. Alternatively, or after a period of transition is over, no
52 compensation at all would be paid. This would amount to a tax system where the
53 government kept the tax revenue (and used it for unrelated purposes) or a permit
54

²⁵ Compared with conventional command-and-control regulations, both taxes and permits provide an explicit price signal about the marginal cost of limiting emissions.

scheme where all permits were auctioned and the government retained the sales revenue. Partial matching versions of each type of scheme might also be imagined.

Under a tradable permit system, policy makers determine how much total pollution can occur (through the issuance of permits). Taxes control the maximum amount that a firm may pay for each increment of emissions, but they do not dictate with certainty how much control will actually occur.

The lack of control over emission levels with taxes could be a distinct disadvantage in terms of an international agreement. Taxes would have to be varied frequently given the inadequate information base of the authorities to determine the appropriate tax level and the need for adjustments in response to changes in the level of economic activity and changes in relative and absolute price levels. The need for frequent changes in tax levels would add to business uncertainty.

Tradable permit systems may be more susceptible to 'strategic' behaviour than tax systems. In order for a tradable permit system to work effectively, relatively competitive conditions must exist in the permit (and product) market. The degree of competition will help determine the amount of trading that occurs and the cost savings that will be realised. Should any one firm control a significant share of the total number of permits, their activities may influence permit prices. Firms might attempt to manipulate permit prices to improve their positions in the permit market (say, by withholding permits and forcing others to cut production or keeping new entrants out). These risks would be reduced by: (a) using time-limited permits — that is, permits for emissions for a period of say five years, which might be in line with the design of an existing international tradable quota scheme;²⁶ and (b) the government auctioning permits.²⁷

Tradable permits appear to have some advantage over taxes when time and uncertainty are introduced into the analysis. Under a tax scheme, there would be a high level of uncertainty about investment in emission intensive activities with long payback periods such as coal fired power stations and research and development in technologies to reduce emissions. Such uncertainty would arise from uncertainty about the future nominal level of the tax and the impact of that tax given possible changes in relative prices, the absolute level of prices and the level of economic activity.

A tradable permit scheme can be designed to reduce uncertainty about the future in a number of ways. One approach would be to issue permits with different durations (Beitram 1992) or for a set of future (for example, five-year) periods. Firms undertaking emission intensive investments with long payback periods would be able to reduce uncertainty about future costs by buying permits for the desired number of periods. The development of a forward or futures market for permits (that could be coupled with permits of different duration) would provide an even better mechanism to spread the risks associated with uncertainty about future policy toward emissions. Firms undertaking research and development into technologies to reduce emissions would be able to hedge the risks associated with the payoff from such technologies through operations in the futures market (Epstein and Gupta 1990). Similarly, firms investing in emission intensive activities would be able to hedge against the risks of future policy changes through futures markets operations.

²⁶ Granting permits for moving periods of say five years as compared with eternal permits would reduce the possibility of a monopolist hoarding permits and 'forever' exposing future buyers to leasing permits at monopoly prices.

²⁷ Auctioning could be used to help avoid a situation under grandfathering where one large firm was allocated a significantly large share of permits.

To summarise, permits may be somewhat more effective than taxes in achieving given emission targets. The lack of control over emissions with taxes could be a disadvantage. The frequent changes in taxes that may be required would add to business uncertainty. Permits may be more susceptible to strategic manipulation than taxes but this problem can be reduced, as explained above. Permits appear to have a distinct advantage in creating the basis for a futures market that could enable a more efficient spreading of the risks about future policy uncertainty.

10.8 Summary

The following main points can be drawn from the above analysis:

- Policy instruments for global climate change must be identified at two different levels: those that might be used by a coalition of countries and those that might be used by individual nations unilaterally or to achieve compliance with a multilateral agreement on greenhouse targets.
- Governments may have different sets of criteria for assessing international as well as domestic greenhouse policy instruments. Among these criteria are efficiency/cost effectiveness, distributional (including intergenerational) equity, flexibility in the face of new knowledge, understandability to the general public and consistency with national institutions and traditions.
- A coalition of nations may choose one or a mix of policy instruments including tradable quotas, feasible forms of joint implementation, harmonised domestic carbon taxes, international carbon taxes, non-tradable quotas and various international standards. At both the international and national levels, market-based approaches are likely to be more cost effective than other instruments. At the international level, all of the potentially efficient tax or quota solutions should be available to facilitate future negotiations. The cases of harmonised domestic carbon taxes and an international carbon tax (both coupled with international 'side-payments') seem to be more complicated and less flexible than a tradable carbon quota system. For a global treaty, a tradable quota system is the only potentially efficient arrangement where an agreed level of emissions is attained with certainty (subject to enforcement).
- In principle, individual countries can choose from among a large set of available instruments, including carbon taxes, tradable permits and deposit refund systems as well as technology standards, performance standards and product bans. A choice of tradable quotas at the international level would provide maximum flexibility for instrument choice at the domestic level.
- The consequences of climate change policy will be determined by the choice of policy instrument as well as the design and implementation of those policies.

