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Chap 4 MITIGATION COST

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CHAPTER 3
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

DRAFT

August 15, 1994

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6 FORTHCOMING

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Foreword to Writing Team 6/7 Draft Text

The following text is a preliminary and incomplete draft of the chapter on the cost of GHG emission reduction. It is the first integration of twelve contributions written after three overall meetings of the writing team. This draft is currently circulating among the writing team. Revisions continue to be made and a new version will be brought to Geneva. The results of the Geneva meeting will be discussed in a meeting of the writing team in Paris on September 12.

The delay in achieving a complete version of this chapter is due both to the amount of work involved in reviewing and summarizing all of the costing studies we could find, and to the existence of critical methodological debates which made a consensus judgement on the meaning and value of the studies we reviewed difficult to achieve. Priority was given in this draft to articulating these differences clearly and laying the groundwork for improved consensus in later versions. Because most of the studies, and debates, have concerned GHG emissions associated with the energy system, we have not yet completed our review of studies addressing non-energy GHG sources.

As a result of these factors, although the research and assembly of materials for the whole chapter is essentially complete, this draft is still missing the following subsections:

- subsection 3.3. about the issues raised by non-energy GHG sources with respect to the treatment of technology;
- subsection 4.6, which will summarize the studies concerning non-energy GHG sources;
- a concluding section 5, which will summarize the main findings and issues.

Moreover, some work remains to be done to harmonize the first three sections with section 4, to complete the references, and to put the whole text into a consistent format. Some of this work will be incorporated in the new draft to be brought to Geneva.

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. As a result models that could be used to examine CO₂ emissions were available long before the development of such modeling capability 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 debates 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 (1977, 1979) [INSERT FULL REFERENCE]

² Nordhaus (1977, 1979), Manne (1984) [INSERT FULL REFERENCE]

³ Edmonds-Reilly (1983) [INSERT FULL REFERENCE]

⁴ Lovins, et al (1981) [INSERT FULL REFERENCE]. 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", *Policy Sciences* [INSERT FULL REFERENCE]

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* [INSERT FULL REFERENCE].

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 outcomes. 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. This problem is further complicated by the fact that both the types and the outcomes of the models are the subject of controversy within the modeling community itself.

To help avoid either uncritical acceptance or total distrust of current analyses of emission reduction costs, this chapter will present the results of a detailed review of current literature on the costs of emission reduction in section 4, following a discussion of three main sources of misunderstanding:

- the various concepts of costs used in the literature (section 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 2); and
- the reasons for the current wide range in the results of these cost assessments, and the meaning of competing methodologies for capturing economy-technology linkages (section 3).

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.

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). [ADD OTHER REFERENCES??]

⁷ See, for example, Ascher, W. *Forecasting: An Appraisal for Policy-Makers and Planners*. (Baltimore: Johns Hopkins University Press, 1978). [INSERT 1983 BOOK]

1. The Measurement of Costs

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

In assessing the costs of emission reduction, it is 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 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 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.
- 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; and
- 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 deforestation, 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 strategies. To the extent that such positive side-effects offset the gross costs of specific emission reduction measures, then these measures represent what has been called a "no regrets potential": measures that are worth undertaking whether or not there are climate-related reasons for doing so.⁸ 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 most of the studies discussed in this chapter do not include this category of secondary benefit, and some do not include one or both of the first two categories.

To avoid any possible misunderstanding, 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

⁸ 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.

chapter 3 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 described in chapter 3 (whether these benefits are accounted for in terms of explicit monetary values or purely normative emission reduction targets). Box 1.1 [FORTHCOMING] aims at clarifying the differences between gross costs and net costs and explaining some possible theoretical confusions.

1.2 Taxonomy of Emission Reduction Cost Concepts

In all of the studies reviewed in this chapter, 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 that 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. To understand many critical debates about the costs of climate policies, it is useful to distinguish four type of cost concepts found in the economic literature and used in costing analysis:

1. **the direct or financial 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. These costs represent the "up-front" cost of the measures considered. They depend upon both technico-economic data and the relevant interest rate; and can be calculated in the absence of an explicit scenario but they do not provide an overall cost assessment unless they are fed into a coherent framework that incorporates the costs described below. The calculation of direct costs can be used to construct technology cost curves of the kind described in Figure 1.1.
2. **financial costs for a given sector** Here a sectoral model is used to integrate and determine the consistency of a set of measures, 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. Other sectoral models, such as transportation, forestry, or agriculture models, exist but they have not yet been used extensively for analysis of GHG emission reduction.
3. **macroeconomic costs** measure the impact of a given strategy on gross national product (GNP) or the gross domestic product (GDP). These aggregate indices measure the monetary value added of goods and services produced in single year and provide 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.
4. **welfare costs** Neither financial costs nor GNP variations provide direct measures of human welfare. There are many reasons for this, including the fact that human welfare does not increase linearly with consumption and the nature of the relationship between distribution of income and overall welfare (cf. chapter ???). It

suffices at this stage to mention three well-known gaps between GDP measurements and welfare:

- a given economic growth rate may correspond to various consumption flows and an emission reduction policy requiring the movement of resources from investment to consumption may affect overall welfare for a given level of GDP;
- spending money on disaster relief or environmental rehabilitation enhances economic growth without increasing welfare; and
- methods used to calculate any index of "equivalent welfare" depend on market product calculations and do not account for the goods and services produced by non-market and informal economies.

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 cost does not mean that technology A whose cost is lower than technology B (at the level of direct cost) will be chosen in an optimized electricity system (at the level of a sectoral cost calculation), since an optimization model, aiming at minimizing the overall cost of delivering a given amount of energy, will not select an energy efficiency improvement if this improvement is made in a period of time where the electric supply is in excess. Similarly, a sectoral optimization of a sector may not give the same results as some form of overall macroeconomic optimum if, to give a single example, the effect of the optimized investment in the energy sector is prevent investment in other industries or sectors such as education or health. On the other hand, aggregate macroeconomic analysis of costs may not capture important changes in the underlying technological and behavioural determinants of emission reduction costs to the extent that these changes remain below the level of "noise" of the more general 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,⁹ 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. However, 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). Thus, the cost figures provided by current economic modelling should be interpreted as estimates of losses (or gains) in the overall activity level of an economy, not as estimates of impacts on overall welfare. Such analyses should also indicate clearly the reasons for the choice of the specific cost measurements chosen and suggest the desirability of examining other indicators (unemployment, distribution of income, security and political stability, etc.) when reaching policy-relevant conclusions about GHG emission reduction.

1.3 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

⁹ [CGP, other references]

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.

Even before the adoption of the precautionary principle in the Framework Convention on Climate Change at the UN Conference on Environment and Development in 1992, the core of the debate about GHG emission reduction was about the existence and size of so-called "no-regret strategies". The term "no regrets" is meant to imply that there would be no regrets in adopting the measures in question since they are already cost-effective and thus worth doing even if there were to turn out to be no climate change reasons for doing so. It 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.

The discussion of "no regrets" potential triggered a sensitive policy debate; with proponents of the view that such a potential existed calling for significant policy intervention in energy markets to implement "no regrets" strategies, and critics suggesting that no such intervention is justified since those same energy markets already deliver economically efficient levels of emission reduction potential (i.e. there is no "no regrets" potential). We will come back in section 3 below to a more detailed examination of this debate; here we are concerned only with the degree to which it is related to the choice of the baseline (or reference) scenario and to the choice of the policy mix.

The discussion can be summarized rather simply, though rather abstractly, in graphical form. (See Figure 1.2). 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.¹⁰

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)¹¹. That is, there is

¹⁰ 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) or to a point below and to the right of A (reducing both emissions and economic activity).

¹¹ If increased emission reductions reduce the size of the economy, then those reductions have "cost" society the amount of the reduction in the size of the economy. Put another way, moving down to the right on the curve in Figure 1 is equivalent to saying that, if the resources devoted to emission reduction had been put to other uses, the economy would have grown more. Under such conditions, this reduction in growth is the net economic cost of emission reduction.

no "no regrets" potential. Conversely, moving up to the left on the curve will increase economic activity but also increase emissions. An appropriate policy mix can minimize the net cost of lower emissions but can never offset it totally.¹² However, if the baseline scenario 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); in fact emission reduction policies may both reduce emissions and increase economic activity.

If an economy is below the production frontier, the net cost of preventive policies can be negative until the production frontier is reached. The question is whether the reference or baseline scenario to which emission reduction scenarios are compared is on this frontier or not. Analysts who argue that a "no regrets" potential exists implicitly suggest that any baseline scenario is below the frontier; the policies they propose would move the economy up toward that frontier. Their opponents argue that, if such a potential had existed, it would already have been adopted by the energy marketplace. Such analysis therefore assume that any cost-effective emissions reduction is already embodied in any baseline scenario, which therefore is already on the frontier. In this sense the 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 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 failures; and (iii) that a policy decision is made to eliminate selectively those market 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 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, given the multiple objective that characterize public policy-making, GHG emission reduction policies are likely to be a by-product or joint product of policies developed in part for other reasons.

Figure 1.3 illustrates different views about the relation between cost and emission reduction. Each curve in Figure 1.3 shows how 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. That is 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 (i.e. there exist "no regrets" strategies). Curve C includes only the "negative cost potential" described in section 1.1 above; curve D includes also "economic double dividends" caused, for example, 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.

A final issue has to do with the international dimensions of emission reduction costs. 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. For example, 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.¹³ These international dimensions have been accounted for only partially, if at all, in modelling work 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). More work needs to be done in this area.

¹³ 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. [IS THIS EXAMPLE USEFUL? NEEDED?]

¹² Goulder ref [INSERT FULL REFERENCE]

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 energy technologies used and the underlying technological and socio-economic conditions that give rise to energy demands. Most energy model explore energy options and alternatives, and possible future economic conditions, based upon particular assumptions about the nature of technological change and long-term development paths of the economy. This section of the chapter will explore this latter question in more detail.

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 levels of energy consumption per capita, 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 differences¹⁴ suggest the importance of certain 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;

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

- *structural changes* in the production system and in particular the role of high or low energy intensive industries and services. The energy content of industries such as steel, non ferrous metals, heavy chemistry or paper and pulp is between four and six times the energy content of the other industries. At the other end of the spectrum, a simple phone

¹⁴ [RÉFÉRENCES]

call on a given commodity futures market can generate substantial value added for an insignificant energy content. A shift in the relative size of primary production and service industries in an economy may or may not affect the overall level of economic activity but will have significant implications for energy use.

Of course, these factors are not ignored by current economic models. They are in some way captured by changes in economic parameters such as the structure of household expenses devoted to heating, transportation or food, the share of each activity in the total value added, the share of energy costs and transportation costs in the production function of industrial sectors. This type of treatment is convenient for addressing the questions traditionally posed by policy makers since the beginning of economic modeling just before the second world war¹⁵, to provide information on the consequences of economic policies (of a monetary devaluation, of a fiscal policy, of an incentive to final demand through public investment programs etc.) over the short term (1 to 3 years), or to develop consistent medium term (4 to 10) economic scenarios to frame sectoral planning and policy (mainly in energy and transportation). For these time horizons and objectives it is logical to hold constant, or assume continuation of historical trends in, the main characteristics of development patterns, or the speed and direction of the transformation of these characteristics.

For the longer term periods under consideration in greenhouse debates these assumptions cannot be easily maintained, and economic parameters can not easily be viewed as the sole command variables used to predict the future of our production and consumption systems. For example, a given amount of value added produced by the steel or chemical industries may correspond to very different levels of material production (and thus energy demand) depending upon the level of sophistication of the final product; in the same way, the differences in household budgets devoted to transportation may not fully express the differences in mobility and transportation patterns prevailing between towns with or without public rail transport system, or between car uses in towns with very different levels of congestion.¹⁶

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

In principle, alternative configurations of the factors determining development patterns could be formally combined to give internally consistent scenarios characterized by various physical and technical characteristics and economic equilibria for a given rate of economic growth. Of course, this does not mean that all of these possible scenarios are viable. What matters here is that these underlying technological and consumption pattern factors are

¹⁵ [RÉFÉRENCES]

¹⁶ [INSERT REFERENCES TO STRUCTURAL CHANGE LITERATURE]

critical not only for the definition of the baseline scenario but also for the assessment of actual emission reduction costs for a given emission reduction policy or objective.

The emission reduction costs attached to each possible baseline scenario depend not only on the absolute level of the required emission reduction and on the array of available technologies (energy efficiency, fuel switching, biomass planting, modal choices in transport) but also on the timing of this emission reduction.¹⁷ In this connection, three groups of partly related factors become very important:

- the *flexibility (conversely inertia) of consumption patterns* underlying the activity of GHG-emitting sectors such as energy, transport or cement. This flexibility parameter determines the speed of adaptation to a given economic or non economic signal and encompasses two aspects. The first one is the rate of renewal of existing end-use equipment, which is likely to be an important factor only in the case of buildings, which have longer lifetimes than most capital stock. A more critical inflexibility stems from the systemic linkages between consumption patterns, technology and the spatial distribution of activities. To take an extreme illustration, it would be far more costly to move away from oil-based automobile fuels in big conurbations where urban structure makes the use of cars almost compulsory than in a town of about 40 000 inhabitants where it would be easier to satisfy a significant proportion of intra-urban personal transportation with electric buses and bicycles. Similar considerations apply with respect to the energy supply system, in which the flexibility of policy response is associated with the size and lead times associated with new energy supply technologies. For example, such considerations have prompted the development of methods in the electric power industry whereby such flexibility can be incorporated into electric power planning.¹⁸

- *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 overnight.¹⁹

- *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 this, will tend to increase the costs of emission reduction.

¹⁷ Grubb 1993, Hourcade 1993. [GET FULL REFERENCES]

¹⁸ Northwest Power Planning Council. 1991. "1991 Northwest Conservation and Electric Power Plan", Volume II, Portland, Oregon

¹⁹ Robinson, 1991, Stern and Aronson, 1987? [GET FULL REFERENCES]

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" effects.²⁰ 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, 2U/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, create 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 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 system (combined rail-road versus road dominant) and will certainly have gone beyond a bifurcation point.²¹ 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.

2.1.2 Current and Future Socio-Economic Development Patterns

It has been suggested in the preceding subsections that underlying socio-economic conditions have a large impact both on the level and type of emissions and on emission reduction costs, and also that different "packages" of such underlying conditions can cluster in ways that give rise to quite different development paths for a given economy. We can expect such different paths to give rise to different "base case" emission levels and different cost curves for emission reduction or adaptation. We now turn to six specific examples of important underlying socio-economic factors that could give rise to these different development paths. The purpose here is to describe briefly the nature of these six factors and some of the ways that they can influence future emissions and costs of emission reduction. Note that to the degree that such factors are amenable to conscious control or choice, decisions about them will usually be taken for reasons that have nothing

²⁰ Arthur 1988 [INSERT FULL REFERENCE]

²¹ Hourcade, J.C. 1992. "Modelling Long Run Scenarios: Some Methodological Lessons from a Prospective Study on a Low CO2 Intensive Country", *Energy Policy*, November.

to do with energy policy or climate change issues.

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. 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.²² 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.²³

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 services²⁴;
- the effects of telecommunications on travel and transportation energy use²⁵;
- saturation in the consumption of some goods and services, and the emergence of new goods and services.

Clearly quite different configurations of these factors are possible, resulting in potentially large differences in raw materials intensities, independent of the size of the economy. It is also clear that emission reduction costs per unit of economic activity (e.g. dollars per unit GDP) will depend on both the mix and level of such intensities. Not only will emission reduction costs vary among economies with different structures, but, for any given economy, these costs will depend in part on the current level of material intensity. In general it will be cheaper to reduce material intensities from higher rather than a lower starting point since it is likely that part of the reason for lower current starting points is that some of the cheaper efficiency gains have been realized.

2.1.2.2 Development patterns in the Third World

The importance of development pattern assumptions for the assessment of emission reduction costs is of particular importance in the case of developing countries. As a major part of the needed infrastructure to meet development needs is still to be built, the spectrum of future options is considerably wider than in industrialized countries. The traditional approach of using "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

²² 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.

²³ [INSERT REFERENCE TO IAEE 93 CONFERENCE PAPER]

²⁴ X. Chen, 1994, "Substitutions of Information for Energy", *Energy Policy*, January, 15-27.

²⁵ E. Selvanathan and S. Selvanathan, 1994, "The Demand for Transport and Communications in the United Kingdom and Australia", *Transportation Research B*, Vol 28B, No. 1, 1-9.

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 energy demand/GDP elasticities. For instance, Chinese homes are not bound to adopt the same model of energy-wasteful refrigerators that have been installed in American houses. Nor should future factories in developing countries fail to include up-to-date technological improvements, many of which will improve energy efficiency. A growing interest in the preservation of cultural diversity might also favour less energy intensive housing, transportation, leisure and consumption patterns, at least in some cases. 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. On the other hand, high economic growth rates and increases in consumer purchasing power in many developing countries are driving up energy demand growth rates.

Finally, the spatial distribution of the population and economic activities is still not settled, offering 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. In this connection, it should be noted that the large amount of natural resources available in developing countries could be tapped through the use of modern technology leading to more decentralized development patterns than typical of industrialized countries, as in the case of the huge opportunities supplied by the prospects of biotechnology. Turning to the energy supply side, more decentralized societies would also make easier the adoption of renewable energy sources, such as biomass, solar, wind and hydro power.

These examples show that developing countries could adopt anticipative strategies directed to avoid in the long-term some of the problems faced today by industrial societies ("leapfrogging"). 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.²⁶ 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").²⁷

Such possibilities for alternative development patterns highlight the technical feasibility of low carbon futures in the South compatible with national objectives. On the other hand, the barriers to a more sustainable development in the South can hardly be underestimated, ranging from financial constraints to cultural behaviours in industrialized as in developing countries, including the lack of appropriate institutions. Any emission reduction cost assessment for developing countries also depends on implicit assumptions embedded in

²⁶ Martin, J.M.; "L'intensité énergétique de l'activité économique dans les pays industrialisés: les évolutions de longue période livrent-elles des enseignements utiles?", *Economie et Société*, n° 4, 1988, p. 9-27; Darnstadter, J.; Dunkerley, J.; Alterman, J.; "How Industrial Societies Use Energy", Washington D.C., Resources for the Future, 1978.

²⁷ Berrah, N.E.; "Energy and Development: the Tunnel Effect", Paris, *Revue de l'Energie*, n° 356, August/September 1983.

baseline or emission reduction scenarios about the probability of removing these barriers.

2.1.2.3 Links among energy, transport and urban planning

Transportation energy use accounts for a significant proportion of GHG emissions in industrialized countries.²⁸ The size and type of those emissions is a function of the demand for transportation services (i.e. the amount of travel), the mode chosen (auto, air, bus, rail), the efficiency of the vehicles and the types of fuel used. The first two of these, in turn, are greatly influenced by, and influence, the size and configuration of cities and towns.²⁹ Important factors here are:

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

Beyond these specific urban planning issues are a whole set of questions related to the development of new transportation systems and technologies.³⁰ The growth in personal mobility in industrialized countries over the past several centuries has been closely correlated with technological advances in the types of vehicles used, the availability of fuels, and the transportation infrastructure created. In turn, such factors interact in complex ways with urban form and development, and directly affect both the prospects for, and the costs of, GHG emission reduction. For example, the level of future automobile emissions will depend in part on the degree of saturation of automobile densities in urban areas, due to the availability of effective air and high speed ground transportation alternatives.³¹

Clearly, quite different configurations of these factors can be envisaged. And these alternatives would have major impacts on emission reduction options and costs. Obviously the nature and costs of transportation sector emission reduction for a population dependent largely upon automobile transport in highly dispersed suburban developments would be very different than for a population located at the core of dense urban agglomerations with a well-developed urban transit infrastructure. Since towns and cities take shape, and change, over periods measured in decades and centuries the full effect of alternative transportation developments will be manifest only in the relatively long-term.

2.1.2.4 Land use and human settlements

Land use and human settlement pattern changes derived from agricultural and forestry activities as well as rural-rural and rural-urban migrations are among the main sources of GHG emissions in developing countries. In many African countries urban population growth accelerates rural deforestation due to a rapid increase in charcoal consumption in the cities, which requires approximately double the amount of wood to be harvested per meal cooked, compared to the rural cookstoves using fuelwood directly. Deforestation in the Amazon region is a complex phenomenon mainly caused by the expansion of the road

²⁸ 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.

²⁹ Newman, P. and J. Kenworthy. 1989. *Cities and Automobile Dependence: An International Sourcebook*. Borkfield, USA: Gower Technical.

³⁰ Ross, M. 1989. "Energy and Transportations in the United States", *Annual Review of Energy*, Vol 14, pp. 131-171.

³¹ Grubler, A., N. Nakicenovic, and A. Schläfer, "Dynamics of Transport and Energy Systems", International Institute for Applied Systems Analysis, Report RR-93-19, December, 1993.

network, logging and cattle raising activities, agricultural production and population growth fostered by rural-rural migrations due to the absence of guaranteed access to land (agrarian reform) in other regions.

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

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

2.2 Modeling Development Paths and Mitigation Costs

2.2.1 Prediction and Simulation: The Need for Multiple Baselines

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. Different packages of assumptions related to the raw material intensity of various economies, development patterns in the Third World, land use patterns, transportation system development, etc. will give rise to quite different scenarios of GHG emissions and emission reduction potential. This will in turn greatly affect the costs of GHG emission reduction

This uncertainty 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 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. Not only is it problematical to estimate a probability distribution for a given scenario but it would be even more misleading to resort to some probability distribution in order to narrow these uncertainties among different scenarios and provide some kind of average scenario. The point of these alternative base cases is that they 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.³² In the energy field, approaches based on the concept of multiple scenarios were pioneered by Shell International Petroleum Company in the early 1970s,³³ and have been adopted in various forms in the electric utility industry in North America.³⁴ 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 terms.³⁵ Common to such applications is the desire to explore the implications of quite different assumptions concerning underlying socio-economic conditions.

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*³⁶, the publication of which stimulated a extensive debate about alternative development paths. This debate was fueled by the publication of a number

³² For discussion and examples of such approaches see Jantsch, E. *Technological Forecasting*. (Paris: OECD, 1967) [CHECK REFERENCE]; Harman, W. *An Incomplete Guide to the Future* [INSERT REST OF REFERENCE]; Gaul, 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; Glime, 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) 325-338.

³³ 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 [INSERT SOME MORE RECENT SHELL STUFF, INCLUDING KAHANE 1993]

³⁴ 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.

³⁵ See FRN. 1987. *Surprising Futures*. Notes from an International Workshop on Long-Term World Development. Forskningsrådsnanden (Swedish Council for Planning and Coordination of Research) Report 87:1, Stockholm; [SEI backcasting report: GET FULL REFERENCE].

³⁶ Meadows, D., et al. *The Limits to Growth*. [INSERT FULL REFERENCE]

of subsequent studies³⁷, including the Leontieff report launched to illustrate the International Development Strategy adopted by the United Nations in 1974.³⁸ 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.³⁹

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 1974,⁴⁰ Amory Lovins' provocative "soft energy path" analysis⁴¹ helped to launch many exploratory works in North America⁴² and in many European countries⁴³ 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 mainstream energy economists.⁴⁴ In the early 1980s, the publication of the results of the ILASA energy study⁴⁵ sparked a vigorous debate about both modelling methods and alternative energy futures.⁴⁶ 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 Development⁴⁷, and the subsequent UN Conference on Environment and Development in 1992.⁴⁸ 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

³⁷ [INSERT MEASAROVIC AND PESTEL REFERENCE]

³⁸ [INSERT REFERENCE; IS THIS THE SAME AS IGNCZY SACHS "ECODEVELOPMENT REPORT?"]

³⁹ [INSERT REFERENCE]

⁴⁰ Ford Foundation, *A Time to Choose: America's Energy Future*. Energy policy Project, Cambridge, Mass.: Ballinger, 1974)

⁴¹ Lovins, A. *Soft Energy Paths*. (New York: FOE/Ballinger, 1978)

⁴² CONAES (1979); Stobaugh and Yergin (1979), Ross and Williams (1981); Friends of the Earth Canada (1983/4) [INSERT FULL REFERENCES]

⁴³ Leach (1979), Sorenson (1977), Krause (1981), Norgaard, others

⁴⁴ See the country case studies in Baumgartner, T. and A. Middum. *The Politics of Energy Forecasting* (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* [INSERT FULL REFERENCE]

⁴⁵ Hafele, W. *Energy in a Finite World: A Global Systems Analysis*. (Cambridge, Mass.: Ballinger, 1981).

⁴⁶ Keepin and Wynne [INSERT REFERENCE]; See also Thompson, M. "Among the Energy Tribes" [INSERT FULL REFERENCE]

⁴⁷ World Commission on Environment and Development, *Our Common Future* [INSERT REST OF REFERENCE]

⁴⁸ For examples of more recent bottom-up work, see Goldemberg, J. et al. *Energy for a Sustainable World* (New Delhi: Wiley-Eastern(?), 1988); [JOHANSSON RENEWABLE ENERGY BOOK?? OTHERS?]. For top-down studies, see [INSERT REFERENCES]

theory⁴⁹); self-fulfilling or the self-defeating prophecies⁵⁰; "common-knowledge" and "conventions"⁵¹; the coordination game⁵² or, more generally the outcome of repeated games in game theory⁵³; and chaotic behaviour and surprise⁵⁴.