10.9 References

- Anderson, R., 1993: Joint implementation of climate change measures: an examination of some issues. Paper presented at a Workshop on the Experience of the Norway/Mexico/Poland Joint Implementation Demonstration Projects, Mexico, October 28-29, Global Environmental Facility, Washington, DC.
- Anderson, R., L. Hofmann and M. Rusin, 1990: *The Use of Economic Incentive Mechanisms in Environmental Management*. Research Paper no. 51, American Petroleum Institute, Washington, DC, June.
- Atkinson, S. and T. Tietenberg, 1991: Market failure in incentive-based regulation: the case of emissions trading. *Journal of Environmental Economics and Management*, vol. 21, pp. 17-31.
- Barrett, S., 1992a: *Convention on Climate Change: Economic Aspects of Negotiations*. OECD, Paris.
- Barrett, S., 1992b: Reaching a CO₂-emission limitation agreement for the community: implications for equity and cost-effectiveness. *European Economy*, Special edition no. 1, pp. 3-24.
- Barrett, S., 1992c: 'Acceptable' allocations of tradeable carbon emission entitlements in a global warming treaty. *Combating Global Warming: Study on a Global System of Tradeable Carbon Emission Entitlements*, UNCTAD (ed.), United Nations, New York, pp. 85-113.
- Barrett, S., 1993a: Joint implementation for achieving national abatement commitments in the Framework Convention on Climate Change. Revised draft, London Business School (for the OECD), April 19.
- Barrett, S., 1993b: *The Strategy of 'Joint Implementation' in the Framework Convention of Climate Change*. UNCTAD, United Nations, New York.
- Barrett, S., 1994a: Climate change policy and international trade. Paper presented to the IPCC Workshop on Policy Instruments and their Impacts, Tsukuba, Japan, January 17-20.
- Barrett, S., 1994b: Trade restrictions in international environmental agreements. Working Paper GEC 94-13, Centre for Social and Economic Research on the Global Environment, University of East Anglia and University College London.
- Barrett, S., 1994c: Self-enforcing international environmental agreements. *Oxford Economic Papers*, forthcoming.
- Baumol, W. and W. Oates, 1975: *The Theory of Environmental Policy*. Prentice-Hall, Englewood Cliffs.
- Baumol, W. and W. Oates, 1988: *The Theory of Environmental Policy*. Cambridge University Press, Massachusetts.
- Baumol, W.J. and W.E. Oates, 1979: *Economics, Environmental Quality, and the Quality of Life*. Prentice-Hall, Englewood Cliffs, New Jersey.
- Baumol, W.J., J. Panzer and R. Willig, 1982: *Contestable Markets and the Theory of Industrial Structure*, Harcourt-Brace-Javanovich, New York.
- Beavis, B. and M. Walker, 1983: Random wastes, imperfect monitoring and environmental quality standards. *Journal of Public Economics*, vol. 21, pp. 377-87.
- Bell, R.G., and T.A. Kolaja, 1993: Capital privatization and the management of environmental liability in Poland. *The Business Lawyer*, vol. 48, no. 3, pp. 943-961.
- Bertram, G., 1992: Tradeable emission permits and the control of greenhouse gases. *Journal of Development Studies*, vol. 28, no. 3, pp. 423-46.
- Binswanger, H., 1989: *Brazilian Policies that Encourage Deforestation in the Amazon*. World Bank Environment Department Paper no. 16, Washington, DC.
- Bodansky, D. 1993: The United Nations Framework Convention on Climate Change: a commentary. *Yale Journal of International Law*, vol. 18, pp. 451-558.
- Boero, G., R. Clarke and L.A. Winters, 1991: *The Macroeconomic Consequences of Controlling Greenhouse Gases: A Survey*. Crown Copyright, London.
- Bohi, D.R. and D. Burtraw, 1992: Utility investment behavior and the emission trading market. *Resource Engineering*, vol. 14, pp. 129-53.
- Bohm, P. and B. Larsen, 1993: Fairness in a tradeable-permit treaty for carbon emissions reductions in Europe and the Former Soviet Union. *Environmental and Resource Economics*, forthcoming.
- Bohm, P. and C. Russell, 1985: Comparative analysis of alternative policy instruments. *Handbook of Natural Resource and Energy Economics*, vol. 1, A. Kneese and J. Sweeney (eds), North-Holland, Amsterdam.
- Bohm, P., 1981: *Deposit-Refund Systems: Theory and Applications to Environmental, Conservation and Consumer Policy*. Johns Hopkins University Press, Baltimore, for Resources for the Future, Washington DC.
- Bohm, P., 1982: Controlling refrigerant use of chlorofluorocarbon. *The Economics of Managing Chlorofluorocarbons: Stratospheric and Climate and Climate Issues*, J. Cumberland, J. Hibbs and I. Hoch, (eds), Resources for the Future, Washington, DC.
- Bohm, P., 1988: *Economic Instruments for Reducing CFC Emissions*. Report no. 1988:2, Nordic Council of Ministers, Copenhagen, Denmark.
- Bohm, P., 1990: Efficiency issues and the Montreal Protocol on CFCs. Environment Working Paper no. 40, World Bank, Washington, DC. (Forthcoming in *The Environment and Emerging Development Issues*, P. Dasgupta and K.G. Maler (eds), World Bank.)
- Bohm, P., 1992: Distributional implications of allowing international trade in CO₂ emissions quotas. *The World Economy*, vol. 15, no. 1, pp. 107-14.
- Bohm, P., 1993a: Should marginal carbon abatement costs be equalised across countries? Research Papers in Economics no. 1993-12, Department of Economics, University of Stockholm.

- Bohm, P., 1993b: Making carbon-emissions quota agreements more efficient: joint implementation vs quota-tradeability. Paper presented at IIASA, Laxenberg, October.
- Bohm, P., 1993c: Incomplete international cooperation to reduce CO₂ emissions: alternative policies. *Journal of Environmental Economics and Management*, vol. 24, no. 3, pp. 258-71.
- Bohm, P., 1994a: On the feasibility of joint implementation of carbon emissions reductions. Paper presented to the IPCC Workshop on Policy Instruments and their Impacts, Tsukuba, Japan, January 17-20.
- Bohm, P., 1994b: Efficiency aspects of government revenue implications of carbon taxes and tradeable carbon permits. Paper presented at International Institute of Public Finance, 50th Congress, Cambridge, Massachusetts, August 22-25.
- Bovenberg, L. and R.de Mooij, 1994: Environmental levies and distortionary taxation. *American Economic Review*, September.
- Boyd, R., K. Krutilla and W.K. Viscusi, 1994: Energy taxation as a policy instrument to reduce CO₂ emissions: a net benefit analysis. *Journal of Environmental Economics and Management*, forthcoming.
- Buchanan, J., 1969: External diseconomies, corrective taxes, and market structure. *American Economic Review*, vol. 59, no. 1, pp. 174-7.
- Bull, N., K. Hassett and G. Metcalf, 1993: Who pays broad-based energy taxes? Computing lifetime and regional incidence. Working Paper no. 142, Division of Research and Statistics, Board of Governors of the Federal Reserve System, Washington, DC, September.
- Bureau of Industry Economics (BIE) 1992: *Environmental Regulation: The Economics of Tradeable Permits — A Survey of Theory and Practice*, AGPS, Canberra.
- Burniaux, J.-M., J.P. Martin and J. Oliveira-Martins, 1992a: The effect of existing distortions in energy markets on the costs of policies to reduce CO₂ emissions: evidence from GREEN. *OECD Economic Studies*, no. 19, Winter, pp. 141-65.
- Burniaux, J.-M., J.P. Martin, G. Nicolletti and J. Oliveira-Martins, 1992b: The costs of reducing carbon dioxide emissions: evidence from GREEN. Working Paper no. 115, Economics Department, OECD, Paris.
- Bye, B., T. Bye and L. Lorentsen, 1989: *SIMEN: Studies of Industry, Environment and Energy Towards 2000*. Discussion Paper no. 44, Central Bureau of Statistics, Oslo.
- Cameron, M., 1994: *Efficiency and Fairness on the Road*. Environmental Defense Fund, Oakland, California.
- Carraro, C. and D. Siniscalco, 1993: Strategies for the international protection of the environment. *Journal of Public Economics*, vol. 52, pp. 309-28.
- Chichilnisky, G. and G. Heal, 1993: Global environmental risks. *Journal of Economic Perspectives*, vol. 7, no. 4, Fall, pp. 65-86.

- Chichilnisky, G., G. Heal and D. Starett, 1993: International emission permits: equity and efficiency. Columbia University, November (mimeograph).
- Clinton, W.J. and A. Gore, Jr, 1993: *The Climate Change Action Plan*, Washington, DC.
- Crandall, R.W. 1984: The political economy of clean air: practical constraints on White House review. *Environmental Policy Under Reagan's Executive Order: The Role of Benefit-Cost Analysis*, V. Smith (ed).
- Cristofaro, A. and J. Scheraga, 1990: Policy implications of a comprehensive greenhouse gas budget. United States Environmental Protection Agency, Washington, DC, September (mimeograph).
- Cropper, M. and W. Oates, 1992: Environmental economics: a survey. *Journal of Economic Literature*, vol. 30, no. 2, pp. 675-740.
- Csermely, A., P. Kaderjak, and Z. Lehoczki, 1994: Direct impacts of industrial restructuring on air pollutant and hazardous waste emissions in Hungary. Paper presented at the Fifth Annual Conference of the European Association of Environmental and Resource Economists, Budapest.
- Dasgupta, P., 1982: *The Control of Resources*. Harvard University Press, Cambridge, Mass.
- Dasgupta, P., 1993: *An Inquiry into Well-being and Destitution*. Clarendon Press, Oxford, England.
- Dasgupta, P. and Mäler, 1994: *Poverty, Institutions and the Environmental Resource Base*. Environment Paper no. 9, World Bank, Washington, DC.
- DCEIA (Department of Commerce, Energy Information Administration) 1992: *Federal Energy Subsidies: Direct and Indirect Interventions in Energy Markets*, Washington, DC.
- Dean, A. and P. Hoeller, 1992: Costs of reducing CO₂ emissions: evidence from six global models. *OECD Economic Studies*, Paris, no. 19, Winter, pp. 15-47.
- DeWitt, D. and H. Dowlatabadi and R. Kopp, 1991: *Who Bears the Burden of Energy Taxes?* Discussion Paper QE91-12, Resources for the Future, Washington, DC.
- Dornbush, R. and J.M. Poterba, 1991: *Global Warming: Economic Policy Responses*, MIT Press, Cambridge, Massachusetts.
- Dower, R.C. and Zimmerman, M.B. 1992, *The Right Climate for Carbon Taxes: Creating Economic Incentives to Protect the Atmosphere*, World Resources Institute, August, Washington, DC.
- Dudek, D. and A. LeBlanc, 1990: Offsetting new CO₂ emissions: a first rational greenhouse policy step. *Contemporary Policy Issues*, vol. VIII, no. 3, pp. 29-42.
- Dudek, D., Z. Kulezyski and T. _ylicz, 1993: Implementing tradeable permits in Poland: a case study of Chorzow. In Conference Proceedings of the Third Annual Meeting of the European Association of Environmental and Resource Economists (L. Presisner, ed.), Krakow.

- Dudek, D.J. and LeBlanc, A.** 1992: *Preserving Tropical Forests and Climate: The Role of Trees in Greenhouse Gas Emissions Trading*. The Environmental Defense Fund, New York.
- Epstein, J. and R. Gupta**, 1990: *Controlling the Greenhouse Effect: Five Global Regimes Compared*. Brookings Occasional Papers, Brookings Institution, Washington, DC.
- European Commission** 1994: Taxation, employment and environment: fiscal reform for reducing unemployment. *European Economy*, no. 56, pp. 137-77.
- Flavin, C.**, 1989: *Slowing Global Warming: A Worldwide Strategy*, Worldwatch Paper 91, Worldwatch Institute, Washington, DC, October.
- Fankhauser, S.** 1993, *Greenhouse Economics and the Costs of Global Warming*, PhD Thesis, Department of Economics, University College London.
- Freeman, A. and R. Haveman**, 1971: Water pollution control, river basin authorities, and economic incentives: some current policy issues. *Public Policy*, vol. 19, no. 1, pp. 53-74.
- Goulder, L.**, 1992: Carbon tax design and US industry performance. *Tax Policy and the Economy*, vol. 6, J. Poterba (ed.), MIT Press, Cambridge, Massachusetts.
- Goulder, L.**, 1993: Energy taxes: traditional efficiency effects and environmental implications. *Tax Policy and the Economy*, vol. 8, J. Poterba (ed.), MIT Press, Cambridge, Massachusetts.
- Goulder, L.**, 1995: Effects of carbon taxes in an economy with prior tax distortions. *Journal of Environmental Economics and Management*, forthcoming.
- Green, J. and P. Sands** 1992: Establishing an international system for trading pollution rights. *International Environmental Reporter*, February 12, pp. 80-5.
- Greening, L., L. Schipper and H. Jeng**, 1993: Evaluation of the distributional impacts of energy taxes across regions and socioeconomic groups of the United States. Annual Conference on Energy, pp. 432-43.
- Grubb, M. and J.K. Sebenius**, 1991: Participation, allocation and adaptability in international tradeable emission permit systems for greenhouse gas control. *Proceedings of OECD Workshop on Tradeable Emission Permits to Reduce Greenhouse Gases*, Organisation for Economic Co-operation and Development, Paris, June.
- Grubb, M.**, 1991: *Energy Policies and the Greenhouse Effect*, vol. 1, *Policy Appraisal*, Royal Institute of International Affairs, Dartmouth, England.
- Hahn, R. and Stavins, R.** 1991: Incentive-based environmental regulation: a new era from an old idea? *Ecology Law Quarterly*, vol. 18, pp. 1-42.
- Hahn, R. and Stavins, R.** 1992: Economic incentives for environmental protection: integrating theory and practice. *American Economic Review*, vol. 82, pp. 464-68.

- Hahn, R. and Stavins, R.** 1993: Trading in greenhouse permits: a critical examination of design and implementation issues. Prepared for Clark, W. and Lee, H. (eds.), *Global Climate Policy*, March, John F. Kennedy School of Government, Harvard University, Cambridge, Massachusetts.
- Hahn, R.**, 1984: Market power and transferable property rights. *Quarterly Journal of Economics*, vol. 99, no. 4, pp. 753-65.
- Hahn, R.**, 1988: An evaluation of options for reducing hazardous waste. *Harvard Environmental Law Review*, vol. 12, pp. 201-21.
- Hahn, R.W.** 1989: Economic prescriptions for environmental problems: how the patient followed the doctor's orders. *Journal of Economic Perspectives*, vol. 3, pp. 95-114.
- Hahn, R.W. and G.L. Hester**, 1989a: Marketable permits: lessons for theory and practice. *Ecology Law Quarterly*, vol. 16, pp. 361-406.
- Hahn, R.W. and G.L. Hester**, 1989b: Where did all the markets go? An analysis of EPA's emissions trading program. *Yale Journal on Regulation*, vol. 6, pp. 109-53.
- Hahn, R.W. and R.G. Noll**, 1982: Designing a market for tradable emissions permits. *Reform of Environmental Regulation*, W.A. Magat (ed.), Ballinger Publishing Company, Cambridge, Massachusetts.
- Hanisch, T.**, 1991: Joint implementation of commitments to curb climate change. Policy Note no. 1991:2, CICERO, Oslo.
- Hanisch, T., R. Selrod, A. Torvanger and A. Aaheim**, 1993: Study to develop practical guidelines for 'Joint Implementation' under the UN FCCC. CICERO, Oslo (mimeograph).
- Hanish, T., R. Pachauri, D. Schmitt, and P. Vellinga**, 1992: The climate convention: criteria and guidelines for joint implementation. Policy Note no. 1992:2, CICERO, Oslo.
- Hanslow, K., M. Hinchy, J. Small, B.S. Fisher and D. Gunasekerra**, 1994: Trade and welfare effects of policies to address climate change. Paper presented to the IPCC Workshop on Equity and Social Considerations Related to Climate Change, Nairobi, Kenya, July 18-22.
- Harford, J.D.**, 1978: Firm behavior under imperfectly enforceable pollution standards and taxes. *Journal of Environmental Economics and Management*, vol. 5, pp. 26-43.
- Hasset, K. and G. Metcalf**, 1992: *Energy Tax Credits and Residential Investment*. Working Paper, no. 4020, National Bureau of Economic Research, Cambridge, Massachusetts.
- Hausman, J.**, 1979: Individual discount rates and the purchase and utilization of energy-using durables. *Bell Journal of Economics*, vol. 10, pp. 33-54.
- Heal, G.**, 1992: International negotiations on emission control. *Structural Change and Economic Dynamics*, vol. 3, pp. 223-40.
- Herber, B.P.**, 1992: International environmental taxation in the absence of sovereignty, Wp/92/104, Fiscal Affairs Department, IMF, Washington, DC.