2.2.2 Economic Modeling and Development Trends: Some Limits

There is perhaps an unavoidable gap between advanced thinking in social science theory and methods, 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.

Two main approaches have been developed. On the one hand, macroeconomic "top-down" models usually contain rather aggregate energy demand functions (one or two energy services, one composite food variable, 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 as regards to, say, bifurcations in the transportation sector.

On the other hand, "bottom-up" energy 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 energy demand and supply, and point out potential gains in energy efficiency from specific technologies or the potential for fuel substitution. Such models rely on rather precise descriptions of energy 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

⁴⁹ (Azariadis, Guesnerie 1986) [INSERT FULL REFERENCE]

⁵⁰ Henshell, R [INSERT FULL REFERENCES]

⁵¹ Lewis, Aumann, Dupuy [INSERT FULL REFERENCES]

⁵² T. Schelling [INSERT FULL REFERENCE]

⁵³ Fudenberg, Tirole [INSERT FULL REFERENCES]

⁵⁴ [INSERT CHAOS THEORY REFERENCE; HOLLING ON SURPRISE??]

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. As a result, a more detailed discussion of the difference between these approaches (section 3), and of the results obtained using them (section 4), takes up the rest of this chapter. 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 been identified in this section. 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 has suggested that it would be desirable to work with methods that allow the generation of multiple baseline scenarios. These underlying scenarios would not be generated by altering the input parameters of a reference case scenario, but instead would represent different internally consistent sets of assumptions concerning the socio-economic variables and factors discussed above. The point is not to predict what long-term outcomes are most likely (an exercise at which few have been successful⁵⁵), 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.

Despite significant progress in modelling methods over the past several decades, the difficulties involved in broadening the scope of analysis to respond to these requirements are significant. Three main issues can be identified.

2.3.1 Multiple Baselines and the Non-Comparability of Cost Assessments

It has been suggested that 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. This means that a comparison between cost assessments is possible only with respect to variations around a base case scenario, which can be done through sensitivity testing and uncertainty analysis, or between scenarios with similar

⁵⁵ 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.

underlying assumptions about development patterns. It would be misleading to compare cost estimates coming from baseline scenarios with very different, or even contrasting, assumptions about such issues, especially since these differences may not be obvious. 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.⁵⁶ 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 cannot be directly compared and no overall relative cost assessment is possible.⁵⁷

Two examples help to illustrate this sensitive issue. 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 with 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.

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 the "pro-alcohol" program. The existence of this program can be shown to lead to both a lower emissions baseline and lower emission reduction costs.⁵⁸ However, the overall costs and benefits of this program are debatable in terms of macroeconomic impacts, distributional effects, or innovation. The choice of a baseline with or without "pro-alcohol" will entail many types of transaction and political costs and will have many external effects, which are very hard to assess.

⁵⁶ 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.

⁵⁷ JEAN CHARLES WILL ADD HERE TWO ILLUSTRATIVE EXAMPLES FROM THE PAST: THE NUCLEAR RESPONSE TO OIL SHOCKS IN FRANCE AND THE BRAZILIAN PRO-ALCOHOL PLAN]

⁵⁸ La Rovere, in UNEP, 1993

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 Development Patterns in Developing Countries and Economies in Transition

All the difficulties associated with generation and assessment of baseline scenarios are exacerbated when dealing with developing countries and economies in transition. As noted above, virtually all existing economic models are based on the history and experience of development patterns typical of industrialized economies, and assume continuation of these development patterns and of the relationships between underlying socio-economic variables. They provide little basis for exploring very different modes of economic development.⁵⁹ Yet, given the very significant differences between past development patterns of industrialized countries and the current prospects for developing countries and economies in transition, the need for tools capable of exploring such alternative paths seems evident.⁶⁰ For example, we can anticipate 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. This heightens the need for 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. It is also 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.

2.3.3 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 useful ways. 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.

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).

⁵⁹ [INSERT REFERENCE TO MOSCOW MODELLING WORKSHOP OF HDGC PROGRAM]

⁶⁰ 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: HarperCollins Publishers, Ltd., 1993).

1 Indeed, in the long term, both "mitigation" and "adaptation" measures are part of the long-
 2 term adaptive responses of societies to a whole host of conditions and perceived problems,
 3 only a small number of which have to do with climate change. From this point of view, it is
 4 not entirely clear what should be understood by a "reference case" or "non-intervention"
 5 scenario in the long term.

6 All of these issues suggest that there is considerable work to be done to improve our
 7 capability to assess alternative patterns of development and technological change and their
 8 interactions with the costs and impacts of alternative emission reduction strategies. That
 9 being said, there is much that can be learned from existing cost analyses, to which we now
 10 turn. Before presenting a review of such studies, however, it is important to examine in
 11 more detail the manner in which technological change is treated in existing modelling
 12 analyses and, in particular, the debate between "top-down" and "bottom-up" approaches
 13 that was introduced above.
 14
 15
 16
 17

1 3. Technology Dynamics in Economic Models

2 A review of GHG emission reduction cost estimates shows dramatic disparities in
 3 modelling results. It is difficult to disentangle the various reasons for these differences,
 4 given (1) the diversity of tools used to calculate cost estimates, (2) the many and varied
 5 assumptions employed, and (3) the disparities in geographical coverages of different
 6 studies. However, a key factor in explaining the disparity of modelling results is the way
 7 in which technology is treated in different models.
 8
 9

10 A critical distinction is between "top-down" and "bottom-up" studies.
 11

12 Top-down models analyze aggregated behavior based on economic indices of prices and
 13 elasticities; these models are mainly macro-economic models that try to capture the overall
 14 impact of a climate policy, that policy being usually in the form of tax because of the
 15 difficulty of assessing other types of policy instruments.
 16

17 Bottom-up models rely on detailed analysis of technical potential, focusing on the
 18 integration of technology costs and performance data.
 19

20 Although an understanding of this modelling dichotomy is helpful, it is important to
 21 recognize that not all models fall neatly into one of these two categories. In reality, each
 22 category encompasses several types of models and, moreover, several "hybrid models" are
 23 now available in which analysts attempted to merge top-down and bottom-up model
 24 characteristics. However, the discussion in this text will maintain the dichotomy, for it still
 25 dominates the current literature and debate, and remains the main source of cost assessment
 26 divergence. Top-down models are often presented as concluding that relatively large
 27 carbon taxes would be required to counter current emission trends, which would result in
 28 significant economic costs, while bottom-up models conversely conclude that substantial
 29 emission reductions could be achieved with low taxes and low costs or even net savings.
 30

31 Thus, despite its drawbacks, the top-down/bottom-up categorization remains meaningful
 32 for policy making; it has been portrayed as opposing the optimism of the "engineering
 33 paradigm" to the pessimism of the "economic paradigm" (Grubb, Richmonds et al 1993).
 34 From an engineering standpoint the evidence is that the best available technologies have not
 35 been adopted so far; in the energy field, this has been labeled the "efficiency gap", namely
 36 the gap between the energy efficiency of equipment actually chosen by consumers and the
 37 energy efficiency of the technology that could theoretically minimize the costs entailed for
 38 providing a given amount of energy service. This "efficiency gap" is the most typical
 39 example of the "no regret" potentials pictured in Figure 1.2 in the form of negative cost
 40 measures. In response, the professional reflex of an economist will be to call attention to
 41 the reasons why consumers do not adopt technologies that appear to be optimal and will
 42 tend to suggest that accounting for these reasons would reduce the magnitude of, or
 43 eliminate, the efficiency gap that is actually achievable through various forms of
 44 government intervention.
 45

46 However, beyond this critical debate and beyond this analytical difficulty there is a more
 47 general issue about the way existing models handle technologies, consumption and
 48 production behavior, and markets. To deal with the efficiency gap is not only a matter of
 49 describing technologies per se, but it is also a matter of describing the processes of
 50 technology adoption, and this latter is intimately related to the decision making behavior of
 51 economic agents and to the way that markets actually operate.
 52

That is why, before entering the basic features of the "bottom-up" and "top-down" archetype models and into the explanation of the advantages and limits of each of them, it is necessary to explain why a comprehensive typology of existing models is more complex and to discuss what is implied by the choices made by each modeler in terms of characterizing technologies and describing technology adoption behavior.

3.1 Critical dimensions of a typology of existing models

3.1.1 Diversity of models, diversity of purposes

It is impossible to interpret fairly the outcomes of economic models applied to assess the costs of climate policies without paying due attention to the fact that the models have been built for different purposes and that the methodological choices consistent with these purposes play a critical role in determining the way in which technology adoption and market behavior is portrayed.

(1) The major purpose of some models is to "predict" (forecast) the future, in this case subject to implementation of the policy likely to minimize the costs of achieving a target of GHG emission reductions. This purpose imposes very strict methodological constraints on the modeler. He/she must execute a base case forecast, which amounts to a best guess projection of the most likely future; to do this requires an endogenous representation of economic behavior and general growth patterns. Indeed, to forecast means, for an economic modeler, that it is possible to derive from current trends (generally captured in econometric relationships) the description of the laws of motion of economic growth in a given period so that it becomes possible to extrapolate these laws without, or with the minimum of, exogenous ad hoc hypotheses. This approach has been typical of government and sectorial forecasting activities (in energy, transport, heavy industries such as steel industries) and in early climate change scenario analysis. It remains both necessary and convenient for analyzing the short term impacts of climate policies; a number of critical underlying development variables can reasonably be assumed to remain constant for these time periods. Most of short-term, econometrically driven macro-economic models work in this perspective; for the long-term (middle of the next century), the Jorgenson-Wilcoxon model is the only one of these type of models that can be classified in this category. It is noteworthy that none of these models tries to work on the basis of forecasts of explicit technological trends, in the engineering sense.

(2) The major purpose of some models is to "explore" the future and in so doing to provide counterintuitive assessments. In particular, such models would entail the analysis of the outcome of various sets of hypotheses about economic behavior, resources endowments or technical progress. This leads to a scenario analysis approach¹, which involves building up different coherent visions of the future (each of which, of course, can undergo sensitivity testing) based on different values for key assumptions. These assumptions may address only factors such as economic or population growth or may extend to detailing the physical availability of energy or technical progress. The first step in such analyses is the generation of a "reference" or "non-intervention" scenario. This is then contrasted to alternative cases involving an array of policy measures, such as carbon taxes or energy efficiency regulations, giving rise to one or several "policy" or "intervention" scenarios².

1. 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.

2. See the discussion in (INSERT REFERENCE TO IS92 EVALUATION CHAPTER)

but the policy analysis is relevant only in the context of each baseline scenario. This approach is increasingly used for climate change analysis and was the basis for the 1992 IPCC scenarios.³ It is shared by both the bottom-up and top-down type⁴ models and indeed tends to favour the development of hybrid models (which will be discussed at greater length below). In terms of representing and simulating the behavior of economic agents, two methodologies predominate. One involves an assumption of least-cost optimization, in which society maximizes over the long-run the utility of consumption. The other involves the effort to predictively simulate real world behavior in terms of technology adoption.

(3) The major purpose of some models is to assess the feasibility of alternative futures, often defined in terms of desirability rather than likelihood. This contrasts with the two previous approaches, both of which were concerned with either explicitly or implicitly projecting futures that are likely or at least plausible. However, these approaches do not typically take into account in any explicit way alternative development paths. Instead, the first two approaches tend to embed assumptions about the future trends of fundamental underlying socioeconomic variables, such that these assumptions are invariant between scenarios. This third approach involves the development of a vision of a future state of the system being studied, and then an analysis of how that future system might be realized. This "backcasting" methodology allows for identification of major changes as well as discontinuities in present trends that might be required if a desirable future is to be attained.⁵ Two types of research can be carried out in this approach. Most involve normative scenarios about desired futures such as the many alternative energy studies referenced as the backcasting approach. But it is also possible to use a backcasting methodology as a purely analytical tool by simply linking bottom-up analyses about technology evolution to a macro-economic framework such as in the preliminary attempts at Imacim model (Hourcade, 1993), so as to be able to assess the economic consistencies behind different and competing views about the long run.

3.1.2. Two different representations of technology: the meaning of the "aggregation gap"

The terms "top" and "bottom", in the usual jargon of the economic modeler, are commonly linked to the distinction between aggregate models and disaggregate models. This demands clarification. The top-down label is indeed derived from the way in which the first energy-economy models were constructed. The developers of these models applied econometric techniques to data on energy consumption, prices, incomes and other variables to estimate price and income elasticities. These elasticities were in turn used to generate equations that could be used to forecast household energy use and the use of energy in

3. 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.

4. 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. *Future Atmospheric Carbon Dioxide Scenarios and Limitation Strategies*. Noyes Publications, Park Ridge, New Jersey; Manne, A. and L. Schramm, 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.

5. 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.

1 producing others goods and services. These models were criticized for not providing a
2 complex enough description of the determinants behind energy demand dynamics and, as a
3 consequence, simulation technico-economic models were developed (a good example of the
4 first bottom-up models were the MEDEE models developed by the IEPE [France] for the
5 European Commission) in order to understand why the income elasticity of energy demand
6 could evolve over time and to explore the potential for a possible decoupling between
7 energy consumption and economic growth.

8
9 But a simplistic reading of the aggregate versus disaggregate distinction between models
10 can be misleading. Some macro-economic models are very detailed: the
11 Jorgenson-Wilcoxon model (DGEM) for example distinguishes among thirty-five industrial
12 sectors (and the corresponding commodity groups) and 672 different household types,
13 broken down by demographic characteristics; and the Cambridge Multisectorial Model
14 (MDM) distinguishes 49 industrial sectors. In many models, such as the DGEM, the
15 so-called aggregate demand functions of consumer expenditure are constructed by
16 summing "individual demand functions", in effect dispensing with the simplistic notion of
17 there being a "representative consumer". More precisely, each category corresponds to a
18 "representative consumer" and this level of disaggregation allows for testing the income
19 distribution effects of various types of climate change policies.

20
21 The aggregated versus disaggregated distinction between top-down and bottom-up models
22 is perhaps more appropriately explained from an engineering standpoint. From this
23 perspective, even the most detailed top-down models are considered to be too aggregated
24 because even detailed individual household demand functions only allocate that demand
25 among a very limited number of commodity groups such as energy, food, non-durable
26 goods, other services and investment. Energy is thus portrayed as a single composite
27 service (or grouped in two or three broad categories of services) whereas the engineer
28 would wish to have a very detailed description of energy end-use demands so as to be able
29 to account for technological margins of freedom for cooking, heating, air conditioning,
30 transportation, etc. In the same way, even in a disaggregation of the industrial sector into
31 around 40 to 60 sectors, energy will be grouped into two or three commodities (electricity,
32 gas and petroleum products for example) whereas a process model preferred by engineers
33 would have to account for more complex representations of electrical load-curves and for a
34 number of petroleum products (feedstock, gasoline, diesel, heavy fuels, light fuels, etc.).
35 Beyond the energy sector and its purely technological aspects, the specialist in agriculture
36 for example would consider that to group agriculture into a single aggregated sector does
37 not permit representation of the actual forces behind long term trends in food markets and
38 other agricultural products and the impacts of these trends on land use, given the specifics
39 of each geographical region.

40
41 The disaggregation dichotomy is in essence related to fundamental differences in the focus
42 of the analysis. Macro-economists focus on financial flows across the whole economy and
43 can provide rather sophisticated analytical tools at this level, while sectorial specialists
44 focus on the market dynamics stemming from a given industrial structure but with little
45 consideration devoted to overall feedbacks with the rest of the economy, and, finally,
46 engineers or (engineer-economists) focus on technical margins of freedom likely to be
47 evidenced at a micro-economic level.

48
49 This gap tends to be enlarged when longer time periods are under consideration. For many
50 modelers, the application of very disaggregated macro-econometric models is impossible
51 over too long time periods because of the lack of reliability of econometric relationships
52 over such periods. The Jorgenson-Wilcoxon model is a noticeable exception to this point
53 of view, and we will explain further the reasons why, but the common practice used to

1 achieve robust models over longer time periods is to choose higher levels of aggregations
2 simply because the econometric relationships among these aggregated variable are generally
3 more reliable and the behavior of the model more stable (the error terms for five original
4 variables for example can compensate each other in the error term of a new composite
5 variable). This explains why the medium term models of the HERMES type in Europe
6 work with around fifteen sectors, and why Global 2100 works with three products,
7 electrical energy, non-electrical energy and a composite good aggregating the remaining
8 goods and services.

9
10 From this point of view, bottom-up models stand at the other end of the spectrum,
11 conveying very detailed technical information specially for short to medium term periods.
12 But in fact, the difference is not a simple case of aggregation, it is a matter of how
13 technology is described. On the one side, one tries to capture technology in the engineering
14 sense: a given technology (coke oven steel versus electric-arc steel, an incandescent light
15 bulb versus a fluorescent light bulb) with a given technical performance at a given micro-
16 economic cost. On the other side, the term technology in macro-economic models has a
17 rather different meaning: whatever the level of disaggregation of the model, it is represented
18 by the share of the purchase of a given input in intermediate consumption (steel products to
19 make cars for example) and by the allocation of the output (sales revenue) among the cost
20 of intermediary inputs, returns to labour, and returns to capital. These shares constitute the
21 basic ingredients of the economic description of a technology in which, depending upon the
22 choice of production function, the share elasticities represent the degree of substitutability
23 among inputs (cf Box 1.1 for the description of this type of approach in the
24 Jorgenson-Wilcoxon model).

25
26 This characterization makes it difficult to establish explicit links between production
27 functions in economic models, on the one hand, and technology projections, on the other.
28 For example, there is a gap between the findings of Jorgenson (1983) and
29 Hogen-Jorgenson (1990) with respect to the negative correlation between technological
30 change and energy prices in the U.S. economy and the observation of accelerated
31 innovations at a technical level. The reason is that the term technology refers to two
32 different things. For an economist, productivity growth is correlated with many other
33 factors than mere technology characteristics; a depressed demand or growing uncertainties
34 can result in a lower economic productivity even if the technical efficiency of equipment is
35 very high. Consequently both descriptions can be internally consistent, but each may
36 represent a different definition of technological change.

37
38 In the same way, the substitution among capital, energy and labour described in
39 macroeconomic models (e.g. for testing the impact of offsetting a tax on energy by a
40 decrease in payroll taxes) does not necessarily mean that, at a micro level, enterprises
41 actually choose less energy-intensive and more labour-intensive technologies from the array
42 of technological choices confronting them. This may of course happen but the
43 macroeconomic substitution between energy and labor in macroeconomic models
44 encompasses many different processes: energy savings due to changes in the use of
45 equipment, changes in the structure of final demand in the direction of less energy-intensive
46 goods, a decrease in the level of risk taken by an entrepreneur when employing someone,
47 etc. All such factors will affect the substitution between energy and labor, even without any
48 change in the technical characteristics of the production technology itself.

49
50 These factors mean that both descriptions of technology and technological change make
51 sense but each captures a different aspect of that change. Many misunderstandings result
52 from ignoring these differences.

3.1.3. *Representing economic behavior: how do market mechanisms really 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. This is usually presented in what is referred to as the dual form: 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 energy service requirement. However, both for firms and households it is recognized that cost minimization is only a first order optimization, that changing prices, demand, and technologies could lead to firms adjusting their output levels and households adjusting their energy service requirements. Neither models are as good at assessing this second order optimization, although top-down modelers can at least claim that the behavioral parameters in their models may incorporate to some extent these second order adjustments.

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 energy end-use, be that for production decisions or consumption decisions. The most complete form of this bottom-up approach is represented by global optimization models such as EFOM, promoted by the European Community, and MARKAL, promoted by the International Energy Agency. These type of models use linear and dynamic programming techniques and apply them to the entire energy system in order to find the unique 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 given the optimal choices of all other 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 energy system. 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.

If the approach is assumed to be prescriptive, it suggests to decision makers the optimal set of technologies from a social time preference perspective. It does not tell decision makers how to realize this optimal set.

While optimization models represent perhaps the extreme bottom-up approach, other bottom-up models and analysis focus more on "bounded" life cycle cost minimization. In other words, the cost minimizing technology is chosen for each energy end-use and energy supply need, but this optimization is independent of the technologies chosen for other energy end-uses or other energy supply needs. Depending on the degree of independence between each decision locus in the economy, it could be that this latter approach will give results that do not differ significantly from the results of the more comprehensive optimization approach.

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 (see later discussion of consumer surplus) 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. Examples of these types of models include MEDEE-3ME in Europe, LBLREM, ISTUM and ENERGY 2020 in North America, and the models used by electric utilities in North America, notably REEPS and COMMEND.

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; for this purpose attention must be devoted to descriptions of market mechanisms and of economic agents' behaviors when confronted with these mechanisms.

With regard to market mechanisms, the 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"⁶ forms of production functions which introduce some rigidities in the adjustment. Most of the long run models however assume that over the long run these inertia disappear.

But this dominant interpretation is not the only one possible. Differing expectations about the future can be incorporated into top-down models. They are generally incorporated in the following two very different ways. (1) The myopic assumption is that economic decisions are based on static expectations, namely static projections of current price conditions prevailing at time zero. This is the approach adopted by Green for example. (2)

6. 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 perfect foresight assumption is that economic decisions are based on all available information about the future, future long term price trends being part of this available information. This suggests that some form of long term optimization is integral to economic agents decision making behavior.

In summary then, all of the models represent the technology adoption of businesses and households as rational decisions based on market prices and all available information. Consumer preferences are taken as given. Depending on how the particular model is constructed, consumer decisions may be represented explicitly as involving maximization of utility subject to a budget constraint, or implicitly in demand equations that relate consumption of energy and other goods to prices and income. As to production decisions, they result from profit maximization subject to constraints defined by the available technologies. However, it is important to note that the utility or profit maximization assumed in such models is not necessarily reproducible in terms of detailed simulation of engineering-economic costs. As will be detailed later, consumer preferences and either producers' surplus or intangible costs, which are difficult to quantify, are nonetheless integral to the technology adoption decision. Top-down models, with their parameters estimated from aggregate data, can at least claim that all of these decision factors are in fact incorporated into the own and cross price elasticities emerging from the estimated model parameters. In this sense, utility and profit maximization becomes a much richer term, but also one that is unfortunately somewhat ambiguous, as we shall discuss in section 3.2.2.

3.1.4. Technology and behaviors over the short term or the long term, two different questions addressed

These methodological choices about the representation of technology and behaviors are not unconnected with the time horizon considered by the model. 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 within 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 period 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 as stated in the previous sub-section) but paradoxically the theoretical rules describing a market equilibrium can be applied; their usefulness is indeed to 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; what is the sense of pretending that one has foresight about a recession in 15 years time that will cause capital stock utilization rates to diverge from their long-term average?

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 model, the general equilibrium models for long run equilibrium analysis that seek to reflect an idealized equilibrium economy with optimal allocation of resources.

On the bottom-up side, the distinction is also very clear; over the short term, the challenge is to tap efficiency potentials given a basket of technics and to calculable the magnitude of the margins of freedom provided by the existence of the efficiency gap. Once tapped, however, these potentials disappear and the critical issue becomes the new margins of freedom brought about by continuing technological innovation.

However, a common assumption must be noted. In all the models, the assumption is that, over the long term, the economy tends to become optimal either in the form of general equilibrium in top-down models or in the form of a maximum of technical efficiency in bottom-up models. This may seem surprising, given historical evidence of the non-optimality of existing economies over decades (unemployment, poverty for example, erratic technological choices for example). But one must cautiously distinguish between a tool aiming at pointing out some logical implications and a forecasting exercise aiming at predicting the future real world.

3.1.5 Typology of models in the energy field

FORTHCOMING

3.2 Overall Lessons from the Efficiency Gap Controversy in the Energy Field

The outcome of greatest interest to policy makers - carbon reductions at zero or negative net economic cost - could come about on the basis of three combinations of factors.

(1) In the first case, it may be that the national bill for energy services can be reduced through non-tax measures that improve the economic efficiency of energy service markets and/or accelerate the diffusion of new low-carbon technologies. In this case, reduced energy service bills will result, and this will lead to enhanced economic output.

(2) In the second case, it may be that the national bill for energy services cannot be lowered as carbon emissions are reduced because energy service markets and technology diffusion processes are already functioning optimally. Any measure to reduce carbon emissions will increase energy service bills and therefore dampen economic output. In other words, micro-economic market behavior cannot be improved upon by government intervention. However, it may be that current taxation policies are inefficient from a macro-economic perspective, thereby preventing society from allocating resources to reach the production possibility frontier (Figure 1.2). If properly designed, policies to reduce carbon emissions

may be able to improve upon macro-economic inefficiency sufficient to offset the negative effect on economic output of the micro-economic adjustments. For instance, carbon taxes might replace other taxes and be applied and recycled in ways that have a net positive effect on economic output.

(3) In the third case, carbon reduction policies have both micro-economic efficiency effects (Case 1) and macro-economic efficiency effects (Case 2), resulting in a mutually reinforcing package of micro-economic and macro-economic policy measures.