- Hinchy, M. and K. Hanslow, 1994: Optimal greenhouse policy in a multi-country world of growing economies. ABARE paper presented to the Conference of Economists, Economic Society of Australia, Gold Coast, Queensland, September 25-28.
- Hinchy, M., K. Hanslow and B.S. Fisher, 1994a: A dynamic game approach to greenhouse policy: some numerical results. Paper presented to the IPCC Workshop on Policy Instruments and their Impacts, Tsukuba, Japan, January 17-20.
- Hinchy, M., K. Hanslow, and B.S. Fisher, 1994b: A dynamic game approach to greenhouse policy: more numerical results. Paper presented to the Tasman Institute Conference on Environmental Health and Economic Wealth: Conflict or Concord?, Canberra, March 15-16.
- Hinchy, M., S. Thorpe and B.S. Fisher, 1993: *A Tradable Emissions Permit Scheme*. ABARE Research Report 93.5, Canberra, Australia.
- Hirst, E. 1993, 'Price and cost impacts of utility DSM programs', *The Energy Journal*, vol. 13, no. 4, pp. 75-94.
- Hoel, M. and I. Isaksen, 1993: Efficient abatement of different greenhouse gases. Memorandum no. 5, Department of Economics, University of Oslo, April.
- Hoel, M., 1992: International environmental conventions: the case of uniform reductions of emissions. *Environmental and Resource Economics*, vol. 2, pp. 141-59.
- Hoel, M., 1993a: Efficient climate change policy in the presence of free riders. Memorandum no. 4, Department of Economics, University of Oslo, April.
- Hoel, M., 1993b: Should a carbon tax be differentiated across sectors?. Memorandum no. 9, Department of Economics, University of Oslo, June.
- Hoel, M., 1993c: Harmonization of carbon taxes in international climate agreements. *Environmental and Resource Economics*, vol. 3, no. 3, June, pp. 221-32.
- Horowitz, M. and H. Haeri, 1990: Economic efficiency v energy efficiency: do model conservation standards make good sense? *Energy Economics*, vol. 12, no. 2, pp. 122-31.
- Horton, G., J. Rollo and A. Ulph, 1992: The implications for trade of greenhouse gas emission control policies. Working Paper prepared for UK Department of Trade and Industry, London.
- Houghton, R., 1992: A blueprint for monitoring the emissions of carbon dioxide and other greenhouse gases from tropical deforestation. Woods Hole Research Center, Woods Hole, Massachusetts (mimeograph).
- Howden, M. and R. Munro, 1994: Methane from Australian livestock: implications for industry and climate change. *Resource Sciences Interface*, no. 4, pp. 5-9.
- Howe, C., 1994: Taxes versus tradable discharge permits: a review in the light of the US and European experience. *Environmental and Resource Economics*, vol. 3, forthcoming.

- IIASA (International Institute for Applied Systems Analysis), 1992a: *Proceedings of the International Conference on Economic Instruments for Air Pollution Control, Plenary Sessions*. vol. 1, Laxenburg, Austria, October 18-20.
- IIASA 1992b: *Parallel Sessions*. vol. 2, Laxenburg, Austria, October 18-20.
- Ingham, A., A. Ulph and D. Ulph, 1993: Carbon taxes and energy markets. Nota di Lavoro 2.93, Fondazione ENI Enrico Mattei, Milan, Italy.
- International Energy Agency, (1993): *Taxing Energy: Why and How*. Economic Analysis Division, OECD, Paris.
- IPCC (Intergovernmental Panel on Climate Change) 1990: *Climate Change: The IPCC Scientific Assessment*, Cambridge University Press, Massachusetts.
- IPCC 1992: *Climate Change: The Supplementary Report to the IPCC Scientific Assessment*. Cambridge University Press, Massachusetts.
- Jaffe, A. and R. Stavins, 1991: *Evaluating the Relative Effectiveness of Economic Incentives and Direct Regulation for Environmental Protection: Impacts on the Diffusion of Technology*. Discussion Paper no. QE1-11, Resources for the Future, Washington, DC.
- Jaffe, A. and R. Stavins, 1993: Prices, regulation and energy conservation. Paper presented at the Conference on Market-Based Approaches to Environmental Protection, Stanford University, December 3.
- Jaffe, A. and R. Stavins 1994a: The energy paradox and the diffusion of conservation technology. *Resource and Energy Economics*, vol. 16, no. 2, pp. 91-122.
- Jaffe, A. and R. Stavins, 1994b: The energy efficiency gap: what does it mean? *Energy Policy*, forthcoming.
- Jaffe, A. and R. Stavins, 1994c: Energy-efficiency investments and public policy. *Energy Journal*, vol. 15, no. 2, pp. 1-23.
- Jaffe, A. and R. Stavins, 1994d: Environmental regulation and technology diffusion: the effects of alternative policy instruments. Working paper, John F. Kennedy School of Government, Harvard University, Cambridge, Massachusetts, June.
- Jaffe, A., P. Peterson, P. Portney and R. Stavins, 1995: Environmental regulation and the competitiveness of U.S. manufacturing. *Journal of Economic Literature*, forthcoming.
- Jochem, E. and E. Gruber, 1990: Obstacles to rational electricity use and measures to alleviate them. *Energy Policy*, May.
- Johnson, I., 1993: Operational criteria for joint implementation: a response. Paper presented to the International Conference on the Economics of Climate Change, OECD/IEA, Paris, June 14-16.
- Jones, B.P. and P. Tobler, 1993: Policy measures to achieve greenhouse targets. ABARE paper presented at the National Agricultural and Resources Outlook Conference, Canberra, February 2-4.

- Jones, T.**, 1993: Operational criteria for joint implementation. Paper presented to the International Conference on the Economics of Climate Change, OECD/IEA, Paris, June 14-16.
- Jorgenson, D. and P. Wilcoxon**, 1992: Reducing US carbon dioxide emissions: an assessment of different instruments. Discussion Paper no. 1590, Harvard Institute of Economic Research, April. (Forthcoming in the *Journal of Policy Modelling*, vol. 15, nos 5&6.)
- Jorgenson, D. and P. Wilcoxon**, 1994: The economic effects of a carbon tax. Paper presented to the IPCC Workshop on Policy Instruments and their Implications, Tsukuba, Japan, January 17-20.
- Jorgenson, D., D. Slesnick, and P. Wilcoxon**, 1992: Carbon taxes and economic welfare. *Brookings Papers on Economic Activity: Microeconomics*, pp. 393-431.
- Joskow, P. and Marron, D.** 1993, What does a megawatt really cost? Evidence from utility conservation programs. *The Energy Journal*, vol. 13, no. 4, pp. 41-74.
- Kahn, A.** 1992, Least cost planning generally and DSM in particular. *Resources and Energy*, vol. 14, pp. 177-85.
- Katz, M.** 1992, Demand side management: reflections of an irreverent regulator. *Resources and Energy*, vol. 14, pp. 187-203.
- Keeler, A.G.**, 1991: Noncompliant firms in transferable discharge permit markets: some extensions. *Journal of Environmental Economics and Management*, vol. 21, pp. 180-9.
- Kohn, R.W.**, 1991: Transactions costs and the optimal instrument and intensity of air pollution control. *Policy Sciences*, vol. 24, pp. 315-32.
- Koopmans, G., M. Mors, and J. Scherp**, 1992: The likely economic impact of the proposed carbon/energy tax in the European Community. Paper presented to an International Workshop on Costs, Impacts and Possible Benefits of CO₂ Mitigation, Laxenburg, Austria, September 28-30.
- Krause, F.**, 1989, *Energy Policy in the Greenhouse: From Warming Fate to Warming Limit - Benchmarks for a Global Climate Convention*, Dutch Ministry of Housing, Physical Planning and Environment and the European Environmental Bureau, The Hague, The Netherlands.
- Krupnick, A., M. Walls and H. Hood**, 1993: The distributional and environmental implications of an increase in the federal gasoline tax. Discussion Paper ENR 93-24, Resources for the Future, Washington, DC.
- Krutilla, K.**, 1991: Environmental regulation in an open economy. *Journal of Environmental Economics and Management*, vol. 20, no. 2, pp. 127-42.
- Kuik, O., P. Peters, and N. Schrijver (eds)**, 1994: *Joint Implementation to Curb Climate Change: Legal and Economic Aspects*, Kluwer Academic Publishers, Dordrecht/Boston/London.
- Larsen, B. and A. Shah**, 1992: World fossil fuel subsidies and global carbon emissions. Policy Research Working Paper Series no. 1002, World Bank, Washington, DC.
- Larsen, B. and A. Shah**, 1994a: Global climate change, economic policy instruments and developing countries. Paper presented to the 50th Congress of the International Institute of Public Finance, Cambridge, MA, 22-25 August.
- Larsen, B. and A. Shah** 1994b: *Global Tradeable Carbon Permits, Participation Incentives and Transfers*. World Bank, April 19, Washington, DC.
- Lashof, D. and D. Ahuja**, 1990: Relative contributions of greenhouse gas emissions to global warming. *Nature*, vol. 344, pp. 529-31.
- Leary, N. and J. Scheraga**, 1994: Policies for the efficient reduction of CO₂ emissions. *International Journal of Global Energy Issues*, vol. 6, nos. 1/2, pp. 103-7.
- Lenstra, W. and M. Bonney**, 1994: The role of regulation in Dutch climate change policy. Paper presented to the IPCC Workshop on Policy Instruments and Their Implications, Tsukuba, Japan, January 17-20.
- Liroff, R.A.**, 1989: The evolution of transferrable emission privileges in the United States. Paper presented at the Workshop on Economic Mechanisms for Environmental Protection, Jelenia Gora, Poland.
- London Economics**, 1993: *Study of Economic Policy Instruments for the Control of Air Pollution in Poland*, London.
- Magat, W.A.**, 1979: The effects of environmental regulation on innovation. *Law and Contemporary Problems*, vol. 43, pp. 4-25.
- Mahar, D.**, 1988: *Government Policies and Deforestation in Brazil's Amazon Region*. Environment Department Working Paper no. 7, World Bank, Washington, DC.
- Malueg, D.**, 1990: Welfare consequences of emission credit trading programs. *Journal of Environmental Economics and Management*, vol. 18, no. 1, pp. 66-77.
- Manne, A.S. and R.G. Richels**, 1991: International trade in carbon emission rights: a decomposition procedure. *AEA Papers and Proceedings*, vol. 81, no. 2, pp. 135-9.
- Markandya, A.**, 1994: Environmental taxation: a review of experience in economies in transition. Paper presented at the 50th Congress of the International Institute of Public Finance, Cambridge, Mass.
- Markusen, J.**, 1975: International externalities and optimal tax structure. *Journal of International Economics*, vol. 5, no. 1, pp. 15-29.
- McCann, R.J. and S.J. Moss** 1993, *Nuts and Bolts: The Implications of Choosing Greenhouse-Gas Emission Reduction Strategies*. Policy Study no. 171, Reason Foundation, Los Angeles, California.
- Miller, A. and I. Mintzer**, 1986: *The Sky is the Limit: Strategies for Protecting the Ozone Layer*. Research Report no. 3, World Resources Institute, Washington, DC.