To explore these possibilities for "no regrets" carbon reduction policies, it is necessary to accurately model (1) the functioning of the energy service markets within the energy sector, and (2) the interactions of the energy sector with all other sectors of the economy under alternative tax policies.

3.2.1 Bottom-Up Approaches to Analysing the "Efficiency Gap"

In the bottom-up approach, energy demand is calculated on the basis of detailed energy efficiency and life-cycle cost comparisons of widely established and currently emerging end-use technologies. This engineering-economic life-cycle cost analysis commonly reveals a so-called efficiency gap, i.e., many years after their market introduction, the greatest market share is not held by end-use devices with the lowest life cycle costs, but by less energy-efficiency devices that are cheaper on a capital cost basis (first-cost basis) but more expensive on a life cycle cost basis.

This so-called efficiency gap is interpreted as an inefficient market outcome. It is attributed to problems in well-established markets (market failures) and/or problems that impede rapid establishment of markets for new technologies (diffusion barriers). Correspondingly, energy demand under business-as-usual policies is considered to be excessive from an economic efficiency point of view. Bottom-up models then proceed to calculate the level of energy demand that would result if investments in end-use devices were based on lowest life-cycle costs.

The bottom-up approach is uniquely suited for modelling the impact of specific incentive and regulatory policies on energy service markets because it models individual end-uses and sectors in a highly disaggregated manner. Bottom-up scenarios of future energy demand assume that policy intervention can shift consumer behavior from historically sub-optimal patterns to economically more efficient choices, and that well-designed policies can remove barriers to the rapid adoption of specific new energy-efficient technologies.

Bottom-up studies may also identify overlooked economic efficiency opportunities on the energy supply-side. For example, micro-economic analysis suggests that there should be a much greater diffusion of cogeneration technologies. However, much of this diffusion has been precluded because of the norms of past electric utility regulatory practice, on the one hand, and the perspectives of municipal planning, on the other. This issue is discussed in Section 2, above.

In the bottom-up approach to estimating the "no regrets" potential for carbon emission reduction, the economic benefit of policy scenarios is calculated by comparing the cost of energy services based on least-cost supply mixes and least-cost levels of energy demand to a business-as-usual case in which the historic pattern of consumer efficiency choices and energy supply markets is continued into the future. In a second stage of most bottom-up assessments of carbon reduction potential, any net economic gains from market-correcting

policies are put to use to pay for more expensive carbon reduction measures, such as renewable energy supplies that are not yet cost-competitive. The "no regrets" or zero net cost potential of carbon emission reduction is then defined as the point where financial savings from cost-effective efficiency measures and supply resources are just offset by expenditures for more expensive resources.

Additional "no regrets" opportunities identified in bottom-up analyses are those that are also recognized in the top-down approach, i.e., efficiency gains from incorporating environmental externalities of associated changes in other emissions levels, improvements in the efficiency of R&D spending, removing fossil fuel price subsidies, improving regulation and competition in the utility sector, and a shift to more efficient tax structures in the energy sector and the economy at large.

3.2.2 How to Explain and Assess Market Imperfections

The debate about market imperfections in energy markets has been active since the 1970s and there have been many empirical estimates of the magnitude of market imperfections. Unfortunately, however, the tests and their results are ambiguous, leaving room for alternative interpretations.

3.2.2.1 Definitions of Market Imperfections

The key reason for ambiguity is disagreement on the definition of market imperfection and market failure; empirical evidence is of questionable use if there is no agreement on what that evidence implies.

Neoclassical economic theory focuses especially on three market failures that may prevent private markets from achieving resource allocations that maximize economic welfare. These are externalities, public goods and increasing returns to scale (referred to as natural monopoly market conditions). Protagonists on either side of the top-down versus bottom-up debate can agree that these three market failures exist in energy markets. Natural monopoly explains the need for public intervention (public ownership or public regulation) in natural gas and electricity markets, although in future this rationale may be limited to the transmission and distribution phases of these markets. The existence of various environmental externality costs is acknowledged. Finally, the national security benefits of preferential development of domestic energy resources is an example of a public good aspect of energy markets.

However, the bottom-up approach to explaining the efficiency gap has approached the issue of market imperfection from a completely different perspective. In this case, if analysis shows that a given energy efficiency or fuel-switching technology will be profitable from a social engineering-economic perspective, then it is assumed that the zero or incomplete market penetration of this technology is evidence of market failure, and a rationale for government intervention in the market.

For most economists, the conceptual basis of this rationale for intervention is troubling. It suggests that the results of cost-benefit analyses by public policy analysts - even with respect to private investment decisions - should be preferred to the implicit cost-benefit analyses by private agents (firms and households) when making day to day market consumption and investment decisions. For such second guessing of private market agents to be justified, economists will want conclusive evidence that these agents are behaving in sub-optimal ways, even when their own decision values are included in the analysis.

While economists are willing to acknowledge that markets do not function perfectly (acknowledging oligopoly for example), they are generally loath 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. An example of consumer surplus would be the extra satisfaction / value that a consumer derives from a particular type of car or light bulb that may not be reflected in the capital and operating costs of that commodity. Common examples of intangible costs are differences between two goods in terms of (1) the cost of becoming sufficiently informed about each in order to seriously consider each as an option, (2) the perceived risks associated with capital or operating costs of each, (3) the various transaction costs associated with each (finding, ordering, shipping, installing, operating), and (4) externally or internally imposed restrictive investment criteria that differ from the social time preferences of consumers and the opportunity cost of capital of firms.

Thus, two interpretations of these so-called market failures / market imperfections have emerged. One interpretation, generally associated with bottom-up analysis, presumes that the engineering-economic estimation of an efficiency gap provides the empirical evidence of the existence of market failures / market imperfections. The other interpretation, generally associated with top-down analysis, presumes that the estimation of the efficiency gap may simply provide empirical evidence of the minimum size of the sum of offsetting differences in intangible costs and offsetting differences in consumer surplus.

In this section, we review the alternative explanations for the market failures / market imperfections.

(i) Lack of information. Lack of information is frequently presented by energy analysts as a market imperfection. Yet it is obvious that the consumer or firm never has full information of all potentially profitable purchases; this "bounded rationality" has been recognized by economists for some time. Acquiring information about potentially profitable purchases is thus frequently referred to as one of the "transaction costs" of economic activity. Empirical evidence demonstrating that lack of information hindered the purchase of a profitable energy saving investment is not, therefore, seen by most economists as evidence of market imperfection. Economists would want to find out if perfect information existed about investments that saved labour, materials or capital, or if these inputs to the firm's production function or the household's consumption function were somehow treated differently in investment decision making.

There are two counter arguments to this conventional perspective of economists.

The first argument is that information is, for some reason, asymmetric. That is, information leading to energy saving investment is especially inadequate such that households and firms are biased in their purchase behavior away from outcomes that would be the most profitable to them. Therefore, the lack of information is a market imperfection in its resulting bias effect on investment behavior.

The second argument is that information about new energy saving products is a "public good" in that more rapid diffusion of these new products would benefit everyone, but because no one agent can capture these dispersed benefits the information is underprovided by the market. This second argument is probably valid, but it is presumably equally valid for all types of investments, even those that may enhance labour, materials and capital productivity, and sometimes working against reduced energy consumption. However, it is difficult to see why this second argument, if it is valid for energy saving investments, would not equally apply to all types of investments.

Lack of information will generally tend to disadvantage new technologies, but all new technologies not just those that happen to result in greater energy efficiency and/or less carbon emissions.

(ii) Overly restrictive investment criteria. The application of short payback periods or high discount rates to the evaluation of energy saving investments are cited as another market imperfection. These restrictive investment criteria may be explicit - in the case of some firms - or implicit - calculated afterwards from data on household consumption patterns. Here again the challenge is to demonstrate that the restrictive investment criteria are somehow wrong, perhaps in that they bias investment toward the short-term again at the expense of energy efficient products or processes. This seems clear in the trade-off between capital and energy, the former being generally an up-front expenditure and the latter being an operating cost over time. However, the trade-off between energy and labour or energy and materials is not so clear because both labour and materials are also operating costs.

In any case, restrictive investment criteria are perhaps best interpreted as the consequence of other decision factors.

One factor is perceived "risk". If an investment is perceived to be risky, investors are interested in recouping their capital outlay as soon as possible, in case something goes wrong such as the equipment proves to be faulty, or cost forecasts of labour, energy or materials prove incorrect.⁷

Another factor, especially among renting households, is "tenure uncertainty". Renters have little incentive to make efficiency investments if such investments are of a fixed capital nature because the benefits accrue to the next renters. For the tenants, therefore, a fairly short payback period would make sense.

"Capital constraint" is also cited as a factor that could lead to restrictive investment criteria. Households are clearly constrained, although lending institutions are increasingly willing to recognize the trade-off between higher mortgage payments and higher utility bills resulting in greater capital availability for households with projected lower utility bills. The capital evaluation process in all firms generally identifies more internal profitable investment opportunities than each firm is willing to outlay in a given year. But this should not be surprising when one remembers that an important distinction must be made between *ex ante* and *ex post* returns on investment. Managers of firms have learned from experience that each investment has some level of associated risk. Therefore, in the interests of prudence, managers set a cut-off rate of return that is usually well above the firm's cost of capital. For the economy as a whole this practice seems to work, because the *ex post* returns on

7. Of course dealing with risk via the discount rate (real or implied) can lead to perverse outcomes if the real issue is risk asymmetry between alternative technologies. If one technology is perceived to be riskier than the other, this asymmetry should be reflected by outcome probability distributions or by more cruder methods of risk minimizing decision strategies, such as minimizing maximum regrets (referred to as "minimax regrets"). Riskiness may be related to lack of information; if you know more about technology A than technology B, you may assume a risk factor when considering technology B. But risk asymmetry may also result from acquiring more information. Consumers may learn that a certain type of double-glazed window has a risk of frosting-up under certain moisture and temperature conditions. Thus, relative perceived risk may or may not be correlated with the degree of information about technology alternatives. In either case, however, risk analysts agree that the differential risk information should be incorporated into the expected value calculation of each alternative, and not accounted for by crude adjustments to shorten the investment horizon, with their potentially perverse outcomes.

investment still hover down at the 8 to 11% level. But the universal application of high discount rates or short payback periods to all investments by firms is problematic if this practice fails to distinguish the different level of risk associated with each investment. For example, energy analysts may argue that energy efficiency investments are not as risky as the average investment considered by firms.

Restrictive investment criteria will work especially to the disadvantage of high capital / low operating cost technologies. In this case, the disadvantaged technologies will tend to be technologies that have higher energy efficiency. But this is not necessarily the case. Technologies that have lower operating costs because of lower labour and material costs will also see their prospects improved if investment criteria somehow became less restrictive. And it is not inconceivable that such technologies might also lead to reductions in energy efficiency. Finally, in terms of carbon emission reduction, while there is normally a link between energy efficiency and emission reduction, there is nothing to guarantee that this is always the case.

(iii) Hassle and other hidden transaction costs. This third decision factor works, like lack of information, works to the disadvantage of new technologies. New technologies have higher transaction costs. We have already noted that it costs more to gain information about such technologies. But these technologies can also result in higher indirect costs related to their acquisition; these can include the costs of ordering, receiving, installing, operating and maintaining. Households and firms have learned from experience about these indirect costs of new technologies, but while these costs are a very real factor for decision making, an estimate of their tangible monetary value is very difficult to obtain with any confidence.

3.2.2.2 Estimating the Magnitude of Market Imperfections

Since the mid 1970s considerable research has been conducted on decision making related to energy using equipment. Much of the research has been conducted by government and energy utilities. In North America in the 1980s and 1990s electric utilities have been extensively involved in this research as they seek to develop more effective demand-side management programs.

However, most of this research has not attempted to determine the relative importance of the decision factors listed above. Instead it tended to operate at more aggregate levels, empirically estimating phenomena such as implicit discount rates, without examining in detail the causal factors for the higher or lower implicit discount rates values.

Research has also focused on hindsight analysis of the realized costs and benefits of individual demand-side management programs. Here the evidence is again mixed. Some argue that the experiences of utilities in the U.S. have shown that it is possible to "transform the market" at a relatively modest cost. Transform the market means to get the market (for specific energy services) to make a significant shift toward technologies with higher energy efficiencies, but higher capital costs. Others argue that this market transformation has been more expensive than is currently recognized because not all costs are being properly accounted. The truth is probably somewhere in between, and this is the general message of more recent empirical research.

The results of this research may be characterized with the following points.

- * There is little research estimating the consumer surplus associated with more and less energy efficient technologies.

- * Consumers are often very poorly informed about new technology options. Although less so than for households, this is also true for firms.

- * Tenure uncertainty, especially the split-incentive between tenants and landlords can be a significant explanatory factor in the penetration of certain fixed good energy efficiency investments.

- * Firms and households are rarely found to assess differential risk between technologies, other than by treating new technologies with more caution. Generally, risk is accounted for by high discount rates or short payback periods, mechanisms which may have perverse impacts with respect to differential risk.

- * Restrictive investment criteria are implicitly (households) and explicitly (firms) applied to all investments, although the relative importance of various causal factors is not clearly understood. For firms, research suggests that the location of decision making responsibilities within firms is a significant determinant in the penetration rate of energy efficiency investments. For households, research suggests that lower income households are especially unlikely to undertake energy efficiency investments, even when such investments are subsidized by utility or government demand-side management programs; causal factors include lack of information and lack of financial capability.

- * Little empirical work has been done to quantitatively estimate hassle factors. However, some recent research has shown that energy saving equipment initiated via demand-side management programs underperforms relative to initial expectations; presumably this is in part caused by problems with equipment installation, operation or maintenance. Some of these problems may be reduced as a technology gains a larger market share.

3.2.2.3 Implications of Addressing Market Imperfections

Regardless of whether or not one agrees on the definition of market imperfections, there are important issues raised by government policies designed to change market outcomes, and most sides agree that these issues must be addressed, although there is likely to be disagreement on the costs and benefits of such efforts.

The final empirical estimation of the efficiency gap depends on the estimation of the positive feedbacks between a reduction in energy service costs and an increase in energy consumption. If this positive feedback occurs, it can partially offset the carbon emission reduction benefits of the energy efficiency measure. This may have been the case with car transportation, in which the energy savings progress in automobile efficiency after 1973 was partly offset (at 80% in France) by a movement toward more powerful engines and a degradation of traffic conditions. Of course, again it is extremely difficult to quantitatively isolate causal factors. Was the increase in automobile use in part a consequence of the efficiency improvement, or can it be completely attributed to other factors?

There is also the issue of the cost of correcting market failures/market imperfections. Even if one could agree on the definition and magnitude of imperfections, the next problem is to determine how and at what cost they can be overcome or at least reduced. The true cost of efficiency improvement has only been examined more seriously in recent years through the utility regulation process in the U.S.; while public energy efficiency policies are rarely evaluated in a rigorous manner, the utility regulatory process in the U.S. requires independent and verifiable evidence of the true cost of energy efficiency gains. Research in

1 this area suggests that the costs of overcoming so-called imperfections may be higher than
2 originally suspected.

3
4 Thus, the amount of the efficiency gap potential that is likely to be identified in a "no
5 regrets" analysis may be substantially reduced when one accounts for the full costs of
6 overcoming market imperfections. More generally, some economists underline the risks of
7 technological forcing, by which a command-and-control policy would lead to the adoption
8 of technologies which would poorly replace the complex system of economic agents'
9 preferences as manifested through decision making processes. On the other hand, it is not
10 possible to conclude that no such potential is available.

11 3.2.3 Top-Down Approaches to Capturing Actual Behaviours:

12 The top down models may be classified into three major types. These are

- 13 • Traditional macroeconomic models
- 14 • Coupled energy-economy models
- 15 • Computable General Equilibrium (CGE) models

16
17 Traditional macroeconomic models began being used in connection with energy models in
18 order to understand the economic impacts of the oil price shocks of the 1970's. Examples
19 of traditional macroeconomic models used in analysis of climate policy issues are the DRI
20 model, the HERMES model developed by the European Commission or the Multisectoral
21 Dynamic Model (University of Cambridge) these models tend to have a relatively short time
22 horizon, extending to perhaps 2010, and to include hundreds of thousands of equations
23 representing all aspects of advanced industrial economies. Their purpose has always been
24 to trace out the shortrun dynamics of policy changes, and they are designed in a way that
25 allows varying levels of unemployment and other transitional effects.

26 Coupled energy-economy models typically combine a simplified model of the economy
27 with a detailed model of the energy sector. Two examples are the Edmonds-Reilly model
28 and Global 2100. These models are often based on detailed process models for energy
29 supply, but usually incorporate only simple demand equations for energy use. The two
30 examples extend over the longest time horizons, to 2100 or beyond.

31 In recent years, a new generation of models called Computable General Equilibrium models
32 have been developed. Examples of such models applied to climate issues include DGEM,
33 GREEN and the Goulder model. These models contain more complete representations of
34 the economy than found in the coupled energy-economy models, and focus on a time
35 horizon longer than that of traditional macroeconomic models but shorter than that of the
36 coupled energy-economy models. Thus far, all CGE models have based their energy
37 demand and supply relationships on econometric estimates and historical data rather than
38 detailed process models.

39 This brief historical survey suggests that there is not a single "Top-down" approach and
40 that the techniques are evolving rapidly. It can be said however that a basic "modesty
41 principle" guides this type of methodological approach as regard to technical adaptation and
42 innovation: this stems from the recognition that the factors that matter for determining the
43 cost of adopting any specific technology cannot be known very easily and that it is more
44 convenient to rely on observation of consumer choices in the market which give evidence
45 on the net result of all these hidden costs.

46 That is why, at the end of the spectrum totally opposite to the bottom-up approach, the

1 fundamental methodology of top-down models is to rely purely on time series econometric
2 techniques to estimate equations for household energy use and also for use of energy in
3 producing other goods and services; for energy models, a "four-factor" production function
4 is commonly used and states output as a function of capital, labor, materials and energy
5 inputs, the key coefficient being the "elasticity of substitution", which summarizes the
6 possibilities for substituting other inputs for energy when the price of energy changes. As
7 explained earlier, this amounts to representing technology in the form of a proxy; the main
8 advantage of the econometric approach is that the responses of production and consumption
9 patterns to change in energy prices and environmental controls are derived from extensive
10 historical experience.

11 More "pure" versions of top-down approaches are used in middle terms models
12 (HERMES, MDM); over longer time periods however, the DGEM model suggests an
13 endogenous representation for technical progress, mainly price-induced. Econometric
14 techniques were used in developing DGEM to estimate how the technical progress
15 parameter has changed in response to energy price changes, based on historical data and all
16 factor inputs and prices, including energy. This way of representing technical progress
17 provides a summary of deeper economic decisions about the allocation of resources to
18 research and development; this is the idea that, at least over the long run, it can be assumed
19 that technical progress is induced by the same economic motivations that determine choices
20 among available technologies. In many "top-down" models of this kind, econometric
21 equations can assume technical progress in energy supply technologies, for example, by
22 allowing capital to be substituted more easily for fossil energy in electricity generation over
23 time in order to represent progress in nuclear or renewable technologies.

24 Other long term "top-down" models depart from this strictly econometric approach and
25 introduce either judgmental elasticities or even explicit modelling of technology. Even if
26 this description will be viewed as too aggregated from a pure engineering perspective, it
27 does try to go beyond the implicit description of technology contained in standard
28 macroeconomic modelling. There are many reasons for such a change:

- 29 • first the standard econometric approach, using a rather high level of
30 disaggregation, requires a system of national accounts that successfully integrates
31 capital with the economy and production with very long time series data. This is a
32 major impediment for most developing countries and also for countries in transition
33 where the reliability of registered data is uncertain and where on going structural
34 changes in institutions are likely to create breakthrough in economic trends; this is
35 also an impediment for sectors which do not have an elaborated sectoral accounting
36 structure for energy that can be fruitfully coupled with economic balances;
- 37 • second many specialists are reluctant to use econometric relationships beyond one
38 decade and, in order to encompass long time periods, have chosen some kind of
39 "hybrid" procedure; in this procedure, a good part of economic relationships are
40 captured in a conventional way but at a higher aggregation level (e.g. one composite
41 non-energy good in Global 200) or the models rely on some kind of explicit
42 treatment of assumptions about technology.

43 This "hybrid" top-down model makes use of the following basic concepts:

- 44 a) linkage to a "process model" representing the energy sector In
45 contrast to standard top-down models which represent energy supply with the same type of
46 production function and estimated parameters as used for non-energy sectors, some
47 energy-economy models use "bottom-up" methods with detailed technology-based

representations of energy supply, thanks to the use of process models of energy use: two examples are the Gas Research Institute's modelling system, and the other is the linkage of Brookhaven's MARKAL model with the MACRO model developed by Al Manne [INSERT SOMETHING FOR EUROPE]. The process models that support some of the linked energy-economy models have included more explicit representations of improvement in technologies. They typically are optimization models that specify in their constraints the date on which new technologies will become available. For example, GLOBAL 2100 chooses the type of new electricity generating technology and adds from a menu of technology types which include fossil and non-fossil technologies. The cost per unit of capacity for non-fossil technologies, such as renewable and nuclear, declines over time.

This means that the treatment of the supply side measures uses, in fact, a "bottom-up" approach; the fact that assumption about technology differs as a function of expert opinions about the potentials of each technology (See the Williams' critic about the first results of Global 2100 (Williams REF) does not matter here. Disagreements are indeed about well-defined expert judgments and do not raise fundamental issues.

b) a **backstop technology** The process models, and Goulder's CGE model, represent fossil fuels as depletable resources, so that the cost of fossil fuels increases with cumulative past use. The rate of increase is a balance between a depletion effect and an improvement in extraction technology. Over the long run this model introduces the concept of a "backstop" technology. A "backstop" is a energy source that is available in unlimited quantity, at a constant cost, at a given date (e.g. risk-free nuclear energy, bioenergy or photovoltaics). Thus, in the long term, energy prices can rise to the level of the backstop prices, but no higher. The top-down models do not require an explicit description of the backstop technology; the point is that optimism or pessimism about the availability and cost of non-fossil sources (coming from an engineering based expertise) can be completely represented in assumptions about the cost of the non-fossil backstop.

Moreover, the cost of reducing emissions in the backstop period has implications for how high a cost should be incurred in earlier periods. We will not enter here into the theoretical justification of a rule coming from the so-called "Hotelling principle" and derived by solving the problem of finding the time path for emission reduction that achieves a target for carbon dioxide concentrations at some future date at least cost. Mathematically, this rule leads directly to the conclusion that costs are minimised by equating the marginal cost of emission reduction, in present value terms, in all time periods. In particular, since the marginal cost of emission reduction in the backstop period is determined by the difference in cost between fossil and non-fossil technologies, it is possible to start in the backstop period and work backward to determine the shadow process of carbon in each period to which marginal costs should be equated. This shadow price is the optimised carbon tax at each point of time.

A more intuitive explanation comes from thinking about the rate of return on investment. Suppose that \$100 spent on emission reduction either today or in the year 2000 will reduce emissions by 1 tonne. If that \$100 is instead devoted to capital investment, and the returns are reinvested for 20 years, the output of the economy will increase by $(1+r)^{20}$, where r is the social marginal product of capital (or the return to investment for the economy as a whole). If the social marginal product of capital is as little as 0.06, the \$100 investment will grow to \$320. Even if the cost of emission reductions is not brought down through development of new technologies, investing \$100 rather than spending it on immediate emission reduction makes it possible to reduce emissions by 3.2 tonnes after 20 years instead of 1 tonne today.

c) **autonomous energy improvement coefficients** Contrary to the treatment of energy supply, very few attempts have been made to incorporate "bottom-up" information on energy demand in macroeconomic models [CITE COHERENCE IN THE "CRASH PROGRAM"]. Many top-down models however, which incorporate an implicit representation of technology, and treat innovation through equations that relate energy demand to underlying factors such as process, incomes and population, recognize that there has been an important trend toward less energy use per dollar of economic output for many decades and that some of this trend is due to a general improvement in technology that cannot be explained on the basis of energy prices. They represent these factors through an exogenous trend labeled the rate of "autonomous energy efficiency improvement" (AEEI). AEEI is consequently the rate of improvement in energy efficiency that is projected to occur because of the development and adoption of new technologies even if energy prices remain constant.

In fact, depending upon the level of disaggregation of the model, the AEEI coefficient compounds very different trends some of them not strictly related to energy efficiency in the strict sense; in the most aggregated models, it encompasses structural changes in the composition of economic output and saturation of certain end use demands; more systematically it accounts for non energy price induced progress in energy efficiency embedded in overall technical progress and non price policies designed to enhance the uptake of energy-efficient techniques.

As a whole, it can be said that many attempts have been made to account for explicit assumptions about technical change in "top-down" models, with an asymmetry in the treatment of energy supply (energy sector optimisation, costs of fossil fuels as a function of resources exhaustion and technical progress, carbon-free backstop technology) and of energy demand (which remains rather aggregated). Even if the current CGE models have used aggregate econometric representations of the energy sector there is no reason why further development could not go in the same direction.