- 1 **Ministry of Trade and Industry (MITI)**, 1993: Technology renaissance for the
2 environment and energy. Special Committee on Energy and Environment,
3 Government of Japan, Tokyo, September (mimeograph).
- 4 **Mintzer, I.**, 1988: Living in a warmer world: challenges for policy analysis and
5 management. *Journal of Policy Analysis and Management*, vol. 7, no. 3, 445-
6 59.
- 7 **Misiolek, W. and E. Elder**, 1989: Exclusionary manipulation of markets for
8 pollution rights. *Journal of Environmental Economics and Management*, vol.
9 16, no. 2, pp. 156-66.
- 10 **National Academy of Sciences** 1992: *Policy Implications of Greenhouse*
11 *Warming: Mitigation, Adaptation, and the Science Base*. National Academy
12 Press, Washington, DC.
- 13 **Newcombe, K.**, 1989: An economic justification for rural afforestation.
14 *Environmental Management and Economic Development*, G. Schramm and J.
15 Warford (eds), Johns Hopkins Press for the World Bank, Washington, DC.
- 16 **Nordhaus, W.**, 1991: The costs of slowing climate change: a survey. *Energy*
17 *Journal*, vol. 12, no. 1, pp. 37-64.
- 18 **Oates, W. and D. Strassman**, 1984: Effluent fees and market structure. *Journal of*
19 *Public Economics*, vol. 24, no. 1, pp. 29-46.
- 20 **OECD (Organisation for Economic Co-operation and Development)**, 1989:
21 *Economic Instruments for Environmental Protection*, Paris.
- 22 **OECD**, 1992, *Convention on Climate Change: Economic Aspects of*
23 *Negotiations*. Paris.
- 24 **OECD**, 1992a: *Climate Change: Designing a Practical Tax System*, Paris.
- 25 **OECD**, 1992b: *Climate Change: Designing a Tradeable Permits System*, Paris.
- 26 **OECD**, 1993: *International Economic Instruments and Climate Change*, Paris.
- 27 **OECD**, 1994: *Taxation and the Environment in European Economies in Transition*,
28 Paris.
- 29 **Oliveira-Martins, J., J.-M. Burniaux, and J.P. Martin**, 1992: Trade and the
30 effectiveness of unilateral CO₂ abatement policies: evidence from GREEN.
31 *OECD Economic Studies*, no. 19, Winter, pp. 123-40.
- 32 **Parikh, J.**, 1993: Joint implementation: a southern perspective. Indira Ghandi
33 Institute of Development Research, Bombay, August.
- 34 **Parson, E. and R. Zeckhauser**, 1992: Co-operation in the unbalanced commons.
35 John F. Kennedy School of Government, Harvard University, Cambridge,
36 Massachusetts (mimeograph). (Forthcoming in *Barriers to the Negotiated*
37 *Resolution of Conflict*, Arrow et al. (eds), Norton, New York.)
- 38 **Pearce, D. and J. Warford**, 1993: *World Without End*. Oxford University Press,
39 England.
- 40 **Pearce, D.**, 1991: The role of carbon taxes in adjusting to global warming.
41 *Economic Journal*, vol. 101, July, pp. 938-48.
- 42 **Pearson, M. and S. Smith**, 1991: *The European Carbon Tax: An Assessment of*
43 *the European Commission's Proposals*, Institute for Fiscal Studies, London.
- 44 **Pearson, M.**, 1992: Equity issues and carbon taxes. *Climate Change: Designing a*
45 *Practical Tax System*, OECD Documents, Paris.
- 46 **Peck, S. and T. Teisberg**, 1993: Global warming uncertainties and the value of
47 information: an analysis using CETA. *Resource and Energy Economics*, vol.
48 15, no. 1, pp. 87-107.
- 49 **Pezzey, J.**, 1992: Analysis of unilateral CO₂ control in the European Community
50 and OECD. *Energy Journal*, vol. 13, no. 3, pp. 159-71.
- 51 **Pillet, G., W. Hediger, S. Kypreos, and C. Corbaz**, 1993: *The Economics of*
52 *Global Warming*. Paul Scherrer Institute, Villigen PSI, Switzerland.
- 53 **Pindyck, R.**, 1991: Irreversibility, uncertainty, and investment. *Journal of*
54 *Economic Literature*, vol. 29, no. 3, pp. 1110-48.
- 55 **Polinsky, A. M. and Shavell, S.** 1979: The optimal tradeoff between the
56 probability and magnitude of fines. *American Economic Review*, vol. 59, no. 5,
57 pp. 880-91.
- 58 **Polinsky, A.M. and S. Shavell** 1982: Pigouvian taxation with administrative
59 costs. *Journal of Public Economics*, vol. 19, pp. 385-94.
- 60 **Poterba, J.**, 1993: Global warming policy: a public finance perspective. *Journal*
61 *of Economic Perspectives*, vol. 7, no. 4, Fall, pp. 47-63.
- 62 **Poterba, J.M.**, 1990: Is the gasoline tax regressive? NBER Working Paper no.
63 3578, Cambridge, Massachusetts.
- 64 **Poterba, J.M.**, 1991: Tax policy to combat global warming: on designing a
65 carbon tax. Working Paper no. 3649, National Bureau of Economic Research,
66 Cambridge, Massachusetts.
- 67 **Rajah, N. and S. Smith**, 1993: Taxes, tax expenditures, and environmental
68 regulation. *Oxford Review of Economic Policy*, vol. 9, no. 4, pp. 41-64.
- 69 **Ranganathan, H., Neue, H.-U. and Pingali, P.** 1994: Global climate change: role
70 of rice in methane emissions and prospects for mitigation. International Rice
71 Research Institute, Manila, March.
- 72 **Reddy, A.**, 1993: Operational criteria for joint implementation: a response. Paper
73 presented to the International Conference on the Economics of Climate Change,
74 OECD/IEA, Paris, June 14-16.
- 75 **Repetto, R.**, 1986: *Skimming and Water: Rent-Seeking and the Performance of*
76 *Public Irrigation Systems*, World Resources Institute, Washington, DC.
- 77 **Repetto, R., R. Dower, R. Jenkins, and J. Geoghegan**, 1992: *Green Fees: How a*
78 *Tax Shift Can Work for the Environment and the Economy*. World Resources
79 Institute, Washington, DC.

- Richels, R. and J. Edmonds, 1994:** The economics of stabilizing atmospheric CO₂ concentrations. Paper presented to the IPCC Workshop on Policy Instruments and their Implications, Tsukuba, Japan, January 17-20.
- Russell, C., 1988:** Economic incentives in the management of hazardous wastes. *Columbia Journal of Environmental Law*, vol. 13, pp. 257-74.
- Russell, C.S. 1990:** Monitoring and enforcement. *Public Policies for Environmental Protection*, P. Portney (ed.), Johns Hopkins University Press, Baltimore, ch. 7.
- Russell, C.S., W. Harrington, and W.J. Vaughan, 1986:** *Enforcing Pollution Control Laws*. Johns Hopkins University Press, 1-90, Baltimore.
- Sandor, R., J. Cole, and E. Kelly, 1994:** *Study on Model Rules and Regulation for a Global CO₂ Emissions Credit Market*. UNCTAD.
- Schackleton, R., M. Shelby, A. Cristofaro, R. Brinner, J. Yanchar, L. Goulder, D. Jorgenson, P. Wilcoxon, P. Pauly, and R. Kaufman, 1992:** The efficiency value of carbon tax revenues. United States Environmental Protection Agency, Washington, DC (mimeograph).
- Scheraga, J. and N. Leary, 1992:** Improving the efficiency of policies to reduce CO₂ emissions. *Energy Policy*, vol. 20, no. 5, pp. 394-404.
- Scherer, F.M., 1980:** *Industrial Market Structure and Economic Performance*. Rand-McNally College Publishing, Chicago.
- Schillo, B., L. Giannarelli, D. Kelly, S. Swanson and P. Wilcoxon, 1992:** The distributional impacts of a carbon tax. Drafting Working Paper, Energy Policy Branch, US Environmental Protection Agency, February.
- Schmalensee, R., 1993:** Comparing greenhouse gases for policy purposes. *Energy Journal*, vol. 14, pp. 245-55.
- Schmalensee, R., 1994:** The costs of environmental protection. *Balancing Economic Growth and Environmental Goals*. M.B. Kotowski (ed.), American Council for Capital Formation Center for Policy Research, Washington, DC, pp. 55-75, forthcoming.
- Schramm, G., 1992:** Issues and problems in the power sector of developing countries. World Bank, Washington, DC (mimeograph).
- Sedjo, R., 1994:** Forests to capture carbon: tradeable permit schemes. Paper presented to the IPCC Workshop on Policy Instruments and their Implications, Tsukuba, Japan, January 17-20.
- Semeniene, D. and A. Kundrotas, 1994:** From theory to practice: environmental taxes in a time of economic uncertainty. Paper presented at the 50th Congress of the International Institute of Public Finance, Cambridge, Mass.
- Shah, A. and B. Larsen, 1992:** Carbon taxes, the greenhouse effect and developing countries. Working Paper WPS 957, Policy Research Division, World Bank, Washington, DC.
- Shibata, H. and S. Winrich, 1983:** Control of pollution when the offended defend themselves. *Economica*, vol. 50, pp. 425-37.