Two reasons for the remaining gap between macroeconomic models and bottom-up approaches as regards to energy demand are fundamental. First, there is an intrinsic difference in the degree of complexity between the description of energy sector (the number of techniques, observable data), and the description of demand dynamics (number of agents and techniques, role of untangible determinants in the consumer behaviours, role of the uncertainties in the development patterns). Second, as regard to the linkages between the "efficiency gap" and market failures, the top down response to the weakness of a pure "engineering perspective" can be interpreted in two different ways.

Technically indeed the standard "top-down" solution considers that the complexity of behavioural determinants is captured in econometric relationships calibrated over the past and resorts to the standard equilibrium constraints in a competitive market economy. But, these constraints do not suffice to characterise the way markets actually operate; even if most short and medium terms models allow for "frictional" imperfections in the market structure (for example a "mark up" pricing rule), rely on "Keynesian dynamics" which allow for over-capacities, or include "putty-clay" production functions which introduce some rigidities in the adjustments, these types of solutions do not address the kind of imperfections under consideration as regards to the adoption of techniques and consumption behaviours. At this level two interpretations can be given from the observed price and income elasticities:

- Markets behave perfectly, at least over the long run, and the apparent "imperfections:" pointed out by the "bottom-up" models are simply due to the

4.4/
Table 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

Table 4.4.2

Energy & Environmental Division, LBN, 1991.
CO ₂ emissions from developing countries: India, Indonesia, China, Argentina, Brazil, Mexico, Venezuela.
High and low emissions 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 scenarios. 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, Ogilvie, 1993.
Carbon Abatement Potential in Western Africa: Ghana, Sierra Leone and Nigeria.
High and low emissions scenarios 1985-2025. Reductions from baseline in 2025: Ghana 38%, Sierra Leone 25%, Nigeria 24%.
Energy system model, STAIRS.
Le Barre, E., Leger, L. F. L., Mignam, J. D. G., 1994.
Alternative Energy Strategies for Abatement of Carbon Emissions in Brazil.
Three alternative economic growth scenarios, abatement scenarios 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.
Calculations of abatement cost for individual abatement technologies.
Groupmann, 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 2000, 100% in 2100.
Energy system model and macroeconomic assessment of the impact of carbon taxes on final energy prices.

Table 4.3.1 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
	Olvera Martins et al (1992)	OM-2020	45	1.7
	Olvera 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
Hungary	Jacsoy (1990)	Jac-2005	17	-0.1
Poland	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	82	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 4.2.9 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 CO₂ 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.

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	1556	-	-	-
United Kingdom	0	0	12	-	36	63

Source : COHERENCE (1991), p. 60.

Table 4.2.8
Comparison of marginal cost of CO₂ limits in the COHERENCE exercise
(reduction of 10% relative to the 1988 level)

	<u>\$/t</u>
Belgium	46.8
Denmark	20.0
France	22.8
Germany	18.0
Greece	268.
Italy	495.
Netherlands	163.
Spain	1867.
U.K	14.4

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, 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 COs	EFOM-ENV	2010	11 countries
German Institutes (1991)	Bundesrat	Prognos	Econometric simulation	2010	Germany
Johansson, Rodund (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)	GHETA'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 equilibrium demand and price
Horizon Countries	20 (to 30) years 12 EC countries	1980-2030 Netherlands Switzerland	2030 Denmark	2030 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 abroad) 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	Yes	Yes	Yes	Yes	Yes (cross elasticities)
Number of energy products	28	30	?	?	3
Number of processes of supply/demand	300 approx	600	Numerous (complex interactivity between local energy grids)	500 to 1000 Special representation by type of user	
Renewables	Yes	Yes	Yes	Yes	
Link with the global economy	No feed back	No feed back	No feed back	Macroeconomic framework input/output model simulating sectorial economic development No feedback	Exogenous macroeconomic data
CO ₂ constraints	Ratio to 1988 emissions	Ratio to baseline	Ratio to baseline	?	Tax

* Test on three tax scenarios 85%, 80%, 100%.

Table 4.2.4 Effects of Different Types of Tax Revenue Recycling at the Community Level
(Energy Tax of 10\$/b1)

	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 (Zagarié et al., 1991).

² Rate of change after seven years (DC II-CEC, 1992, p. 59).

³ Bureau du Plan -Erasme- "Un redéploiement fiscal au service de l'emploi" (Rapport à la DCXI-CEC) 1993.

Table 4.2.3 Differences of the Macro-Effects of the Energy Tax Between EC Countries in 2001 or 2005
(difference in % with the baseline)

		FRG	F	UK	IT	NL	B	EUR6
GDP	Hermés ⁽¹⁾	0.22	0.06	-0.72	0.72	-0.16	0.57	0.15
	DRI ⁽²⁾	-0.26	-0.13	-0.52	-0.39	-0.39	-0.65	
Private consumption	Hermés ⁽¹⁾	0.27	0.03	-0.57	0.75	0.34	0.23	0.15
	DRI ⁽²⁾	-0.78	-0.39	-0.78	-1.04	-1.18	-0.78	
Employment	Hermés ⁽¹⁾	0.79	0.44	0.56	0.79	0.30	0.88	0.64
	DRI ⁽²⁾	-0.39	-0.13	-0.39	-0.39	-0.26	-0.39	
Inflation	Hermés ⁽¹⁾	0.45	0.80	2.12	0.86	0.80	0.20	0.95
	DRI ⁽²⁾	1.96	1.30	2.22	2.10	2.10	2.00	

(1) Recycling by reduction of social charges in HERMES Model (1993). The reference year is 2001.

(2) Mixed policy test in DRI Model (1993): 30% of the recycling in reduction of employers' social charges, 30% in reduction of personal direct tax, 10% in reduction of corporate taxes, 30% in incentives to energy conservation. The reference year is 2005.

4.2.1
Table Non-U.S. OECD CO₂ Abatement Cost Modelling Studies

Country	Author (year)	Key ^a	CO ₂ reduction from baseline	GNP impact/cost (reduction) from baseline
Australia	Dixon et al (1989)	AD (2005)	47%	2.4%
Australia	Industry Commission (1991)	AICG (2005)	40%	0.8%
Australia	Marks et al (1990)	AM (2005)	44%	1.5% ^b
Belgium	Proost & van Regemorter (1990)	BP (2010)	28%	1.8%
EC	DRI (1992)	ECDRI (2005)	12%	0.8%
Finland	Christensen (1991)	FC (2010)	23%, 21%	6.9%, 4.8% ^c
France	Hermes-Midas (1992: Karadeloglou)	FHM (2005)	11%	0.7%
Germany	Hermes-Midas (1992: Karadeloglou)	GHM (2005)	13%	1.3%
Italy	Hermes-Midas (1992: Karadeloglou)	IHM (2005)	13%	1.9%
Japan	Ban (1991)	JB (2000)	18%, 18%	0.4%, 1.7% ^d
Japan	Goto (1991)	JG (2000, 2010, 2030)	23%, 41%, 66%	0.2%, 0.8%, 1%
Japan	Nagata et al (1991)	JN (2005)	26%	4.9%
Japan	Yamaji et al (1990)	JYC (2005)	36%	6% ^e
Netherlands	NEPP (1989)	NEN (2010)	25%, 25%	4.2%, 0.6% ^f
Norway	Bye, Bye & Lorentson (1989)	NB (2000)	16%	1.5% ^g
Norway	Glomsrod et al (1990)	NG (2010)	26%	2.7%
Sweden	Bergman (1990)	SWB (2000)	10%, 20%, 30%, 40%, 51%	0%, 1.4%, 2.6%, 3.4%, 5.6%
UK	Barker (1993)	UKB (2005)	12%	-0.2%, +0.4% ^h
UK	Barker & Lewney (1991)	UKBL (2005)	32%	0%
UK	Sondheimer (1990)	UKS (2000)	4%	-0.5%
UK	Hermes-Midas (1992: Karadeloglou)	UKHM (2005)	7%	1.9%

^a The letters in the Key refer to the country and author; in cases where a global model is used a "G" is added before the date of the estimate

^b Study combines technology with macro-economic assessment of GDP impact.

^c Unilateral action and global action.

^d Tax case and regulation case

^e Values of both 5% and 6% have been given.

^f National policy scenario and global policy scenario

^g GDP costs for OECD range from 1 to 2%.

^h GNP gain when OECD tax levied with VAT reduced to maintain revenue neutrality. GNP loss when tax used to reduce the PSBR

4.2.2
Table Comparison of the Emissions Reduction Between Energy Tax and Carbon Tax

Geographical field	Horizon	Carbon tax	Energy tax
Global 2100 (Tax: 10 \$/bl)	2030	-50%	-46.5%
Hermes-Midas (Tax: 10 \$/bl)	2005 2005	-12.9% -6.55%	-6.55% -4.40%
Melodie (Tax: 200 \$/t)	2010	-15.7%	-12.6%
Midas (10 \$/bl)	2005 2005	-11.63% -3.98%	-7.52% -3.29%

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	26	-0.4	
	2010	53	-0.5	
	2030	82	-0.6	
National Academy of Sciences, 1991	n/a	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
	2010	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 & Nichols, 1990	2000	7		82**
		20		
Chandler, 1990	2010	0		0
		20		92
Lovins & Lovins, 1991	n/a	58*	0	0
Mills et al, 1991	2000	21	-1.2	-231
Nordhaus, 1990	n/a	6		13
Rubin et al, 1992	n/a	35	0	0 - <0
RIGES	2025	61	<0	<0
FFEF	2030	75	<0	<0

complexity of the consumer preference curve and of the complexity of hidden transaction costs in an economy. Along this line, economy is on the production frontier and mitigation strategies cannot but entail a net cost.

• Markets do not behave perfectly and econometric relationships convey implicitly these imperfections; then, there is room for "no regrets" improvements which can be realized in part with institutional reforms removing barriers to technical adoption and lowering transaction costs (the tenant/landlord tenure uncertainty for heating is a classical example). Calibrated general equilibrium models adopting judgmental elasticities are flexible enough to convey informations about the results of these improvements but it must be recognized that, up to now, one is obliged to resort to "ad hoc" assumption: as to the coupling between econometric models and bottom-up behavioural models, there remain many unsolved consistency problems.

3.3 Beyond Energy: Technology and Non-Energy GHG Emissions

FORTHCOMING

4. Review of Existing Costing Studies

In recent years, there have been numerous studies of the costs of reducing CO₂ emissions in various regions of the world.⁶⁸ Unfortunately, estimates have spanned such a wide range that they have been of limited value to policy making. Figure 4.1.1 from Grubb et al (1993) is illustrative of the current lack of consensus. It summarizes recent projections of the costs of CO₂ emission reduction in the US. 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, and on the "top-down vs. bottom-up" debate. In this section, we present a review of the results of studies that have attempted to provide estimates of the costs of reducing CO₂ emissions. 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 5, some general conclusions about these results, and the issues discussed in earlier section of this chapter, are presented.

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 to systematically compare the results of top-down 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 model comparison provides the most comprehensive application of top-down methodologies to date. The study addressed a wide range of policy questions. How large are emissions likely to grow in the absence of controls? How much market intervention will be required to meet alternative targets? What will be the price tag? In exploring economic costs, the modelers were asked to examine the impacts of timing, research and development, and revenue recycling.

The EMF exercise provides a wealth of useful information for policy making. Although the focus was primarily upon the US, many of the insights are applicable to developed countries in general. It is instructive to examine its results in some detail.

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

⁶⁸ As noted in earlier sections of this chapter, virtually all of the modelling analyses of GHG emission reduction costs consider only CO₂ reductions and ignore the other GHGs. Thus, this section of the chapter discusses only CO₂ reduction studies.

options.

A number of studies have highlighted the importance of GDP growth as a determinant of future carbon emissions.⁶⁹ For its reference case, EMF adopted the average of the IPCC high and low economic growth cases (Report of the Response Strategies Working Group, 1990). Also, for consistency with the IPCC, the study adopted the population growth projections of Zachariah and Vu (1988).

Although the EMF models differed considerably in their technology representation, the study attempted to impose uniformity with regard to world oil prices, the oil and gas resource base, and the cost of backstop technologies. For the reference case, world oil prices were assumed to be \$24/barrel in 1990 and to increase at a real rate of \$6.50 per barrel each decade until 2030. Oil and gas resources were based on the optimistic 95th percentile estimates of Masters and Root (1987).

The study assumed that three types of backstop technologies would ultimately become available: 1) a liquid synthetic fuel derived from coal or shale at \$50/barrel of oil equivalent; 2) a non-carbon based liquid fuel at \$100/barrel of crude oil equivalent; and 3) a non-carbon based electric option at 75 mills/kWh. Although these technologies are initially available in 2010, the models impose constraints on the rate at which they can enter the marketplace. The models also included a variety of carbon and noncarbon based supply options that are available at rising marginal costs.

4.1.1.2 Emission scenarios

Table 4.1.3 describes the principal EMF emission scenarios. The reference case projects future emissions in the absence of control measures. Hence, it indicates the amount of carbon that must be removed from the energy system in order to meet a given target. Figure 4.1.2 compares emission projections for the US. In all models, emissions increase well beyond 1990 levels. There are, however, substantial differences in the rate of increase.

The following identity due to Kaya (1989) helps explain why projections differ:

$$\begin{aligned} \text{The growth rate in CO}_2 &= \text{the growth rate in GDP} \\ &\quad - \text{the decline rate of energy use per unit of output} \\ &\quad - \text{the decline rate of CO}_2 \text{ emissions per unit of energy use} \end{aligned}$$

The models employed common assumptions about GDP growth, but they differed with regard to the last two terms in the identity. The more optimistic one is about the prospects for reducing energy intensity or the availability of low-cost substitutes, the lower the CO₂ growth rate.

The reference case in Figure 4.1.3 represents the average of the model results. If emissions continue to rise in the absence of controls, increasing amounts of carbon must be removed from the energy system in order to maintain a given level of emissions.

4.1.1.3 Carbon taxes

The modelers generally used taxes based on the carbon content of the fossil fuels in order to achieve a prescribed emissions reduction. The magnitude of the tax provides a rough

estimate of the degree of market intervention that would be required to achieve the carbon emissions target.

Table 4.1.4 compares model results for the stabilization and 20 percent reduction scenarios. Estimates range from \$20 to \$140 per ton for the carbon taxes required to hold emissions at 1990 levels in 2010. Estimates of the carbon taxes required to reduce emissions by 20 percent below 1990 levels in 2010 range from \$50 to \$330 per ton.

Two parameters are particularly important in explaining the differences in tax projections: the price elasticity of energy demand and the speed with which the capital stock adjusts to higher energy prices. Neither were controlled in the EMF experiments. Those models using lower price elasticities required higher taxes to achieve the same emissions goal. Those models which assumed greater malleability of capital required lower taxes.

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.

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 cost of controls 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 reduce total tax payments by individuals and corporations without affecting marginal tax rates. The GDP losses calculated in this manner measure the cost of the distortions to the economy caused by the imposition of the carbon tax. There are no credits or penalties for lump-sum recycling of tax revenues.

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. Increasing amounts of carbon must be removed from the energy system in order to hold emissions to a particular target.

⁶⁹ See for example, Nordhaus and Yohe (1983), Edmonds and Reilly (1987) and Manne and Richels (1994).

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.

Interestingly, GDP losses for a given year are influenced by expectations about limits in future years. All three emission reduction scenarios require that emissions be stabilized at 1990 levels by the year 2000. Yet losses are higher in 2000 for the scenarios which eventually require further reductions. The reason is that energy investments are typically long lived. Consumers and producers will be influenced by their expectations about the future.

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 that are more expensive than those that would take place in the absence of the taxes. Economists refer to these as deadweight losses. 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 that there is a good deal of reduction in energy intensity, even under business as usual. Critics frequently claim that top down models systematically underestimate the potential for reducing energy use. Figure 4.1.6 shows that this may not necessarily be the case. The models, on average, project sizable reductions in energy intensity – even in the absence of explicit measures to reduce emissions.

If one is more sanguine about opportunities for reducing energy intensity, the magnitude of the reductions can be easily altered through adjustments in model parameters (e.g., price elasticities and rates of autonomous energy efficiency improvements). The models in themselves have no inherent biases which limit efficiency improvements.

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 large in absolute terms, they are relatively small when measured in terms of a reduction in the GDP growth rate.

4.1.1.6 The relationship between timing and costs

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. 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 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.

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.

4.1.1.7 The potential role of R&D

A closely related issue is 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.

The 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.

4.1.1.8 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. The first

alternative recycling method, the lump sum tax cuts, is in the neutral manner described above.

Note that the GDP costs of the carbon tax vary considerably depending on how the revenues are recycled. In some models, the costs are more than offset with tax policies which encourage investment. On the other hand, 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. Although the alternative of increasing government expenditures was not examined, it is possible that such a policy -- not an unrealistic political outcome -- would increase the GDP costs of the tax over the neutral case.

4.1.2 A Review of Bottom-up Studies

This section summarises the results of selected bottom-up modelling exercises for the United States focusing on three factors that account for differences in emissions-reduction cost: methodology, scope of coverage and assumptions for technological progress. This evaluation 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 should be noted, however, that these scenarios require explicit and effective efforts in technological development, and that policy and behavioural means for effecting the results are not clearly presented in the most optimistic scenarios.

4.1.2.1 Comparison of bottom-up models and results

Bottom-up models produce both positive and negative costs for reducing future greenhouse gas emissions in the United States. Some bottom-up models suggest, for example, that cutting US emissions by 20 percent in 2010 would cost half of a percent of GDP, while others suggest that doing so would add an equal amount to the US economy in that year. These differences may be due both to the bottom-up methodology applied and to specific assumptions for technological options.

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:

- Adaptation method - substituting new technical option 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 behaviour.

The adaptation method can begin 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 framework. Alternative supply and demand options were then substituted into the framework until the demand for energy services is satisfied. Costs are computed using the difference between those of the reference scenario and those of the alternatives. No 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, much like 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 lacks the ability to reiterate its demand and supply functions in order to arrive at an equilibrium solution. Therefore, it cannot account for the feedback effects of the policies it tests.

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.

A very important assumption in most bottom-up models is the rate of GDP growth. GDP growth usually drives the models demand functions, and it is always assumed exogenously. Considerable variation may be seen in GDP 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. Curiously, the higher price scenarios have the lower energy-savings results.

Bottom-up models have been characterised as typically yielding large emissions reductions at low or negative costs. This characterisation may be misleading. 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).

This difference is due to both methodology and to assumptions, though key assumptions

are probably far more important than the methodology-as with top-down models.

The differences due to methodology involve the implementation of alternative energy sources or efficiency measures. For example, RIGES simple assumes penetration of markets for cost-effective technologies. Carlsmith 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, however, is the assumption for the cost of the alternatives. The assumed cost of biomass energy, for example, 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).

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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. In general, these studies have had relatively short-time horizons, focusing on the costs of stabilizing emissions in 2000 or a 20 percent reduction by 2005 (the "Toronto target"). Less attention has been paid to the longer-term issues of timing and R&D policy.

For the macro-economic analyses, the types of policies tested, have been limited to taxes on CO₂ and energy, under alternative domestic fiscal recycling schemes. Emission permit policies have not been examined at the national level. (Studies of the potential benefits from international trade in carbon emission rights will be reviewed in the section on global analyses.)

4.2.1 A Review of Top-down Studies

Top-down studies of non-US OECD countries (see Table 4.2.1) 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. In this section, we review the results of both.

4.2.1.1 National studies

Figure 4.2.1 reports the results of a number of non-US OECD national studies. Annual GDP losses are plotted as a function of emissions reduction, where reductions are measured relative to the model's baseline or business as usual emissions path. Note the story is quite similar to that for the U.S. The costs of emissions reduction tend to be

positive, but there is considerable variation in the magnitude of the losses.

Some of the differences are to be expected, particularly when they are intercountry in nature. Nations differ widely in indigenous resources, supply infrastructure and energy-use patterns. Those with plentiful natural gas supplies, large existing investments in carbon-free alternatives, and/or low energy use per unit of economic activity should see less growth in carbon emissions. Hence, less carbon will have to be removed from the energy system to meet a specific target.

Intercountry differences, however, do not explain the wide variety of results for an individual country. Here, as in the case of the US, we must turn to the models and their underlying assumptions. Unfortunately, sorting out the reasons for the disagreement is more difficult. Unlike the EMF exercise, these studies were conducted independently. There was no opportunity to standardize key inputs. Nevertheless, based on the discussions 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.

The national 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, the amount of fuel switching capability will be mostly restricted to switching among fossil fuels. Consequently, much of the burden for the emission reductions will fall on the demand-side of the energy sector.

The potential for end-use improvements remains one of the more controversial issues in the greenhouse debate. The wide range of opinion is reflected in the models. Those which are optimistic about the prospects for price and non-price induced conservation show relatively low emission reduction costs. Conversely, the more pessimistic models tend to report considerably higher losses.

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 modelers 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.

How a model handles preexisting energy taxes is also important. Many countries rely on energy taxes as a major source of revenue. If a country already has high energy taxes, it will require a larger carbon tax to achieve a given percentage increase in retail energy price levels. This means that the deadweight losses are apt to be higher. Unfortunately, models differ widely in their treatment of preexisting taxes -- adding yet another reason why results are apt to differ. (This was not an 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 maintenance.)

4.2.1.2 Regional studies

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 studies reported in Figure 4.2.1, encompassing both the transition and backstop phases. The longer-term perspective is useful when examining issues related to the timing of the transition away from fossil fuels and the potential role of technical innovation in lowering overall emission reduction costs.

The study examined a range of emission reduction scenarios. Among the more interesting is one in which emissions are permanently held to 1990 levels. Figure 4.2.2 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 4.2.1, 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 higher.

Assumptions about the rate at which backstop technologies can enter the energy system also tend to be important. GREEN, for example, assumes a more rapid introduction rate than the other models. Hence its marginal cost of emissions reduction is lower for each ton of carbon removed. This coupled with the lower baseline, easily explains the ranking of cost estimates among the three models.

Figure 4.2.3 shows the taxes that would be required to stabilize emissions at 1990 levels. The results from ERM, Global 2100 and GREEN are consistent with the above discussion. In addition, the OECD report included results from the IEA model. This econometric model is relatively pessimistic about the prospects for energy conservation and fuel switching. Hence, high energy prices are needed to bring down emissions.

4.2.1.3 The E.C. proposal for a combined carbon and energy tax

Perhaps the most widely discussed proposal for limiting CO₂ emissions is one put forth by the European Community (E.C. Commission, 1991). 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. Using oil as a point of reference, the tax would level off at \$10 per barrel in the year 2000. Nuclear energy and large scale hydroelectric projects would be taxed at a lower rate - approximately 50 percent that of carbon intensive fuels. The E.C. proposal represents a major departure from previous greenhouse initiatives. The goal is both to limit CO₂ emissions and to discourage energy use in general.

If the taxes were restricted to carbon-based fuels, the impacts would be unambiguous. Carbon taxes reduce CO₂ emissions both through their effects on energy consumption and also through fuel choice. But the E.C. tax proposal extends beyond fossil fuels. Coupling an energy tax to a carbon tax will lead to additional conservation, but it will also have an

impact on fuel choice. By raising the price of carbon-free substitutes, the proposal will reduce incentives for fuel switching. This may have an unwelcome impact on future carbon emissions.

Several analysts have looked at this issue and find that extending a carbon tax to other forms of energy reduces the effectiveness of measures to reduce CO₂ emissions. Table 4.2.2 compares the results from four such studies. Note that a broader based energy tax is not as efficient as a carbon tax in reducing CO₂ emissions. Taxing non-carbon based fuels provides a disincentive for fuel switching. Also significant is the impact that a \$10 barrel tax would have on future emissions. If the goal is stabilizing emissions at current levels, the studies suggest that the tax will have to be a good deal higher.

Several studies have attempted to quantify the macro economic impacts of the E.C. proposal. Table 4.2.3 reports results based on the Hermes and DRI models. The comparison is somewhat complicated by the fact that the models make different assumptions about how tax revenues are to be recycled. In the case of Hermes, applying the revenues to reduce social security taxes, produces a positive effect on GDP growth. The DRI model, on the other hand, is less optimistic about the prospects for a so-called "double dividend."

4.2.1.4 The effects of revenue recycling on employment in Europe

Many European countries are 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 as a means of increasing employment.

Table 4.2.4 compares the results from several studies of the impacts of an energy tax on GDP and employment. 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 a payroll tax cut can actually increase employment. One study suggests that recycling through a payroll tax cut only slightly reduces the negative impact on employment while others suggest that an energy tax recycled through a payroll tax cut will increase employment.

The differences among the modeling results can be explained in part by the choice of methodology. Neo-Keynesian models, such as HERMES, allow for unemployment in the short run in response to shocks to the economy and for structural unemployment due to inadequate demand for labor. Recycling through payroll tax reductions can increase demand for labor and reduce both cyclical and structural unemployment. Other factors may also be responsible for increased employment in these models. For example, energy taxes may cause labor to be substituted for energy and technical progress to be biased to save energy and use labor.

The longer term equilibrium models, such as Quest, do not account for unemployment fluctuations. These models may also contain relationships that offset the favorable effects of payroll tax cuts. For example, they may shift the burden of energy taxes onto workers and thus negate the employment-generating effects of payroll tax cuts. How minimum wages, unemployment compensation, and international competition are treated in different

models may also affect their conclusions on payroll taxes.

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 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 "efficient" 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 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 tax rates cannot be linked to "technologies" as in the other UNEP country studies.

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 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 optimisation 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.

4.2.2.4 The general limits of bottom-up exercises

The results of bottom-up exercises on European countries do not escape the well-known general limits in a consistent treatment of consumer behaviour and implementation processes.

The optimisation models in general address the implementation "problem" by assuming perfect rationality of producers and consumers, and perfect information and foresight into the future (evolution of energy prices, of the cost of technologies, etc.), and easy and equal access to finance. Technologies in most cases refer to the best available technologies, and to an ideal process of dissemination (without market power of centralised energy firms, without any barriers to diffusion, etc.).

Simulation models, as for example used in the IPSEP project or in the Danish UNEP study, treat the implementation process by using detailed background data on implementation processes in the end-use and supply sector, for example taking from Demand Side Management Programmes. These data are however not part of an integrated behavioural theoretical framework.

Certain aspects of the barriers to renewables, decentralised supply techniques or energy efficiency measures could be taken into account by way of constraints on development, and the shape of the learning curves. An approach in terms of scenarios as in the recent ECN study (1994) can also lend consistency to hypotheses on potential, costs and bounds on supply and demand processes. Conceptual progress has also been achieved by linking consistently technological, economic and socio-political facts in the "language" of costs and constraints and in the definition of scenarios, notably by the distinction between technical potential and realistic economic potential of energy savings in bottom up studies. These developments represent a degree of progress, but do not necessarily guarantee a common understanding on the part of the practitioners. A related problem is the definition of the different assumptions of the baseline scenario, which could refer *a priori* to different degrees of intensity of public policy and incentives for energy efficiency and promotion of renewable energy forms. Recent Dutch or Danish exercises (UNEP studies, 1994b) consider, for instance, baselines which include a good deal of energy efficiency measures, but arrive at very different results.

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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. Models which assume the existence of market mechanisms will miss many of the important features of these economies. Depending upon the progress of the restructuring, it may be some time before a market equilibrium assumption is appropriate.

The problem is further complicated by the fact that many of these economies are in 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). 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

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. Nevertheless, as we move beyond the OECD, we need to be increasingly circumspect in the interpretation of results.

A key issue in extending the models to emerging economies is the treatment of energy subsidies. Many of the early studies showed relatively high emission reduction costs. See for example, Dean and Hoeller (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.

There is some validity to this criticism. The removal of subsidies will result in costless conservation in addition to that induced by the AEEI factor. The early studies may have, indeed, underestimated the potential for demand-side savings. It is important to note, however, that the criticism applies more to the choice of input assumptions than to the models themselves. The models are not inherently limited to scenarios in which markets clear.

The importance of existing market distortions is underscored in a recent experiment by Manne and Schramm (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 domestic consumers from international price movements may well lead to a drop in carbon emissions over the next several decades.

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.

The implications of these analyses are important. The costs of stabilizing emissions may be relatively small for the countries of this region. Market failures have undoubtedly limited investment in energy efficiency. The potential for cost-effective reductions in energy use is apt to be considerable. Of course, the realizable potential may be a very different matter.

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. (See Appendix 3.1). The economies of the Former Soviet Union and Central and Eastern Europe present significant opportunities and serious difficulties in energy-related carbon dioxide emissions emission reduction. This region in 1990 accounted for over one-fifth of global energy consumption and energy-related greenhouse gas emissions.⁷⁰ However, the former planned economies rank among the most difficult to model because planning severely distorted their economies. Despite efforts at reform, the countries in transition remain the least energy-efficient in the world. Consequently, they may offer inexpensive opportunities for reducing future emissions. The long tradition of allocating resources away from consumer goods, however, also means that potential growth in transportation and household energy use--and greenhouse gas emissions--remains very high (Chandler 1990).

⁷⁰ Carbon Dioxide Information Center, Oak Ridge National Laboratory.

Much of the economic research on the cost of cutting greenhouse gas emissions has been based in western macroeconomics and has tended to treat planned economies as if their economic behaviour approximated that of market economies (Manne and Richels 1992). That approach has led some analysts to conclude that future energy use and greenhouse gas emissions in the planned economies will rise on steep growth curves. Recent studies of the distortions in the planned economies, however, have challenged that view, especially since the revolutions of 1989.

Remarkable political and economic changes, of course, 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. The extent of the transition varies dramatically by country, however, and is far from complete. While Poland and China produce half or even more of their national economic product in the private sector - loosely defined - Russia produces less than 10 percent privately. The most significant fact in the Former Soviet Union and in Eastern Europe is a depression at least equal to the decline in purchasing power of America's Great Depression of the thirties. The depth and length of Russia's and Eastern Europe's depression will affect greenhouse gas emissions for years to come and will inject profound uncertainty in any projection of future emissions levels.

4.3.2.1 Summary of studies

A comparison of emissions reduction cost studies reveals striking differences (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), and unlike the top-down studies mentioned above, most of the bottom-up studies incorporated economic restructuring.

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. (See "Appendix to Section 4.3.2.", below)

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

The debate regarding the value of top-down versus bottom-up modelling is perhaps most clearly focused in application to the transition economies. The key issue is the explicit assumption in top-down models that energy supply and demand are in competitive equilibrium in the planned economies. Applying equilibrium models to planned economies

amounts to assuming that planned economies mimic the behaviour of market economies, and therefore are optimised. This assumption is not consistent with western economic theory, and is impossible to accept empirically, particularly with regard to energy use.

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). Non-market economies lack both meaningful energy prices and hard-budget constraints. This poses significant challenges for modelling such economies.

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.

4.3.2.3 Towards integration - A combined model for Poland

Most analysts would agree that the ideal solution to the top-down versus bottom-up debate would be the integration of the two approaches. A few laboratories are attempting to produce the methodology to make this possible, and perhaps the leading example in the formerly planned economies is work underway at the Polish Foundation for Energy Efficiency (FEWE). This section describes the Polish work and suggests that it might serve as a model for equilibrium cost analysis that incorporates end-use detail.

Poland, an industrial nation of almost 40 million people, provides a good case study for assessing technological options in economies in transition. That nation now produces more than half its national economic product in the private sector, uses coal to satisfy three-fourths of its energy needs, and still suffers from the high energy-intensity levels inherited from its communist past. It is very likely that the policy and technical options for reducing greenhouse gas emissions are similar to those elsewhere in Eastern Europe (Chandler 1994).

The Polish Foundation for Energy Efficiency has developed a new model for a country study effort being funded by the US government to support developing and transition economies' assessments of climate response strategies. The purpose of the effort was to assess current greenhouse gas emissions, project emissions reduction options and changes

in sinks, estimate the cost of options for reducing emissions, and indicate strategies and criteria for reducing emissions.

Almost as interesting as the results of this case study prototype was the methodology employed. If one accepts that planned economies cannot be modelled like market economies, then one is forced to devise an altogether new way of modelling a transition economy. If the Polish economy is in serious disequilibrium, then some way must be found of ascertaining future economic activity that approximates equilibrium, assuming the economy makes a successful transition to market mechanisms. It is important to note that disequilibrium is used in the more fundamental sense than simply that supply does not equal demand, but that the economy does not approach any Pareto optimum for economic welfare.

FEWE created a compound model to remedy these methodological problems. Demographic and economic variables drive the model results, but are modified by sub-models which incorporate sectoral detail about, for example, heavy industry and energy production. The latter involved a major sector-by-sector assessment of the future of heavy industry and energy producers given the need to rationalise state-owned operations. That is, expert groups were formed to determine possible answers to questions such as: How much of the steel industry will be competitive on the international market (assuming the market is open to Poland)? How much of the coal industry can produce coal at a cost less than the world price? How much chemical demand can the national and international market support, and can Poland's producers compete? These estimates were used to constrain the macroeconomic variables.

Two major problems arise with this approach. The first is the danger that the modelling effort becomes a "black box," with hidden assumptions that are not reproducible. The only solution to this problem is to detail the assumptions. The second problem is more difficult. Incorporating exogenous constraints on energy demand will affect energy prices. For example, fuel economy standards in the United States reduced gasoline demand and helped drive down gasoline prices. Reduced prices due to higher technical efficiency leads to the "take back" effect--higher demand due to lower prices. People may commute longer distances and drive long distances on vacations. Research generally suggests that on a global scale, regulation-induced demand reduction can significantly reduce energy prices and therefore offset the demand reduction achieved by, for example, fuel economy standards. Rationalisation of an economy - elimination of wasteful demand caused by central planning - can have the same effect. No model yet exists to solve this problem.

The FEWE model consists of four major components:

A national macroeconomic simulation model.

An Energy Demand Model that is driven by the macroeconomic model and serves to establish a demand balance.

An Energy Supply Model which receives energy demand from the energy demand module component and chooses supply options on the basis of exogenous costs. This model produces output for energy supply and demand and greenhouse gas emissions.

A Technological Options Model, which calculates the levelled cost of a number of practical emissions reduction measures, and estimates their potential and cost for reducing emissions, given the supply and demand schedules received from the three previous components of the model. These options are assumed to be measures that will

not be captured by market mechanisms or price effects consistent with the demand and supply levels estimated in a base case. Several base cases are estimated, however, based on varying rates of structural change, productivity improvements, and investment.

The model is thus driven primarily by labour force participation and investments, and, using exogenously specified parameters, estimates value added, labour productivity, and personal consumption. The values of these parameters are adjusted over a ten-year period to reflect an assumption that a transition to a market economy will require that amount of time. At the end of the period, the modellers assume that macroeconomic relations in Poland compare with current levels in Western Europe. Energy prices are determined exogenously and are taken from projections of world levels.

Within the bounds of accuracy defined by these constraints, the Polish case study evaluated the benefits (emissions reductions) and costs (net) of selection of 25 energy carriers in 25 branches of the economy. In the latter, both changes in activity levels and energy-efficiency levels were estimated and incorporated.

The most difficult work included estimating costs per gigajoule (GJ) of demand reduction--and carbon dioxide reduction--for each of the technical options. (See Figure 4.3.4.) Options able to reduce emissions by up to 100 million tons per year in the year 2010 are available at a cost ranging from little or no cost to over \$200 per ton of carbon reduced. Most options, however, cost less than \$25 per ton.

4.3.2.4 Conclusion

This section has reviewed a selected set of studies of the greenhouse gas emissions reduction potential and associated costs for the post-planned economies. Marked differences are noted in the results for top-down and bottom-up models. However, it is suggested that some form of bottom-up modelling is appropriate for the formerly planned economies because these economies do not mimic market economies and are not in competitive equilibrium.

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Appendix to Section 4.3.2

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4.4 Studies of the Costs of Reducing CO2 Emissions in Developing Countries

Climate analysts have long recognized that GHG emissions and consequent climate change are a global phenomenon and need global responses. Yet in most global emission reduction studies, the analysis for developing nations is usually piggy-backed on the developed country studies. The fact that the developed nations at present account for nearly two-thirds

of GHG emissions has continued to overshadow the results of the very same models which show that within two or three decades the GHG emissions from the developing nations will surpass those from the present developed nations. GHG emission reduction studies for developing countries are therefore not many. The relatively few that do exist are based on methodologies designed for use in developed nations. These models tend to treat the dynamics of developing nations as a caricature of industrialized economies.

4.4.1 A Review of Top-down Studies

This is particularly so, in the case of top-down models where the dynamics of each geographical regions tend to mirror the market based economies of the western world. The models are market driven and assume the existence of future markets, perfect information, competitive economic dynamics on the demand and supply side, and optimizing behavior of producers, consumers and the government. These assumptions are often found to be invalid in developing countries.

In addition, top-down models tend to underestimate the contributions from the informal sectors of developing economies. In many countries, these sectors account for the overwhelming proportion of agriculture and land use activities; and employment and household energy consumption. Activities in these sectors, such as traditional biomass use, deforestation, rice cultivation, animal husbandry, account for significant greenhouse gas emissions. 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. 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

A study by researchers from the OPEC Secretariat used a macroeconomic model to investigate the impacts of OECD type carbon taxes on developing countries (Walker and Birol, 1992). A merit of the study is that it explicitly considered non-commercial energy (NCE) and analyzed the impact of income and price levels on consumption of NCE.

The study finds that the income elasticity of NCE is negative, meaning that consumers shift from NCE to commercial energy as income rises. But more importantly, the study also reports an inverse relationship between non-commercial and commercial energy demand in response to price changes. That is, consumers switch from commercial to NCE in the case of price hikes. Both of these results point to the obvious and what is well known in the developing nations, and yet most often forgotten or ignored in top-down analyses. Based on the above findings, the study concludes that in the absence of effective controls on deforestation, carbon taxes would create incentives to deplete forests for energy use.

4.4.2 A Review of Bottom-up Studies

4.4.2.1 Overview of the assessed emission reduction studies

National climate-change emission reduction studies for developing countries carried out so far have been primarily bottom-up studies. These studies have either assessed the emission reduction potential of individual technologies, or performed an integrated analysis for main emitting sectors such as the energy system. Some of the main studies are listed in Table 4.4.2.

The national studies for developing countries have focused on energy system analysis and CO₂ reductions. In most cases the analysis is carried out for a scenario period from 1988/90 to 2020/30. Emission reductions are generally calculated as an increment to a baseline case which may be defined to reflect reference economic development and energy requirements (UNEP 1994a), or as a high emission case for the energy sector (Sathaye and Goldman 1991). Two main coordinated country study efforts have been carried out by the Lawrence Berkeley Laboratory (LBL) and by UNEP Collaborating Centre on Energy and Environment (UCCEE). The results and methodological framework of these country studies are assessed in relation to similar country study activities for China, West Africa and South East Asia in order to evaluate possible common conclusions.

Not all studies have evaluated the costs of achieving emission reduction. Only the UNEP studies (UNEP 1994a), the LBL study for India (Mongia 1991), and the ADB study for China (Asian Development Bank 1993) have assessed costs. These include direct investment costs, O&M and fuel costs. The Indian and Chinese country studies estimate such emission reduction costs for a specific emission reduction target at different points in time. The UNEP studies have estimated emission reduction costs for a range of target reductions spanning 12.5% to 25% reduction in 2005/10 and 25% to 50% reduction in 2020/30. The levelised emission reduction costs for these targets have been estimated following a cost curve format, in which individual technical options and comprehensive emission reduction strategies are ranked according to marginal costs (UNEP 1994c).

4.4.2.2 Main study assumptions on the development in GDP, primary energy assumptions and CO₂ emissions

Growth rates of GDP, primary energy consumption and CO₂ emissions are shown in Table 4.4.3 for the reference and emission reduction scenarios of the country studies. The economic growth rates range from 3.0% up to 8.0% annual growth, with the bulk of the projections below 5.0%.

There is a general tendency for higher GDP growth assumptions in the UNEP studies compared with the LBL studies. For Brazil there is a variation between 4.7% and 3.2% in the UNEP and LBL study, and for India the variation is between 6.3% and 5.0%. Venezuela on the other hand has a slightly higher GDP growth assumption in the LBL than in the UNEP study. These disparities may be a consequence of different approaches to the definition of national economic growth assumptions. The UNEP studies have defined national scenarios on the basis of a critical evaluation of official national macroeconomic and energy system forecasts. The LBL studies forecasted economic growth and energy requirements using standardised technology data and international development trends as focal points.

The elasticities of primary energy to GDP, CO₂ emissions to primary energy and CO₂ emissions to GDP are shown in Table 4.4.4. Most of the countries expect primary energy consumption to grow more slowly than GDP in the reference as well as in the emission reduction scenario. Many of the countries have already in the reference case a primary energy/GDP elasticity between 0.6 and 0.8, which is low for a developing country. The reference case for China has the lowest primary energy/GDP elasticity among the studies amounting to 0.5. This is explained by the low efficiency of the present energy system and the introduction of nuclear power plants.

In most of the studies the CO₂/primary energy elasticity is above unity in the reference scenario. A remarkably high value is projected for The UNEP Brazil study and for Ghana,

Nigeria and Sierra Leone in the reference. These high values are a consequence of an extensive replacement of biomass by fossil fuels in the reference. The resulting CO₂/GDP elasticity in the reference scenarios for most of the country studies is close to unity.

The different assumptions on the development in GDP, primary energy and CO₂ emissions in the reference case implies that the imposition of emission reduction targets related to future baseline emissions would have quite different implications for the absolute development in emissions in the emission reduction scenarios compared with today's level.

The UNEP reference emissions exhibit a large variation, 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 emission reduction scenario, after the 30% reduction from baseline, Thailand still projects a six-fold increase in emissions, and Brazil project a three-fold increase after a 50% reduction. The rest 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 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.

The LBL high emission (reference) scenario shows a variation 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 low emission (emission reduction scenario) the 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.

A striking difference between the UNEP and LBL approaches is evident in the case of Brazil. The UNEP Brazil study assumes high reference growth in primary energy consumption and increasing CO₂/primary energy intensity. This is partly a consequence of a low projected fuel price increase in the UNEP study, which makes the present biomass energy supply unprofitable seen from a pure "fuel-economic" point of view. The LBL study for Brazil projects a much slower increase in CO₂ emissions in the reference and emission reduction case due to lower economic growth assumptions, lower CO₂/primary energy intensity and a larger potential for end-use demand efficiency improvements in the emission reduction scenario. 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.

4.4.2.3 Emission reduction costs

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 reduction targets increase.

Estimated emission reduction costs for the participating industrialised countries Denmark, and The Netherlands are also presented in the figure for illustrative purposes. In Denmark a substantial negative cost potential is identified, while the Netherlands estimate much higher emission reduction costs. The divergent results can be explained to a certain extent by different assumptions regarding the inclusion of "no-regret" options in the reference case. 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 to + \$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 with France as an exception. The total emission reduction costs are negative for Egypt and Senegal.

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.

4.4.2.4 Technical options in the studies

The country studies have estimated emission reduction potential, and in some cases costs, taking an evaluation of technical options as the starting point. For the emission reduction costing studies, such as the UNEP studies, the emission reduction potential can be related to individual technologies or to comprehensive packages of technologies. The cost and emission reduction potential of the options have been assessed using energy system models to evaluate end-use efficiency improvements, fuel substitution and new supply technologies

in an integrated way. This analysis has in practice been done with different degrees of sophistication (UNEP 1994a).

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 level of aggregation varies, depending on the level of detail in the country studies, ranging from the assessment of 57 options in the study of Egypt, to fewer than ten options in the Brazil, Senegal and Thailand studies.

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.

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.

The studies done by LBL have in general included more details on end-use efficiency measures than the UNEP studies. The two coordinated sets of studies thus complement each other with regard to coverage of all relevant emission reduction technologies.

4.4.2.5 Implementation issues

One general similarity between all the emission reduction studies for developing countries is that they include a significant potential for energy end-use savings in industry/or households. These options have been assessed to have negative or very low emission reduction costs.

In order for the CO₂ reduction to be realised in practice however, such options must be implemented by industries or private households. This requires widespread information and access to financial sources by the many individual decision makers.

No formalised procedure for estimating implementation costs has been defined in any of the developing country studies. Implementation problems were treated in some of the studies by defining expected penetration rates for end-use technologies, assuming for example that 25% of an identified technical potential could be implemented in the short term and a larger share in the long term. These assumptions are made as exogenous input to the bottom up calculations.

4.4.2.6 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). Key assumptions and results of the study are in the following referred (all results refer to the low economic growth alternative of the study).

Baseline scenario 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.

Policy scenario The growth rate of primary energy consumption is reduced to 2.7% and CO₂ emissions increase by 2.1%. Total emissions are reduced by 23% from the baseline in 2050.

The main emission reduction option relating to energy supply is nuclear power, with the nuclear share of primary energy supply increasing from 9.9% in the baseline to 13.9% in the policy scenario. The share of hydropower and natural gas is also increased slightly. Total primary energy consumption are decreased by 14% from the baseline to the policy scenario.

Some macroeconomic implications of the policy scenario have been assessed by comparing total energy expenditures (investments and running costs) with GDP. Total energy expenditures are assessed to amount to as much as 20% in 1995, decreasing to below 15% in the baseline and below 10% in the policy scenario in 2050. This means that economic savings are assumed to be achievable if a restructuring of the energy system can be carried out as in the policy scenario. Such a process might however be difficult to implement in a capital- and foreign exchange constrained economy such as China.

4.4.2.7 Comparability of studies using different methodological frameworks

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. In general these options comprise end-use energy efficiency improvements, energy supply efficiency improvements and introduction of fuels with lower carbon-intensity. These technologies cover the first and cheapest part of the emission reduction potential and can, especially in the longer term, be supplemented with renewable energy technologies, more far-reaching end-use savings and advanced combustion technologies. The long term emission reduction potential will consequently be extended, and as estimated in the UNEP studies, is likely to be cheaper compared with short term reduction targets.

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 potential and costs.

A uniform methodological framework has been used in the UNEP studies and LBL studies, respectively, and some conclusions can therefore be reached on the comparability of different methodologies on the basis of these studies. The major differences between the methodological approaches used in the UNEP and LBL studies relate to the baseline definitions for the economy and energy sector development, and to the detailed technology assumptions.

Economic development scenario. 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 planning efforts. Formalised macroeconomic models and long-term economic projections, however, do not exist for many of the developing countries, making it difficult to make valid projections. Available 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.

Baseline energy scenarios. Countries which participated in the UNEP study were recommended to base assumptions for expected efficiency improvements in the reference energy system on national economic development programmes and the availability of capital and foreign exchange. Country teams were free to make judgements on the most likely implementation rate for profitable efficiency improvements in the reference. This meant that 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. Another difference in national definitions of reference scenarios relates to assumptions on large structural changes in fuel supply. Major supply system changes were included in the Brazil study. Here the reference case assumes replacement of present biomass use, including ethanol, with fossil fuels. The LBL studies defined the reference energy scenarios in order to reflect a continuation of historical trends. This approach can be said to be in line with the "business as usual" approach used in many energy system analyses for industrialized countries. These reference scenarios in general assume gradual changes in supply structure and a slow rate of implementation of efficiency improvements. Taking Brazil as an example again, this means that LBL's reference scenario assumes biomass to continue in Brazil.

Comparing the UNEP and LBL approaches, it appears that the UNEP approach has a tendency to impose a larger variation in reference emission projection than the LBL.

approach.

Technology data. National specific investigations on technologies were used in the UNEP studies, while the LBL studies used international standardised data on efficiency and penetration rates.

The real difference between the two approaches is difficult to assess because national technology choice and assessment in the UNEP studies was influenced by available international technology data as used in the LBL studies. A major difference does however arise from the technology menu assessed in the two group of studies especially regarding end-use technologies. LBL, through a standard menu of end-use options, achieved a more comprehensive coverage of possible end-use energy savings than the UNEP studies. The technologies assessed in the UNEP studies vary in number and coverage between the countries. Thus Egypt covered all relevant end-use technologies and sectors, while others primarily covered either industry or the household sector alone.

In conclusion the different approaches to the definition of reference scenario and technology assumptions can lead to national emissions forecasts, emission reduction potentials and costs which diverge in absolute terms. Differences may especially arise from reference scenario assumptions on the implementation of efficiency improvements. If a reference scenario is defined to include all profitable efficiency improvements, then all negative cost options are assumed to be included in the reference and only positive cost options are left for emission reduction. The negative-cost options are however scheduled for implementation in the scenario period, regardless of whether they are referred to as profitable efficiency options or negative-cost emission reduction options. This means that the reference and emission reduction scenarios consider the same types of technologies, but that these can be assigned to be part of different scenarios depending on assumptions on efficiency improvements in the reference.

A given emission reduction from baseline will in general be more expensive and will imply the use of more costly and advanced technologies, if it is measured in relation to an "efficient" reference energy system than to an "inefficient" one.

4.4.2.8 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.

A key methodological issue for emission reduction studies for developing countries is to define a common approach for defining reference scenarios for the energy sector and other

main GHG emitting sectors. In this context it should be recognised that the GHG reduction objective should be evaluated in relation to a comprehensive national development context, and that the implementation of any emission reduction option will be interrelated with general economic development and performance. This means the link between energy forecasts and macroeconomic projections must be improved, and that a broader range of national institutions and interests must be considered in the evaluation of emission reduction options and strategies.

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4.5 Global Studies of the Costs of Reducing CO₂ Emissions

The review of existing studies up to this point has focused on country or regional analyses. In addition, there are a growing 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. If significant reductions in emissions are required, they can be accomplished only through international accords and cooperation. It will be helpful to have some sense of the overall costs before confronting the difficult issue of burden sharing.

A global perspective is also important in assessing the costs to individual countries. Actions taken in one region are apt to have "spillover" effects into other regions. Partial equilibrium analyses ignore 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.

Finally, and perhaps most importantly, a global perspective is necessary if we are to identify economically efficient strategies for achieving emission targets. The Framework Convention on Climate Change states that "policies and measures to deal with climate change should be cost-effective so as to ensure global benefits at the lowest possible cost." This means that emission reductions should be carried out where it is cheapest to do so. Analysis at a global scale is needed in order to construct a "least-cost" global emission reduction supply curve.