- Sigman, H., 1991:** A comparison of public policies for lead recycling. Department of Economics, MIT, Cambridge, Massachusetts, November (mimeograph).
- Sinclair, P. 1992:** 'High does nothing and rising is worse: carbon taxes should decline to cut harmful emissions', *Manchester School of Economic and Social Studies*, vol. 60, no. 1, pp. 41-52.
- Sioshansi, F., 1992:** Demand side management and environmental externalities: ramifications on utility resource planning. *Utilities Policy*, vol. 2, no. 4, pp. 321-25.
- Smith, S., 1992a:** The distributional consequences of taxes on energy and the carbon content of fuels. *European Economy: The Economics of Limiting CO₂ Emissions*, Special Edition no. 1, Commission for the European Communities, Brussels.
- Smith, S., 1992b:** Distributional effects of a European carbon tax. Nota di Lavoro 22.92, Fondazione ENI Enrico Mattei, Milan, Italy.
- Stavins, R. (ed.) 1988:** *Project 88 - Harnessing Market Forces to Protect Our Environment: Initiatives for the New President*. Public Policy Study sponsored by Senator Timothy E. Wirth, Colorado, and Senator John Heinz, Pennsylvania. Washington, DC, December.
- Stavins, R. and B. Whitehead, 1992:** Pollution charges for environmental protection: a policy link between energy and environment. *Annual Review of Energy and the Environment*, vol. 17, pp. 187-210.
- Stavins, R. and T. Lylicz, 1994:** Environmental policy instrument design in a transition economy. Working paper, John F. Kennedy School of Government, Harvard University, Cambridge, Mass.
- Stavins, R., (ed.) 1991:** *Project 88 - Round II, Incentives for Action: Designing Market-Based Environmental Strategies*. Public Policy Study sponsored by Senator Timothy E. Wirth, Colorado, and Senator John Heinz, Pennsylvania. Washington, DC, May.
- Stavins, R.N., 1983:** *Trading Conservation Investments for Water*. Environmental Defense Fund, Berkeley, California.
- Stavins, R.N., 1994a:** Transaction costs and tradeable permits. Paper presented at the annual meeting of the American Economic Association, January, Boston, Massachusetts. (Forthcoming in the *Journal of Environmental Economics and Management*.)
- Stavins, R.N., 1994b:** A revealed-preference approach for estimating the CO₂-sequestration supply function. Working paper, John F. Kennedy School of Government, Harvard University, Cambridge, Massachusetts, September.
- Stewart, R. and J. Wiener, 1992:** The comprehensive approach to global climate policy: issues of design and practicality. *Arizona Journal of International and Comparative Law*, vol. 9, pp. 85-113.
- Sutherland, R., 1991:** Market barriers to energy-efficiency investments. *Energy Journal*, vol. 12, no. 3, pp. 15-34.

- Tahvonen, O. and J. Kuuluvainen**, 1993: Economic growth, pollution and renewable resources. *Journal of Environmental Economics and Management*, vol. 24, no. 2, pp. 101-18.
- Tietenberg, T. and D. Victor**, 1994: Implementation issues for a tradeable permit approach to controlling global warming. Paper presented to the IPCC Workshop on Policy Instruments and their Impacts, Tsukuba, Japan, January 17-20.
- Tietenberg, T.**, 1985: *Emissions Trading: An Exercise in Reforming Pollution Policy*. Resources for the Future, Washington, DC.
- Tietenberg, T.**, 1990: Economic instruments for environmental regulation. *Oxford Review of Economic Policy*, vol. 6, no. 1, pp. 17-33.
- Tietenberg, T.**, 1992: *Environmental and Natural Resource Economics*. Harper Collins, New York.
- Tietenberg, T.H.**, 1980: Transferable discharge permits and the control of stationary source air pollution: a survey and synthesis. *Land Economics*, vol. 56, pp. 391-416.
- Treadwell, R., S. Thorpe, and B. Fisher**, 1994: Should we have second thoughts about 'no regrets'? *The Economics of Climate Change: Proceedings of an OECD/IEA Conference*, OECD/IEA, Paris, pp. 255-72.
- Tripp, J.T.B. and D. J. Dudek** 1989: Institutional guidelines for designing successful transferable rights programs. *Yale Journal on Regulation*, vol. 6, pp. 369-91.
- Tripp, J.T.B. and D.J. Dudek**, 1990: Comments on the IPCC Working Group III Economic Measures Paper. Environmental Defense Fund, New York, January.
- Tschirhart, J.T.**, 1984: Transferable discharge permits and profit-maximizing behavior. *Economic Perspectives on Acid Deposition Control*, T.D. Crocker (ed.), Butterworth Publishers, Boston, Massachusetts.
- UNCTAD** (United Nations Conference on Trade and Development), 1992: *Combating Global Warming: Study on a Global System of Tradeable Carbon Emission Entitlements*. United Nations, New York.
- US Congress, Office of Technology Assessment**, 1991: *Changing by Degrees: Steps to Reduce Greenhouse Gases*, OTA, Washington, DC.
- US Environment Protection Agency** 1991: *Economic Incentives: Options for Environmental Protection*. Office of Policy, Planning, and Evaluation, Economic Incentives Task Force, 21P-2001, Washington, DC, March.
- US Environmental Protection Agency** 1989: Policy options for stabilizing global climate. Draft Report to Congress, Washington, DC.
- Victor, D.**, 1991: Limits of market-based strategies for slowing global warming: the case of tradeable permits. *Policy Sciences*, vol. 24, no. 2, pp. 199-222.
- Vousden, N.**, 1990: *The Economics of Trade Protection*. Cambridge University Press, Massachusetts.
- Weitzman, M.L.**, 1974: Prices vs. quantities. *Review of Economics Studies*, vol. 41, pp. 477-91.
- Welsch, H.**, 1992: Carbon taxation in Germany: approaches and prospective effects. Nota di Lavoro 23.92, Fondazione ENI Enrico Mattei, Milan, Italy.
- Weyant, J.**, 1993: Costs of reducing global carbon emissions. *Journal of Economic Perspectives*, vol. 7, no. 4, Fall, pp. 27-46.
- Whalley, J. and R. Wigle**, 1991: The international incidence of carbon taxes. *Global Warming: Economic Policy Responses*, R. Dornbusch and J. Poterba (eds), MIT Press, Cambridge, Massachusetts, pp. 71-97.
- Winters, L.A.**, 1992: The trade and welfare effects of greenhouse gas abatement: A survey of empirical estimates. *The Greening of World Trade Issues*, K. Anderson, and R. Blackhurst (eds), Harvester Wheatsheaf, London.
- Wirth, D. and D. Lashof**, 1990: Beyond Vienna and Montreal - multilateral agreements on greenhouse gases. *Ambio*, vol. 19, pp. 305-10.
- Woodland, A.**, 1982: *International Trade and Resource Allocation*. North-Holland, Amsterdam.
- World Bank**, 1990: Review of electricity tariffs in developing countries. Industry and Energy Department, Washington, DC (mimeograph).
- World Bank**, 1992a: The bank's role in the electric power sector. Washington, DC (mimeograph).
- World Bank**, 1992b: *World Development Report 1992*. Oxford University Press, New York.
- World Resources Institute**, 1991: *World Resources: 1990-91*. Oxford University Press, New York.
- Zeckhauser, R.**, 1981: Preferred policies when there is a concern for probability of adoption. *Journal of Environmental Economics and Management*, vol. 8, pp. 215-37.
- yliez, T.**, 1994a: Implementing environmental policies in Central and Eastern Europe. In *Investing in Natural Capital: The Ecological Economics Approach to Sustainability* (A. Jansson, M. Hammer, C. Folke, and R. Costanza, eds.), Island Press, Wash. D.C.
- yliez, T.**, 1994b: In Poland, it's time for economics. *Environmental Impact Assessment Review*, vol. 14, no. 2,3, pp. 79-94.
- yliez, T.**, 1994c: Pollution taxes as a source of budgetary revenues in economies in transition. Paper presented at the 50th Congress of the International Institute of Public Finance, Cambridge, Mass.