However, all of the caveats expressed above about the limitations of country-specific or regio-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.

Virtually all of the global studies are top-down in approach. The very nature of bottom-up studies means they tend to be specific to particular regions or countries. As a result only top-down studies will be reviewed here.

4.5.1 A Review of Top-down Studies

Several of the models used for regional analyses provide the capability for analyzing costs at a global level. These 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. In order to represent regional differences and trade effects, local economic and technological 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 regional studies, the top-down global analyses indicate that emission reduction will involve positive costs, but the size of these costs varies from study to study. In this section, we will try to understand why these results differ so widely. In doing so, we hope to gain additional insights into the costs of emissions reduction at the regional and global level.

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. We begin by examining the results from the stabilization scenario.

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 cooperation. In the analysis which follows, each region is required to hold emissions to 1990 levels without the opportunity of shifting emission reduction from high emission reduction cost to low emission reduction cost regions. That is, there is no trade in carbon emission rights. Later on, we will explore the potential benefits from relaxing this constraint.

Figure 4.5.2 compares losses in the year 2020. It also shows the reduction in the annual growth rate of CO₂ emissions required to achieve the desired target. Note that losses vary by a factor of nearly three -- from .8 to 2.2 percent of gross world product. Although it is difficult to isolate all of the reasons for the differences, the discussion of the preceding sections points to several possible causes.

The higher the baseline emissions path, the more carbon to be removed from the energy system to maintain a given target, and hence the higher the overall emission reduction costs. The global baseline, however, is not the sole determinant of losses. The GREEN model projects the highest emissions for 2020, hence it requires the largest annual reductions to maintain stabilization. Yet it does not lead to the largest costs. This is because it is the most optimistic of the four models about the rate at which "backstop" technologies can be introduced into the energy system.

Conversely, ERM projects the lowest baseline emissions for 2020. As a result, less carbon must be removed from the energy system to achieve stabilization. Even so, economic losses are still higher than those projected by CRTM. This is because ERM does not include backstop technologies. The marginal costs of emissions reduction is therefore higher.

In a separate experiment, it was determined that ERM and MR project essentially the same baselines when employing identical rates of autonomous energy efficiency improvements. For the OECD study, MR adopted an average annual rate of .5 percent whereas ERM assumed that non-price induced efficiency improvements occur at twice this rate. Standardization for this key parameter brings these two models much closer together in their projections of GDP losses from emissions reduction.

The OECD Model Comparison Project suggests that the principal reason why studies differ is alternative views about the future character of the energy system. In an attempt to place greater reliance on knowledgeable experts, Manne and Richels (1994) polled a group of individuals on their beliefs about key parameters to which emission reduction costs are particularly sensitive.

For each parameter, expert beliefs were encoded in the form of probability distributions which were in turn combined to form a group probability distribution. Using the poll responses to describe the uncertainty surrounding critical parameters, a probability distribution was then constructed for the costs of stabilizing global CO₂ emissions at 1990

1 levels.

2
3 Figure 4.5.3 presents the results of the analysis. The spread of the distribution is quite
4 broad, ranging from .2 to 6.8 percent of gross world product (GWP). The median (that is,
5 the fiftieth percentile) is approximately 1.0 percent of GWP. The distribution is also quite
6 skewed. Because of the long right-hand tail, the mean value lies to the right of the median.
7 It is approximately 1.5 percent of GWP.

8 4.5.1.2 The costs of meeting alternative emission targets

9
10 In addition to stabilization, the OECD project examined scenarios in which the growth rate
11 of emissions in each region is reduced below the baseline by 1, 2 and 3 percentage points,
12 respectively. Figure 4.5.4 plots GDP losses as a function of worldwide emissions.
13 Although there are significant variations across models, the results yield some important
14 insights.

15
16 First, notice that the costs of stabilizing emissions at 1990 levels (approximately 6 billion
17 tons) are lower in 2000 than in later years. The increase in emissions over the present
18 decade is relatively small and there are ample quantities of low-cost substitutes (e.g.,
19 natural gas and demand-side management) to do the job.

20
21 This does not continue as we move out in time. Although technical progress may eventually
22 lower the marginal cost of emissions reduction, more and more carbon must be removed
23 from the energy system in order to maintain a particular target. As a result, annual losses
24 are apt to increase.

25
26 As one would expect, macro-economic impacts rise with the stringency of the target, but it
27 is important to note the non-linear nature of the loss function. Successive reductions are
28 increasingly expensive. As cheaper options to reduce emissions are used up, it becomes
29 increasingly difficult to substitute for, or to economize on, fossil fuels.

30
31 For those models with backstop technologies, the marginal cost of emissions reduction will
32 eventually level off. This accounts for the linear nature of the cost curves for CRTM and
33 MR in the year 2100. ERM, on the other hand, excludes backstop technologies. Hence
34 costs continue to rise non-linearly as a function of emissions reduction.

35 4.5.1.3 The potential gains from international cooperation

36
37 Emission reduction actions aimed at addressing the risk of climate change have a global
38 public good character. That is, they affect global emissions and atmospheric concentrations
39 equally, irrespective of the geographical and sectoral origin of the emissions. The least-cost
40 global solution entails reducing emissions where it is cheapest to do so. If the costs of
41 reducing a ton of carbon were constant and the same in all regions, the location of the
42 emissions reduction would have no effect on global costs. To the extent that marginal costs
43 vary among regions, there are opportunities for efficiency gains through international
44 cooperation.

45
46 Economic efficiency would be enhanced through a system of international trade in carbon
47 emission rights or a global carbon tax. Emission rights trading would allow for a more
48 efficient allocation of emission reductions across regions by letting countries trade to the
49 point where the marginal cost of emissions reduction is the same in all places. A global
50 carbon tax would also result in the marginal cost of emission reduction being equal for all
51 countries.

1
2 Figure 4.5.5 provides some insight into the opportunities for international cooperation. It
3 shows the carbon taxes that would be required, on a region-by-region basis, to achieve a
4 given level of emission reduction (OECD, 1994). Although the emission reduction cost
5 curves are from a single study, virtually all analysts agree that the costs of emissions
6 reduction are apt to vary widely among regions. Efficiency gains can be reaped from
7 shifting emission reductions from high to low marginal cost regions. If the resulting cost
8 savings are shared between participating regions, all can be made better off.

9
10 The potential gains through international cooperation can be demonstrated by comparing the
11 total costs of achieving a global emissions target -- with and without trade in carbon
12 emission rights. Table 4.5.2 reports the results of such an experiment. From the viewpoint
13 of economic efficiency, trade in emission rights is clearly worthwhile. A reduction strategy
14 in which each region reduces its emissions by the same percentage will not be globally cost
15 effective.

16 4.5.1.4 Allocation of emission rights

17
18 Cost effectiveness (as described above) can be achieved through both a common carbon tax
19 or under a system of tradable permits. If we seek to establish international trade in carbon
20 emission rights, a critical consideration will be the allocation of permits. The decision on
21 how emission rights are distributed among regions does not affect global costs, but it will
22 have a major impact on the distribution of net gains and losses and hence on the perceived
23 equity of the agreement. Unfortunately, for the drafters of such an agreement, there is no
24 unique definition of fairness.

25
26 Edmonds et al (1993) studied a variety of schemes for allocating emission rights. At one
27 end of the spectrum they considered a "grandfathered" emissions principle. This is one in
28 which future emission rights are allocated on the basis of rates at the time of joining the
29 protocol. At the other end of the spectrum, they examined a "per capita emissions" principle
30 where emissions are allocated on the basis of adult population.

31
32 Figures 4.5.6 and 4.5.7 present results for a scenario in which global emissions are
33 permanently held at 1990 levels. The allocation of emission rights differ markedly under
34 the two allocation schemes. OECD countries hold on to approximately fifty percent of the
35 emissions rights when the status quo is maintained. With a shift to a per capita emissions
36 principle, their share drops to about twenty percent.

37
38 The implications for costs are as expected. The OECD is much better off with the status
39 quo. Indeed, they would be a seller of emission rights and the wealth transfers would be
40 sufficient to reduce GDP losses to a negligible level. Under such a scenario, the economic
41 burden to developing countries would be substantial.

42
43 A per capita allocation scheme would substantially shift the distribution of net benefits and
44 losses. The OECD countries would incur significant GDP losses and the region labeled
45 ROW (rest of world) is now a winner. Under either scheme, China incurs substantial
46 losses. Unless it can greatly increase its energy efficiency, its huge demands for energy far
47 outstrip its allocation of emission rights.

48
49 In a third scenario, Edmonds et al explored what they refer to as a "no harm to developing
50 nations" principle. Here developing nations receive sufficient emission rights to cover their
51 own emissions and to generate sufficient revenue to cover the economic cost of
52 participating in the protocol. This leave developing countries no worse off in terms of GDP

than had they not participated in the agreement. The results are shown in Figure 4.5.8.

4.5.1.5 Carbon "leakage"

Some proposals for limiting CO₂ emissions call for high-income countries to take the lead in reducing emissions. When actions are limited to a subset of regions, it is important to consider 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:

- Changes in trade structure. The imposition of a carbon tax will change the comparative advantage of production across regions. This can alter the location of the production of energy intensive products; and hence, regional emissions.
- Increased demand for fossil fuels. The implementation of regional emission reduction policies will reduce the demand for fossil fuels and depress their world prices. This will stimulate energy demand and carbon emissions in non-participating regions.
- Changes in relative energy prices. This may induce inter-fuel substitution in non-participating regions, leading to changes in their overall emission levels. (Note that the net impact on regional emissions could be positive or negative.)
- Regional terms of trade gains and losses induced by changes in the world prices of fossil fuels. Trade induced real income changes will in turn lead to regional shifts in consumption and thus carbon emissions.
- Reduced income of energy exporting regions. Reduced world demand for fossil fuels may lead to reduced resource rents, incomes, consumption, and thus carbon emissions in fossil fuel exporting countries (a case of "negative carbon leakage").

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.

Box 1.1
Gross and Net Costs

[FORTHCOMING]

Figure 1.1 Sample technology cost curves

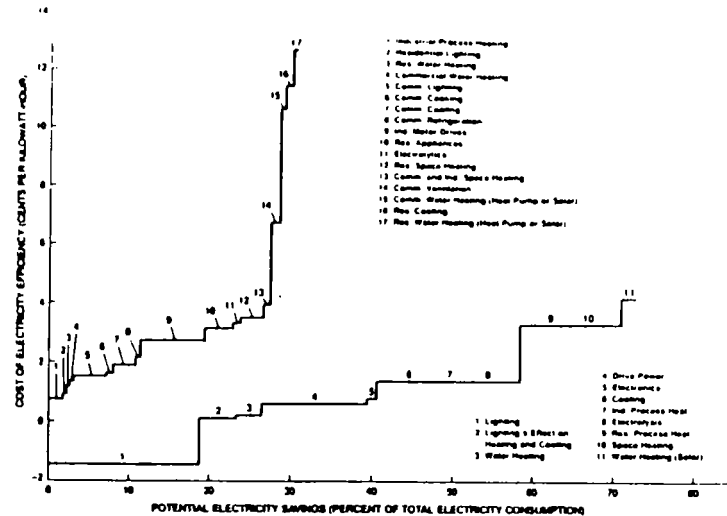


Figure 1. Discrete energy-efficient technology cost curves for the United States. The figure shows two estimates of the potential savings of electric percentage of (system demand) available by using various more efficient technologies, in order of increasing cost per unit saved. These costs compare typical 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. 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. Source: Scientific American, September 1990

Figure 1.2
Relationship Between Economic Activity
and Emission Reduction

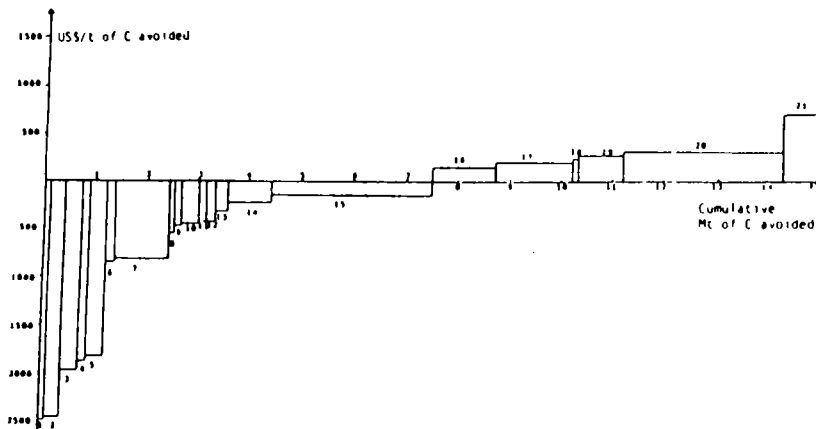
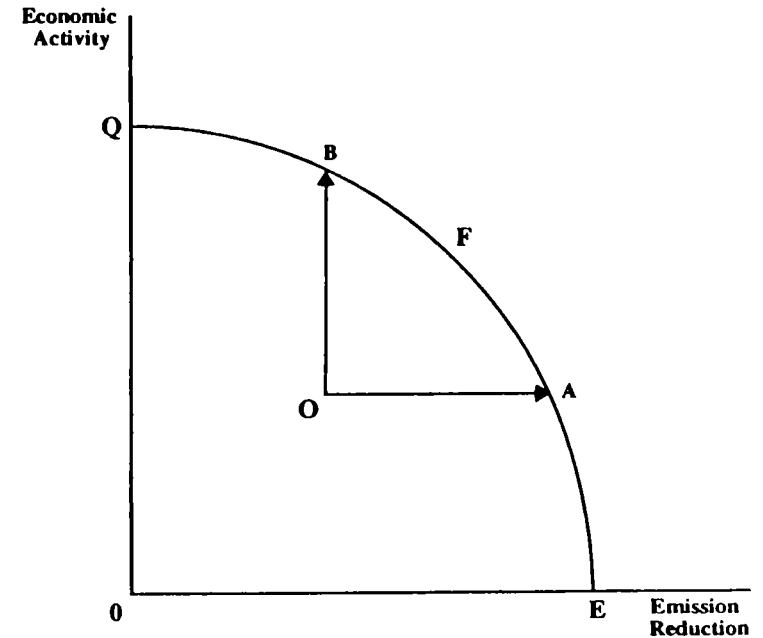
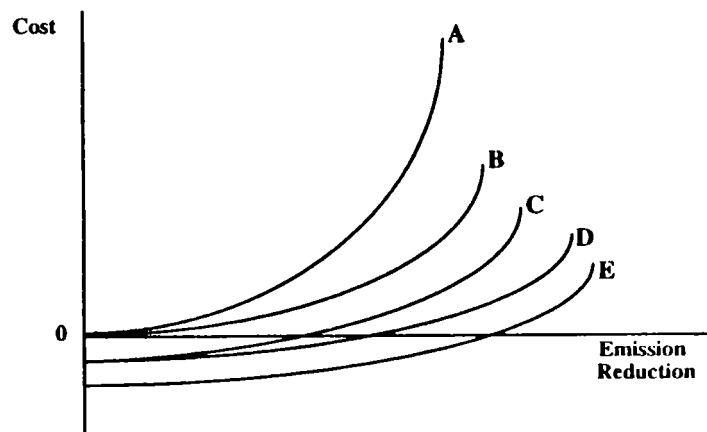


Figure 2. Discrete CO₂ abatement technology cost curve, Brazil. Cumulative amount of C avoided by the year 2000 for several technologies of improvement. 1-Fluorescent (incandescent) efficient (incandescent) standard (incandescent) commercial sector. 2-Fluorescent (incandescent) efficient (incandescent) standard (incandescent) commercial sector. 3-Fluorescent (incandescent) efficient (incandescent) standard (incandescent) commercial sector. 4-Compact fluorescent (incandescent) standard (incandescent) residential sector. 5-Compact fluorescent (incandescent) standard (incandescent) residential sector. 6-Compact fluorescent (incandescent) standard (incandescent) residential sector. 7-Compact fluorescent (incandescent) standard (incandescent) residential sector. 8-Compact fluorescent (incandescent) standard (incandescent) residential sector. 9-Compact fluorescent (incandescent) standard (incandescent) residential sector. 10-Compact fluorescent (incandescent) standard (incandescent) residential sector. 11-Compact fluorescent (incandescent) standard (incandescent) residential sector. 12-Compact fluorescent (incandescent) standard (incandescent) residential sector. 13-Compact fluorescent (incandescent) standard (incandescent) residential sector. 14-Compact fluorescent (incandescent) standard (incandescent) residential sector. 15-Compact fluorescent (incandescent) standard (incandescent) residential sector. 16-Compact fluorescent (incandescent) standard (incandescent) residential sector. 17-Compact fluorescent (incandescent) standard (incandescent) residential sector. 18-Compact fluorescent (incandescent) standard (incandescent) residential sector. 19-Compact fluorescent (incandescent) standard (incandescent) residential sector. 20-Compact fluorescent (incandescent) standard (incandescent) residential sector. 21-Compact fluorescent (incandescent) standard (incandescent) residential sector.

Figure 1.3
Alternative Views on Costs of Emission Reduction

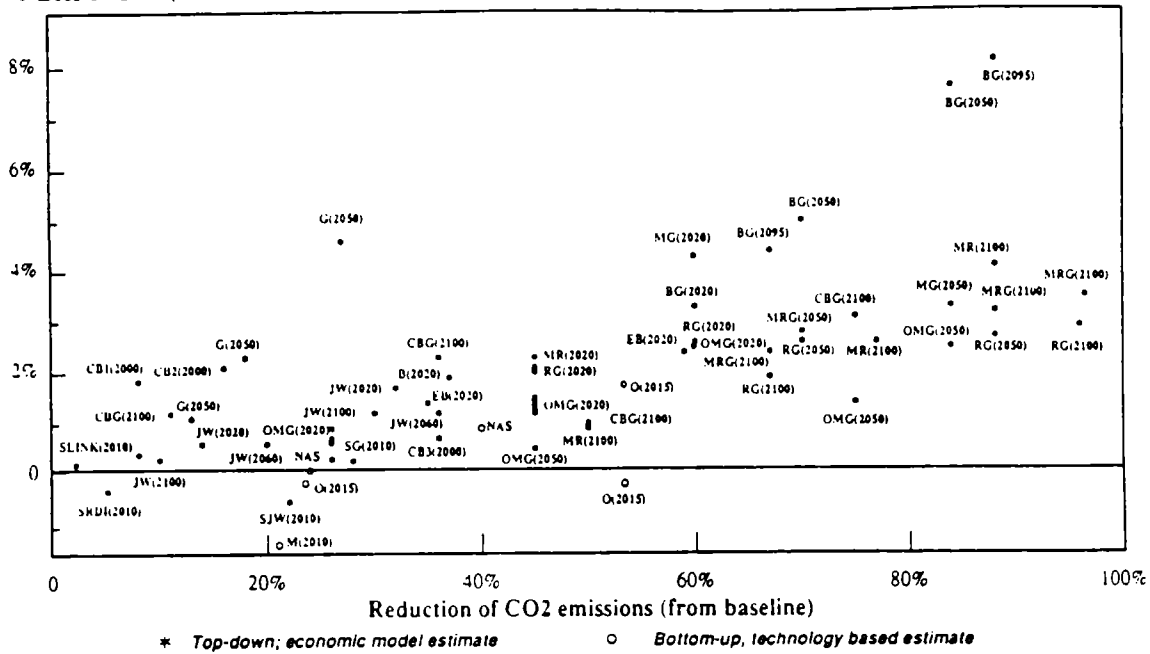


Key:

- A - no reducible market imperfections; inefficient tax recycling
- B - no reducible market imperfections; efficient tax recycling
- C - "negative cost potential" achieved
- D - curve C plus "economic double dividends"
- E - curve D plus "environmental double dividends"

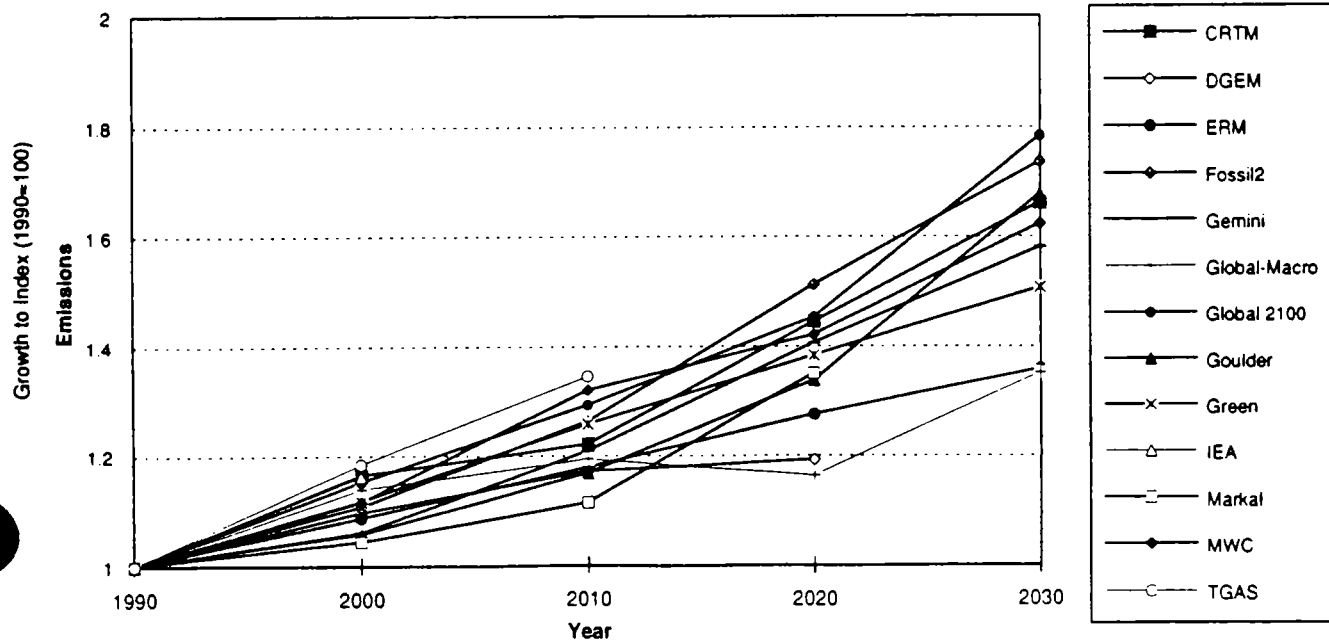
4.1.1
Figure U.S. Studies: Cost of CO₂ Abatement Relative to Baseline Projection
 (Labels are not attached to all points given danger of crowding. For key see Table 1.1)

% Loss of GNP (from baseline) or cost as % of GNP

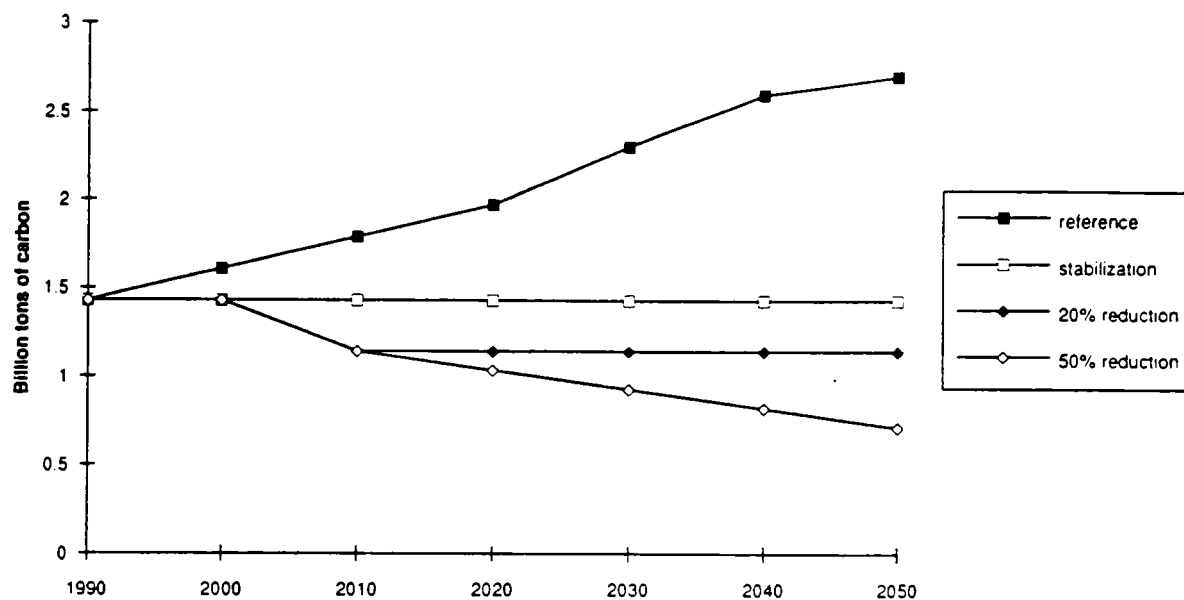


Source: Grubb et al (1993).