Table 10.1: A Taxonomy of Costs of Environmental Regulation

Government Administration of Environmental Statutes and Regulations
Monitoring Enforcement
Private Sector Compliance Expenditures
Capital Operating
Other Direct Costs
Legal and Other Transactional Shifted Management Focus Disrupted Production
Negative Costs
Natural Resource Inputs Worker Health Innovation Stimulation
General Equilibrium Effects
Product Substitution Discouraged Investment Retarded Innovation
Transition Costs
Unemployment Obsolete Capital
Social Impacts
Loss of Middle-Class Jobs Economic Security Impacts

Source: Jaffe, Peterson, Portney and Stavins (1995).

Table 10.2: A Summary of Empirical Evidence on the Redistributive Impact of Economic Instrument

Instrument	Author	Country	Model	Results
Carbon tax	Bull, Hassett & Metcalf (1993)	United States	Computable dynamic general equilibrium model spending behaviour may adjust	Tax burden is nearly proportional with respect to lifetime income
Carbon tax	DeWitt, Dowlatabadi & Kopp (1991)	United States	Partial equilibrium model; spending behaviour may adjust; expenditure data; no recycling of tax revenues	Distributional impact is regressive and varies across regions
Carbon tax	Jorgenson, Slesnick & Wilcoxon (1992)	United States	Computable general equilibrium model; three stages intertemporal optimization for household consumption	Carbon tax is either mildly progressive or regressive depending on the welfare function used
Carbon tax	Poterba (1991)	United States	Partial equilibrium model; expenditure and income data; expenditure data are used	Carbon tax is regressive, but the impact is smaller if expenditure data are used
Carbon tax	Schillo, Giannarelli, Kelly, Swanson & Wilcoxon (1992)	United States	DECO aggregate macroeconomic model; expenditure data; three	Depending on the compensation system adopted, the carbon tax is regressive to compensation systems neutral
Carbon tax	Schillo, Giannarelli, Kelly, Swanson & Wilcoxon (1992)	United States	Urban Institute's TRIM2 microsimulation model; two compensation systems	Carbon tax is regressive w.r.t. pre-tax income in both scenarios, but it becomes regressive to neutral relative to post-tax income
Carbon tax	Pearson (1992)	Europe	Partial equilibrium model; spending behaviour may/ may not adjust (2 models); Eurostat data	Both models indicate that tax on domestic fuels is regressive, while tax on motor fuels is mildly progressive
Carbon tax	Pearson & Smith (1991)	Europe	IFS model of consumer expenditures, compensation system; spending behaviour may adjust	Ireland and UK show a regressive impact. For other countries, the burden is weakly related to income
Carbon tax	Shah & Larsen (1992)	Pakistan	Partial equilibrium model; income and expenditure, data, three scenarios	Carbon tax incidence is either proportional or progressive in a developing country context
BTU tax	Bull, Hassett & Metcalf (1993)	United States	Computable dynamic general equilibrium model spending behaviour may adjust	Tax burden is nearly proportional with respect to lifetime income

Instrument	Author	Country	Model	Results
Gasoline tax	Greening, Schipper & Jeng (1993)	United States	Partial equilibrium model; expenditure data	Gasoline tax affects negatively mainly older married couples with dependent children. Income distributional results not reported
Gasoline tax	Krupnick, Walls & Hood (1993)	United States	Partial equilibrium econometric model; limited adjusting behaviour	Gasoline taxes are regressive, much more than previous studies since income data are used
Gasoline tax	Poterba (1990)	United States	Partial equilibrium model; expenditure data	Gasoline tax is broadly regressive if the lowest income class is ignored. The latter class devotes a smaller share of their budget to gasoline than the lower-middle income class
Tax on GHG emissions	International Energy Agency (1993)	Europe	Partial equilibrium model; expenditure data	Regressive effect on households if no compensatory measures with respect to domestic heating. Less clear result for motor fuels
Tax on direct fuel expenditure	Smith (1992a,b)	Europe	Partial equilibrium model; expenditure data; spending behaviour may/may not adjust; two compensatory systems	Carbon tax is regressive, but if spending behaviour adjusts its impact is smaller; only lump-sum transfers make the impact progressive
Tax on industrial energy use	Smith (1992b)	United Kingdom	Input-output tables + consumer spending simulation program	Modest effect of changes in prices on consumers spending, but negative especially for low income households

Table 10.3: Carbon Tax Incidence in Developing Countries

Tax incidence with respect to				
Institutional considerations	Implications for tax shifting	Income	Expenditure	Life time income
(a) Foreign ownership and control	Borne by foreign treasury through foreign tax credits	Nil	Nil	Nil
(b) Full market power	Full forward shifting (100% on final consumption)	Regressive (pro-rich)	Less regressive	Less regressive
(c) Price controls and legal pass-forward of the tax disallowed	Zero forward shifting (100% on capital income)	Progressive (pro-poor)	Progressive	Progressive
	Completely inelastic supply	"	"	"
	Reduced rents			
	No effect on prices (100% on capital income)			
(d) An intermediate case of (a) and (b) above	Partial forward shifting (31% to capital income, 69% to final consumption)	Proportional	Progressive	Progressive