4.1.2
Figure U.S. Carbon Emissions

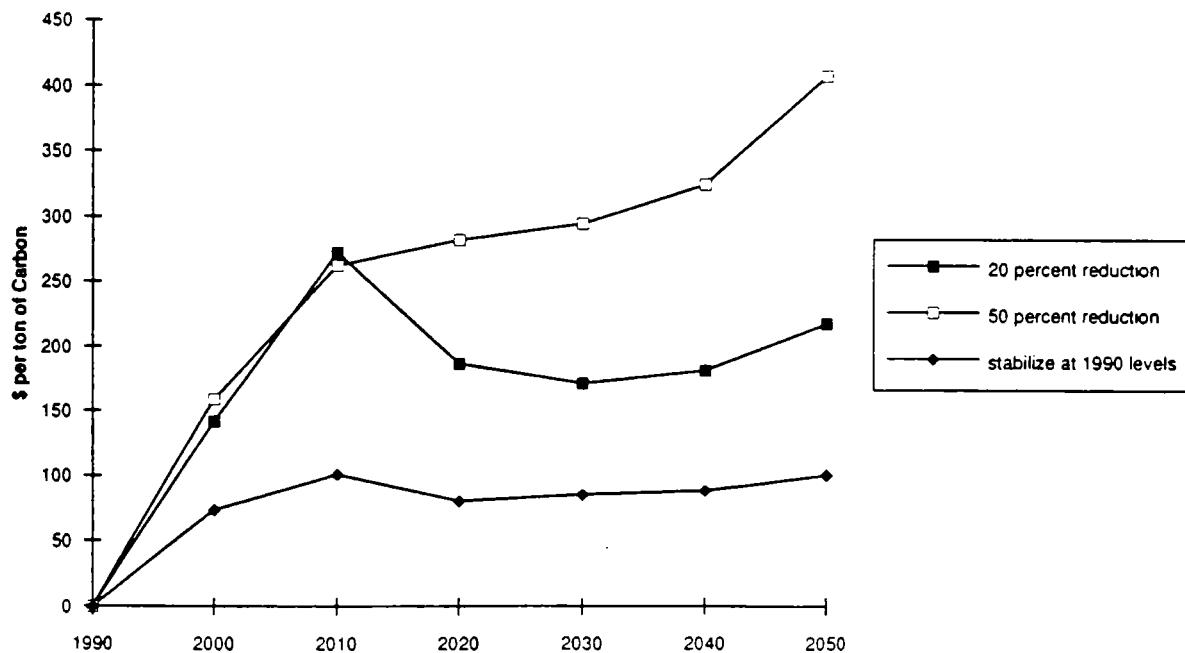


4.1.3
Figure EMF Reference and Emission Reduction Scenarios



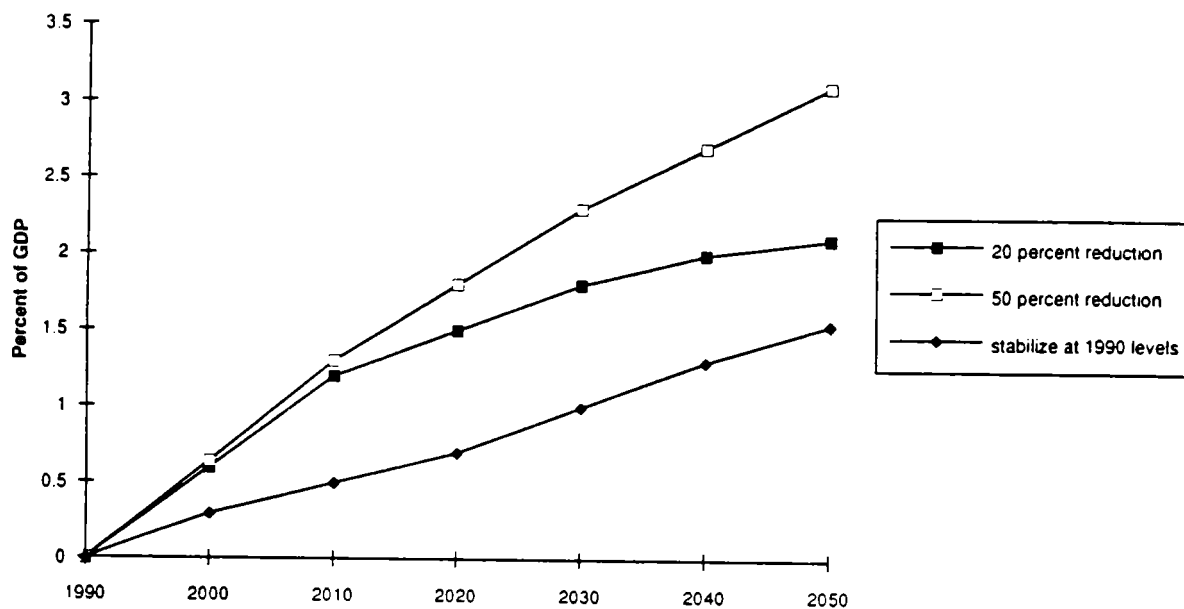
4.1.4
Figure U.S. Carbon Taxes – Average of All Models

Source EMF(1993).

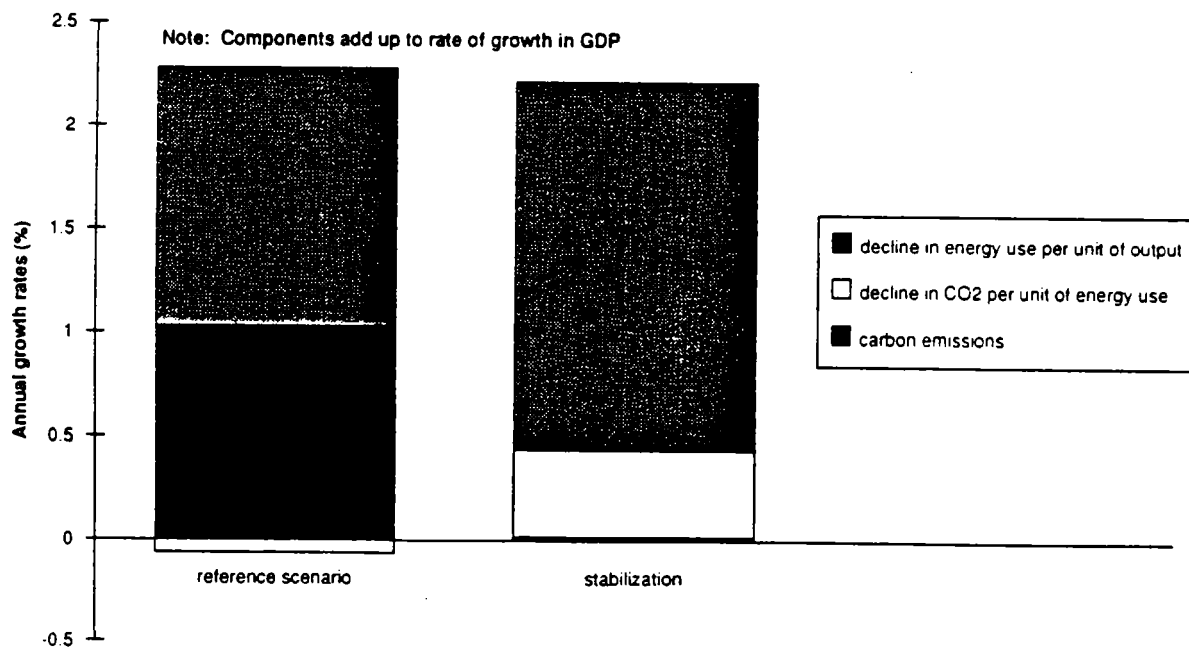


4.1.5
Figure U.S. GDP Loss Projections — Average of all Models

Source: EMF (1993).

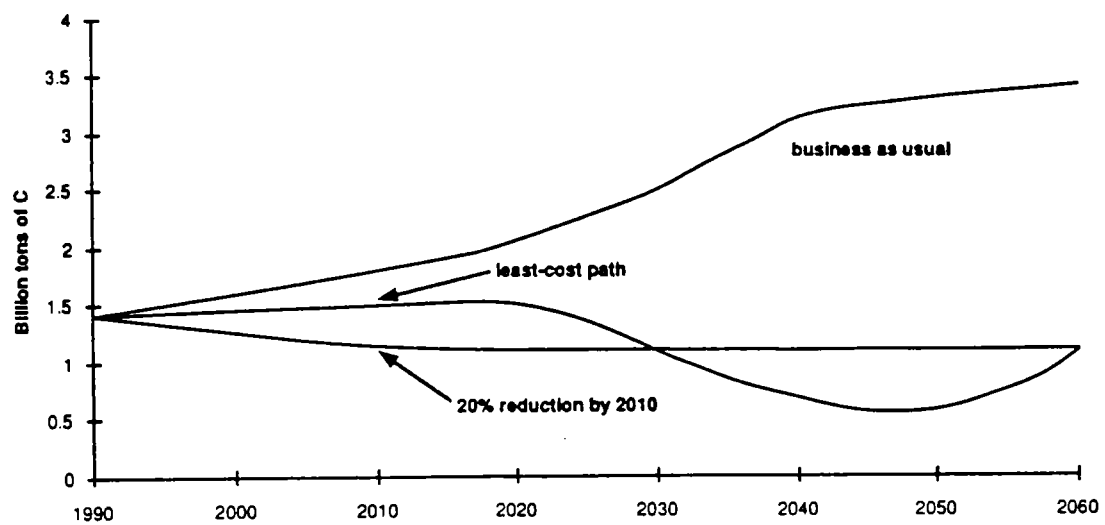


4.1.6
Figure Decoupling Between Carbon Emissions and GDP Annual Growth Rates (1990-2010)



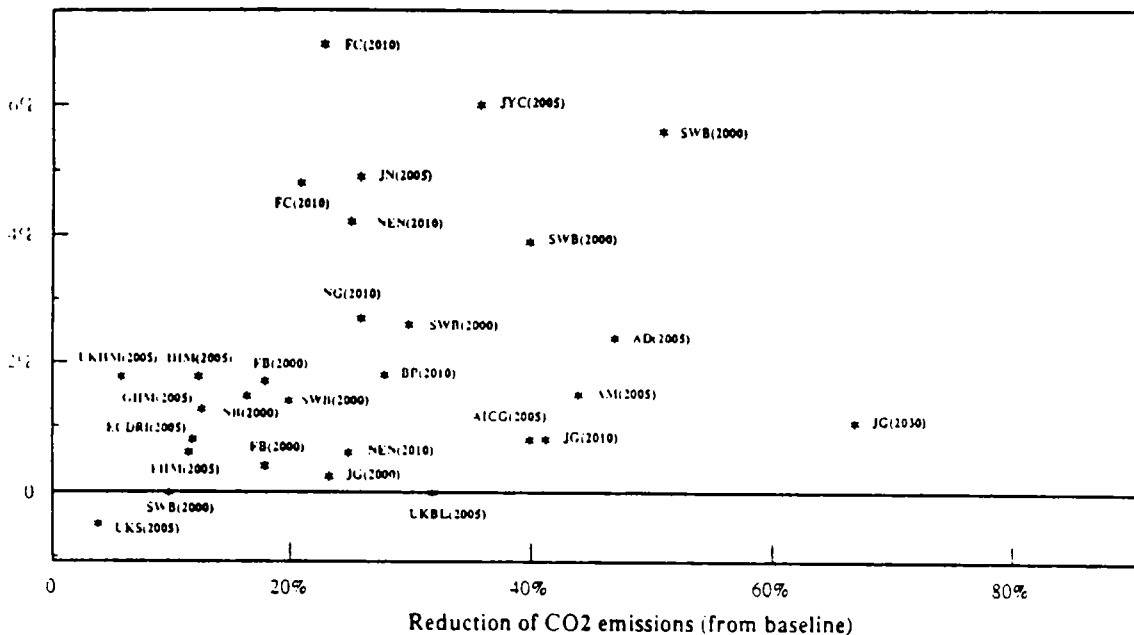
Source: EMF (1993).

4.1.7
Figure Two Alternative Paths Leading to Identical Cumulative Emissions



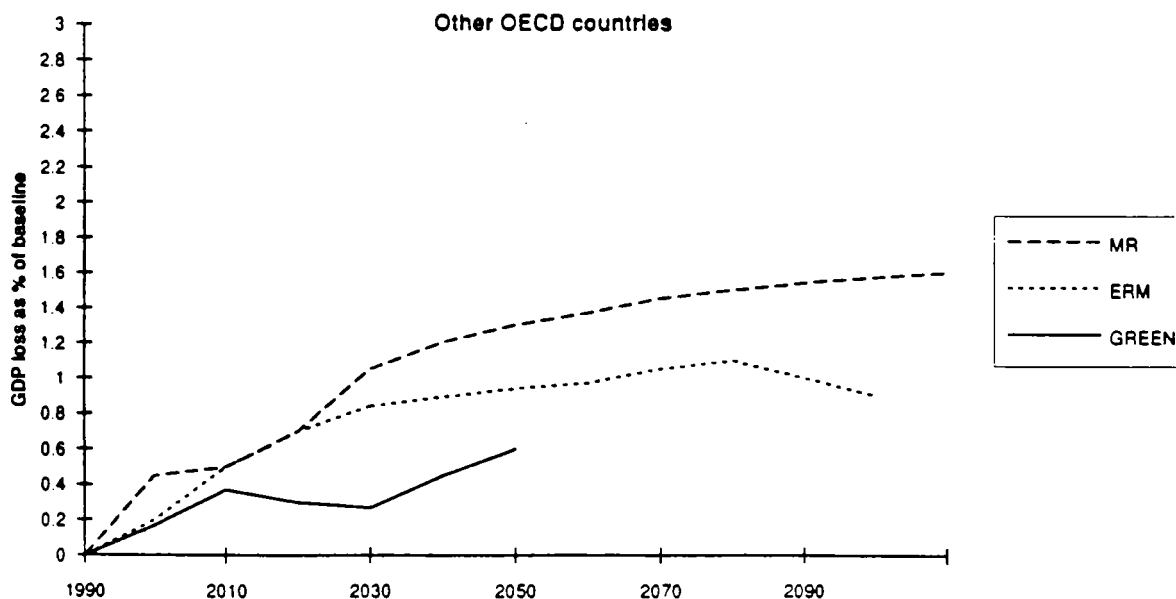
4.2.1
Figure 4.2.1 Non-U.S. OECD Studies: Cost of CO₂ Abatement Relative to Baseline Projection
 (Labels are not attached to all points given danger of crowding. For key see Table 2.1)

Loss of GNP (from baseline) or cost as % of GNP



Source: Grubb et al (1993)

4.2.2
Figure 4.2.2 GDP Losses in the Stabilization Scenario



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

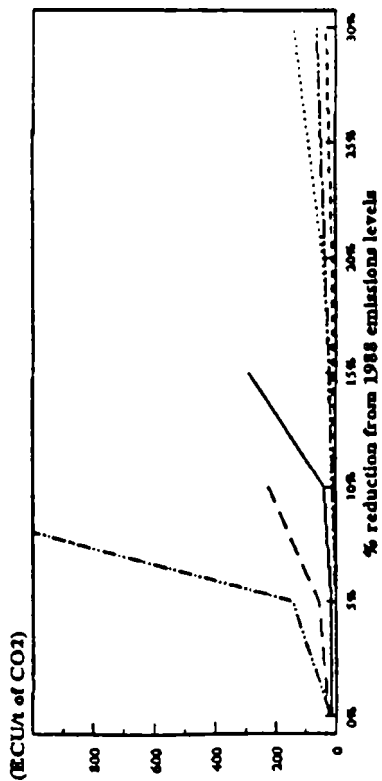
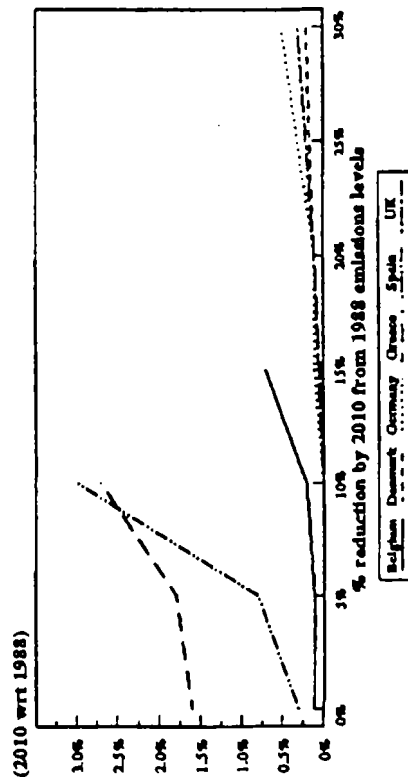
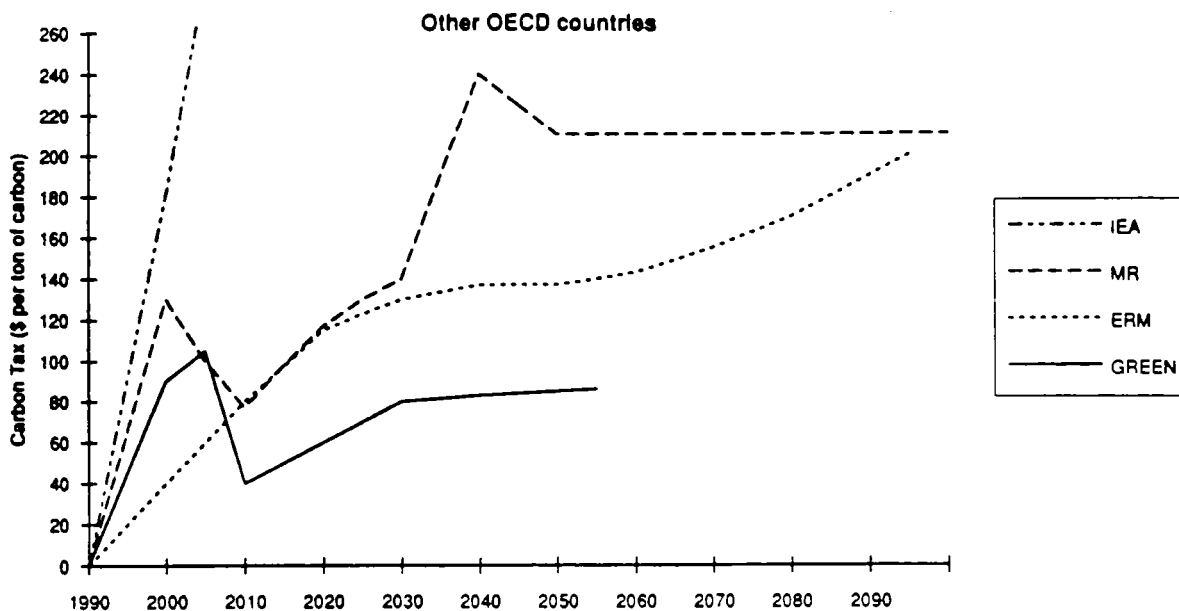


Figure 4.2.5 Cost as a percentage of 1988 GDP



Source: Coherceas (1991), Table 4.4

Figure 4.2.3 Carbon Taxes in the Stabilization Scenario



4.3.1
Figure Comparison of Carbon Taxes in the Stabilization Scenario

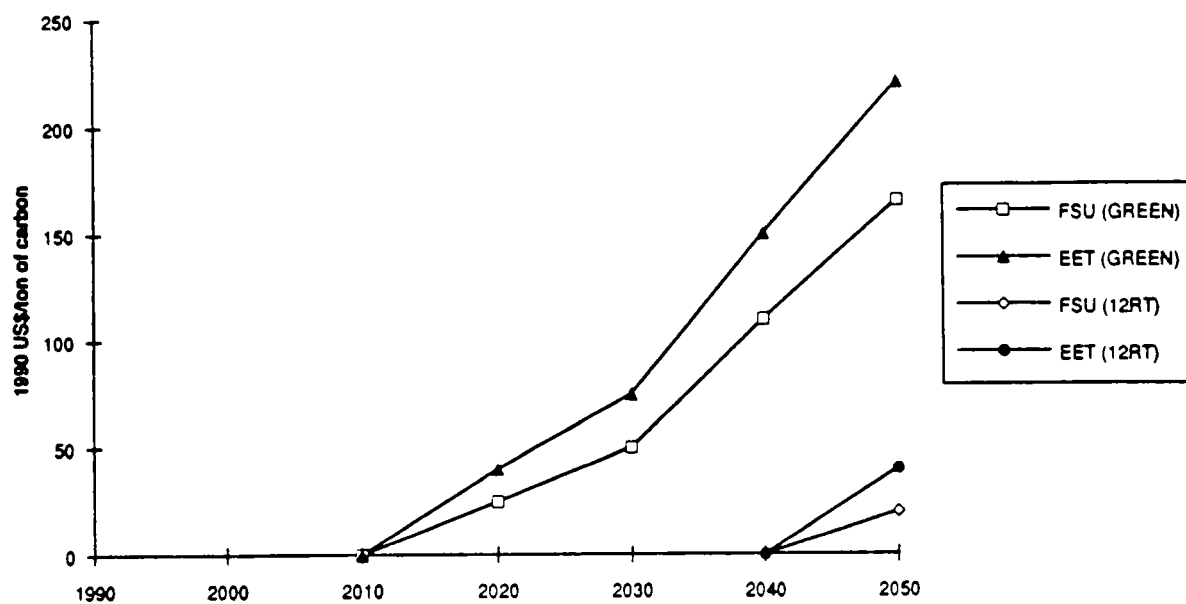


Figure 4.3.2 Cost Studies: Emissions Reduction in the Former Soviet Union

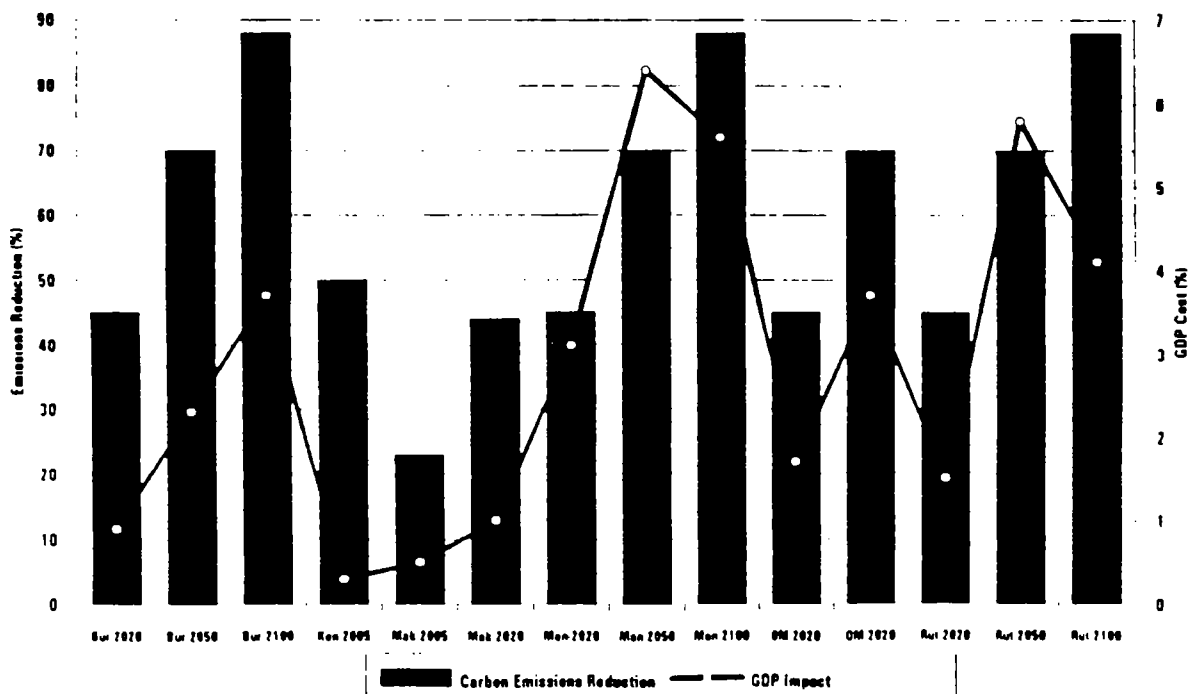


Figure 4.3.3 Cost Studies: Emissions Reduction in Central Europe

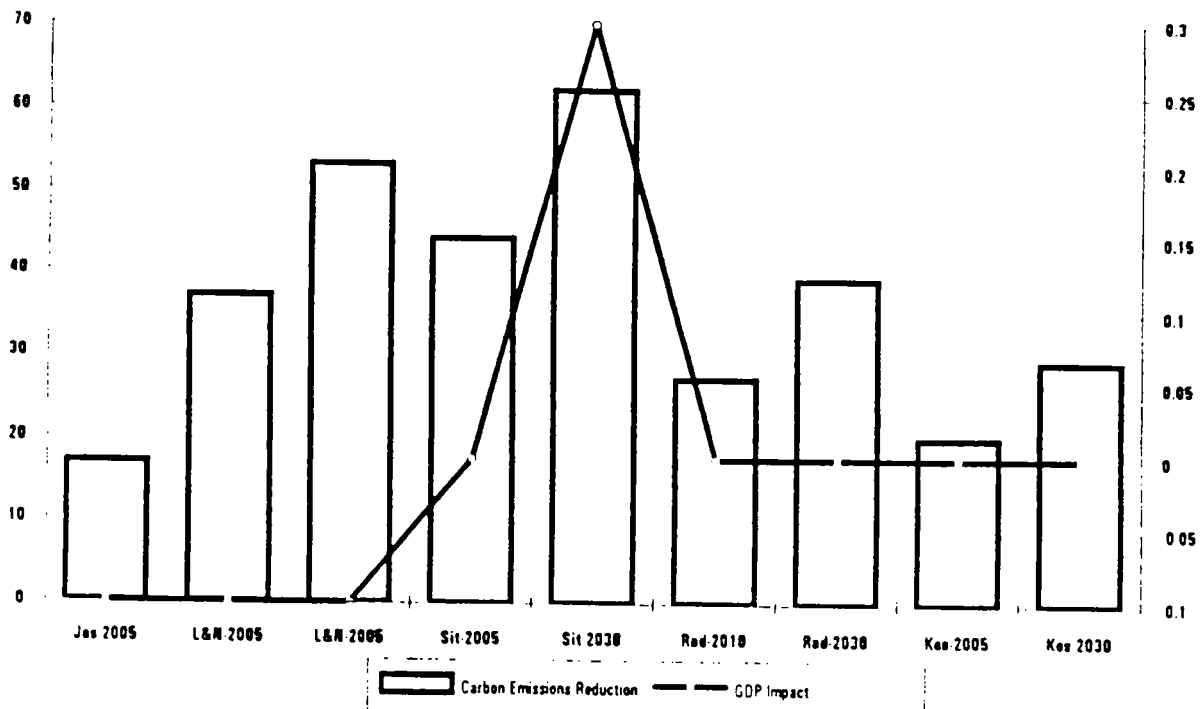
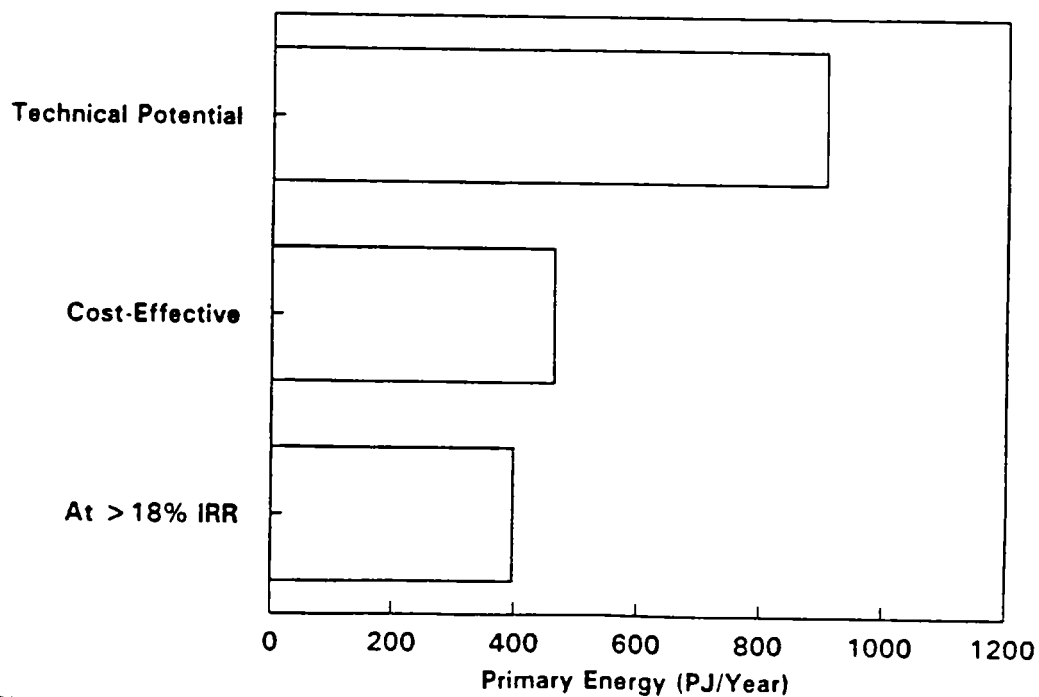


Figure 4.3.4 Efficiency Potential in Poland

(Total Consumption = 4,125 PJ/Year)



SOURCE: FEWE

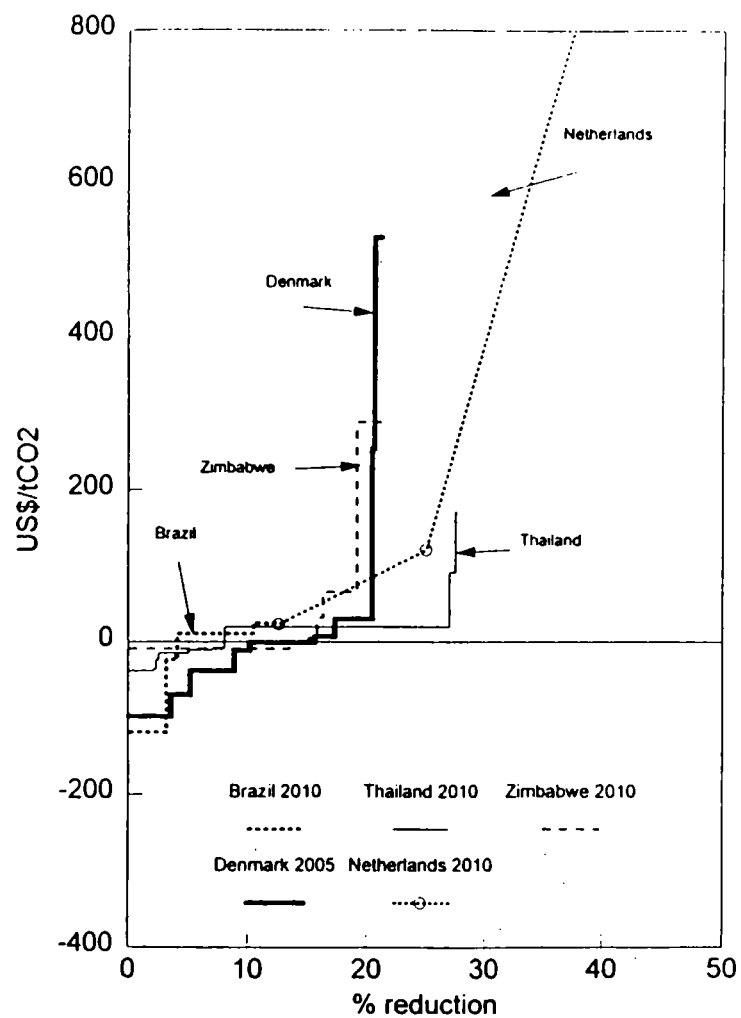


Figure 4.4.1 UNEP Studies: marginal abatement costs for 2005/10

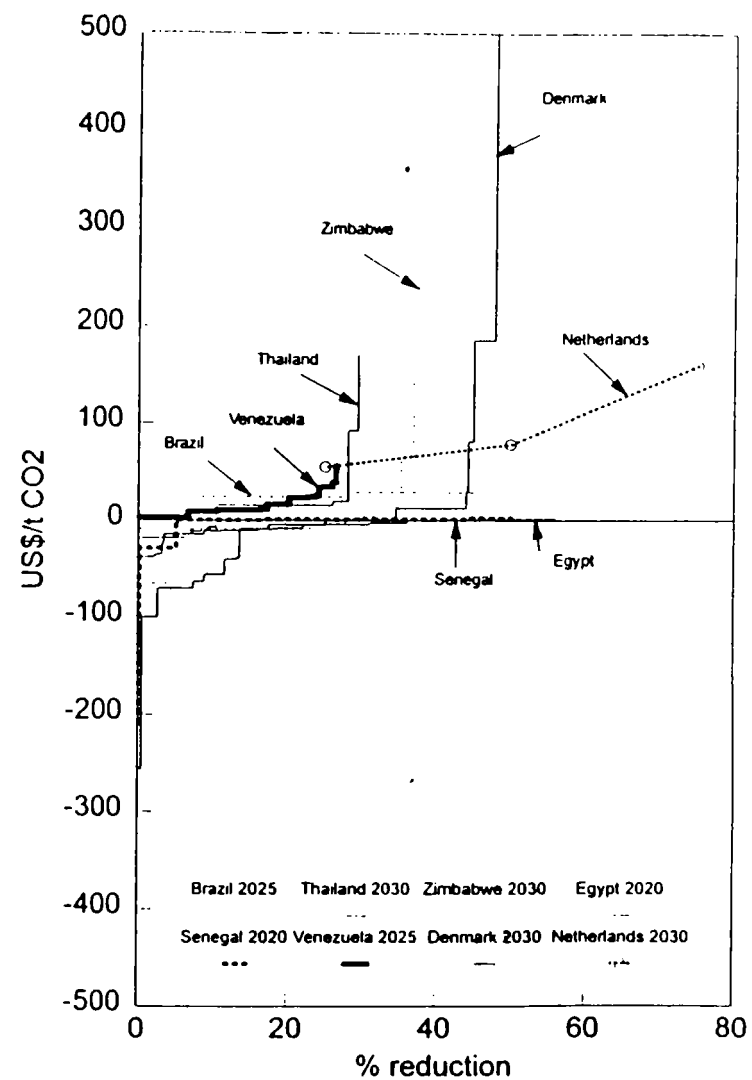
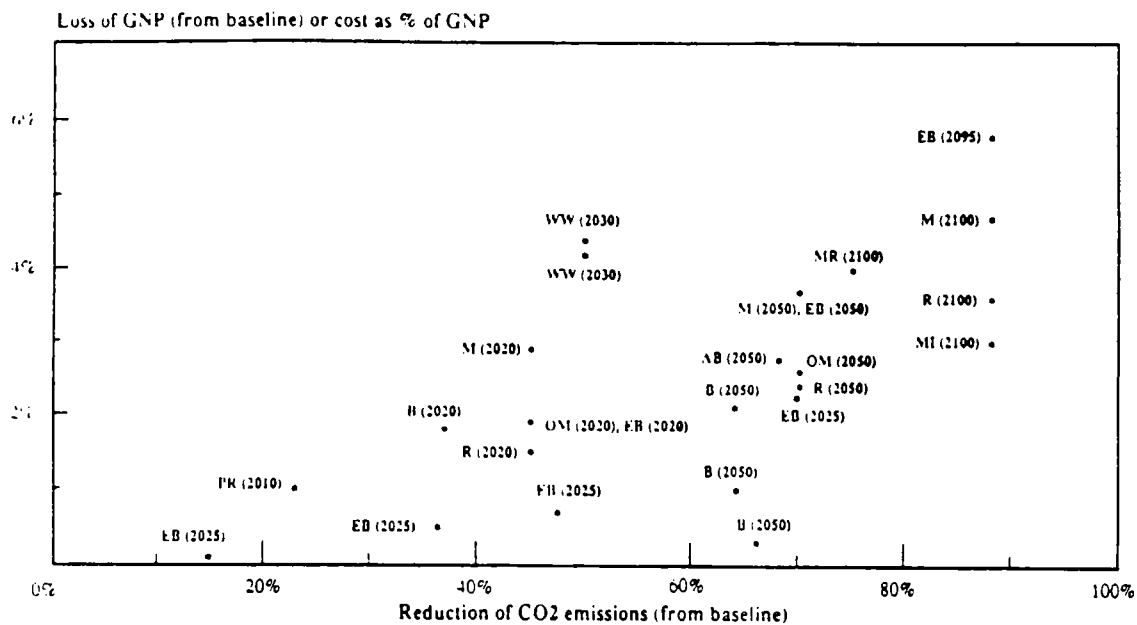


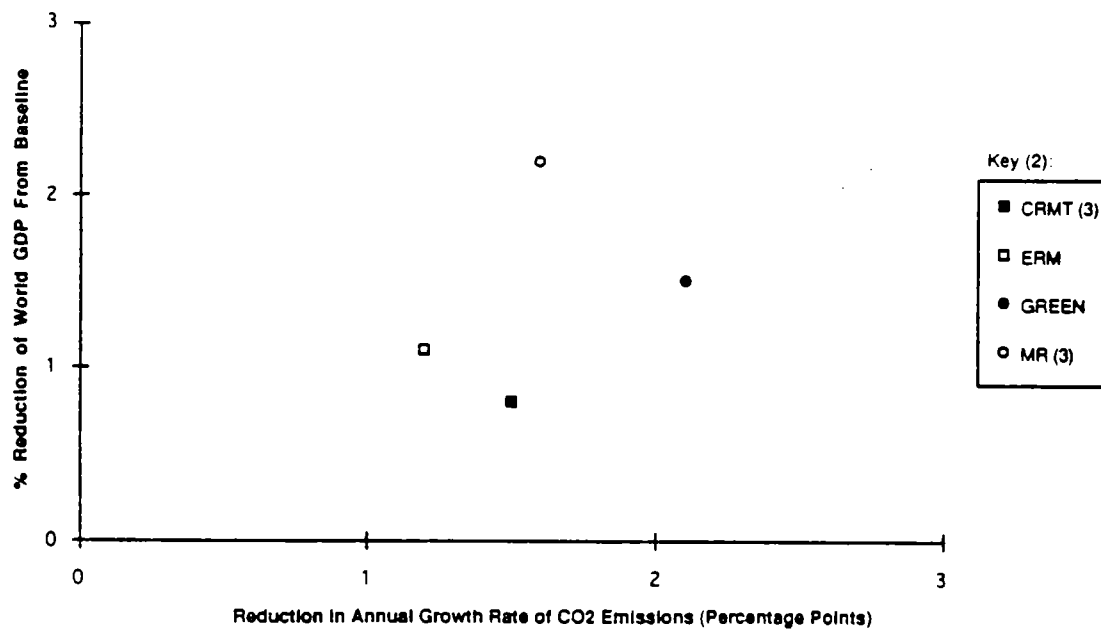
Figure 4.4.2 UNEP Studies: marginal abatement costs for 2020/30

4.5.1
Figure 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).

4.5.2
Figure 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).

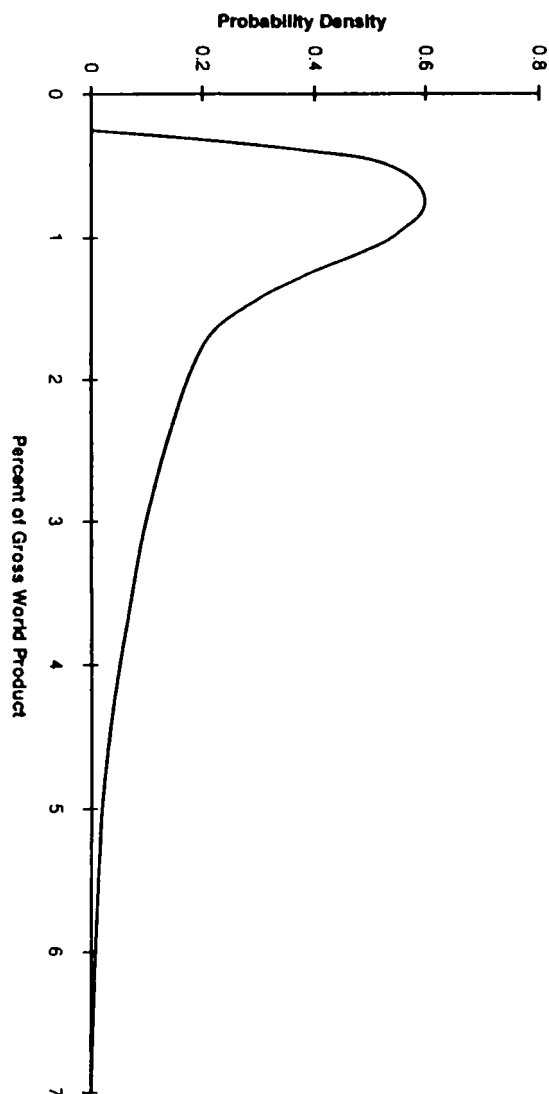
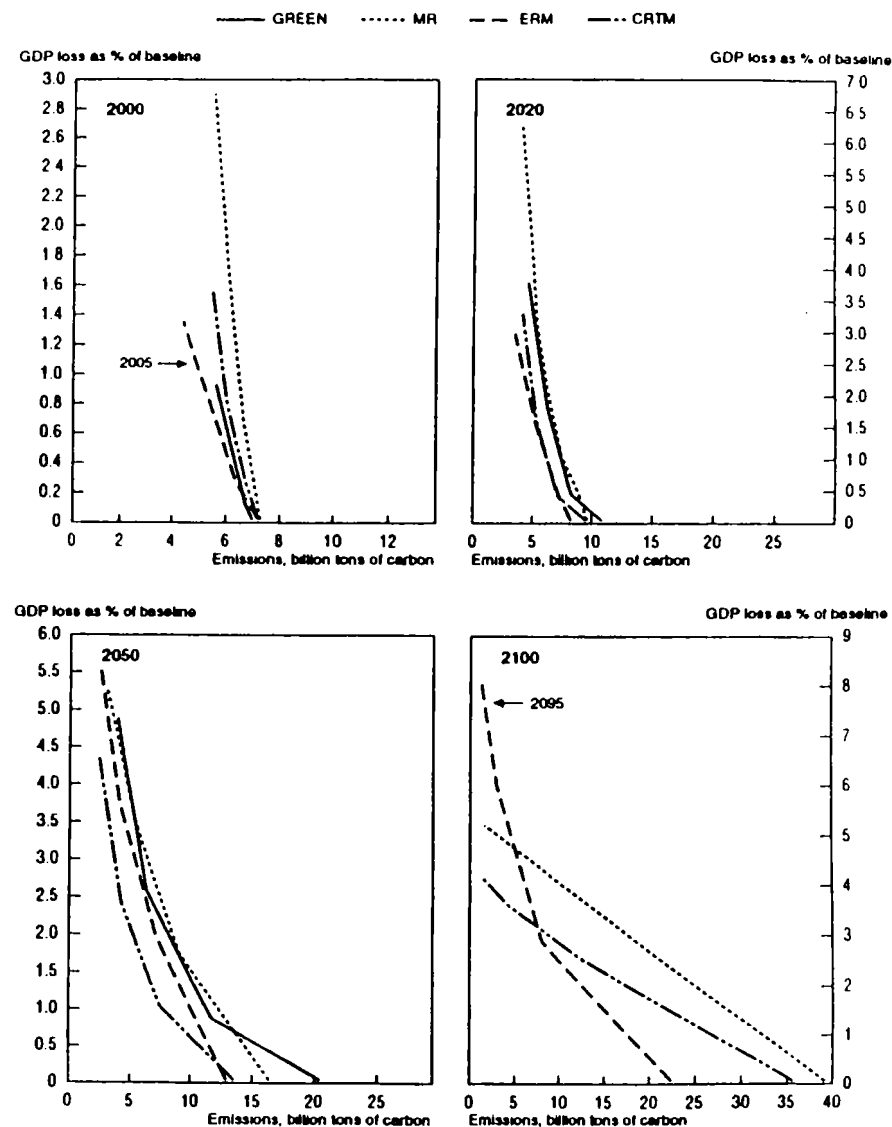


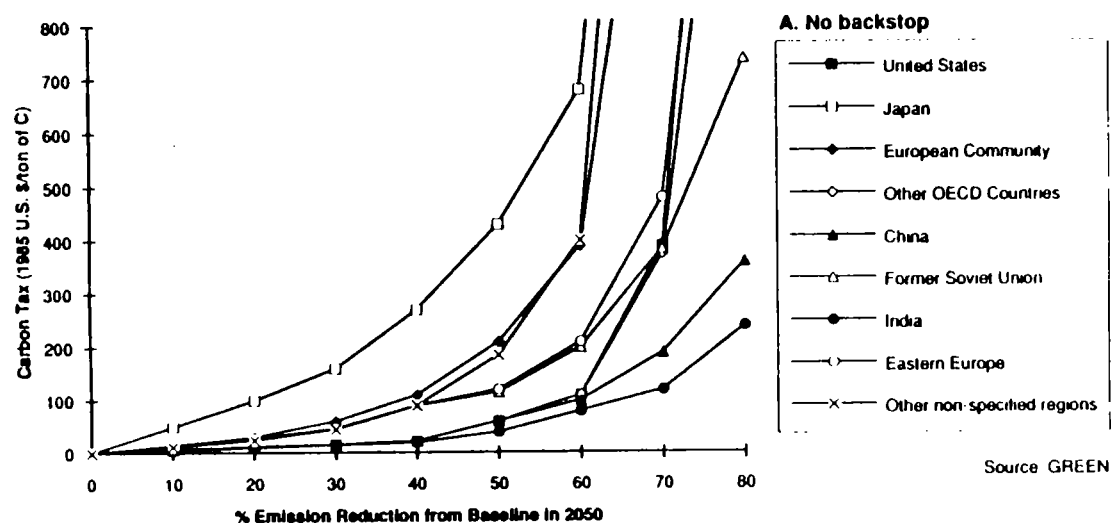
Figure 4.5.3 The Costs of Stabilizing Global Carbon Emissions

Figure 4.5.4 World CO₂ Emissions and GDP Losses

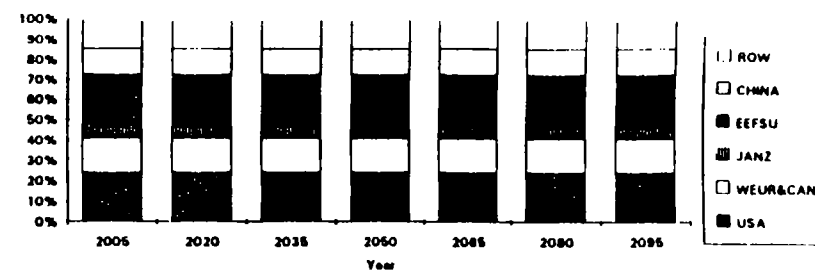


Note: The scales on the different panels are not standardised.
Sources: Deen and Hoeller (1992) and OECD (1993).

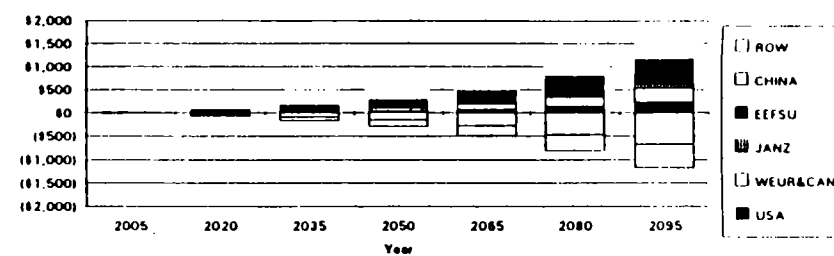
Figure 4.5.5 Regional Carbon Tax Required for Equi-Proportional CO2 Emission Reductions from Baseline



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)

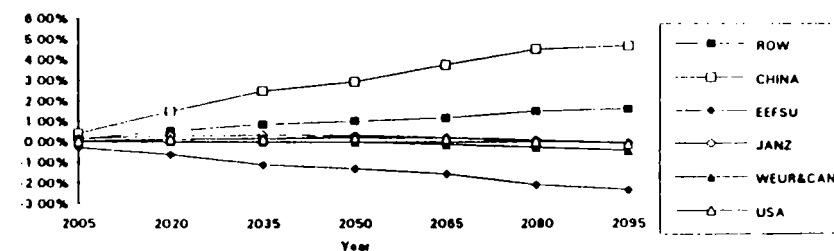
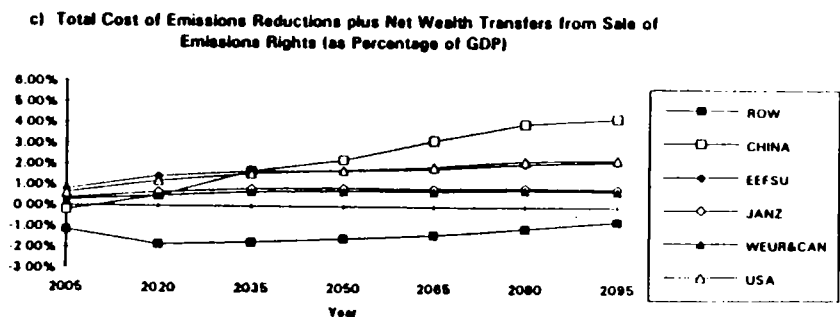
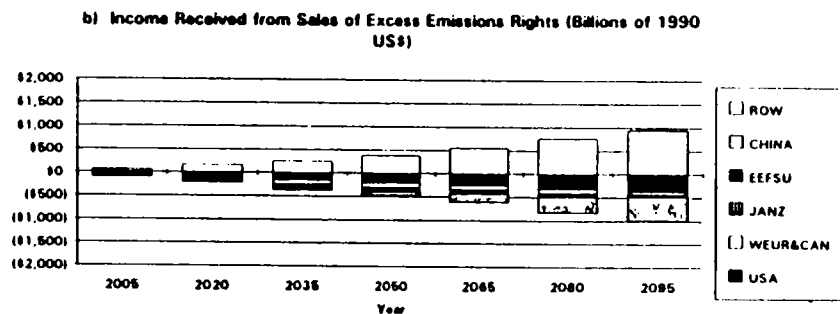
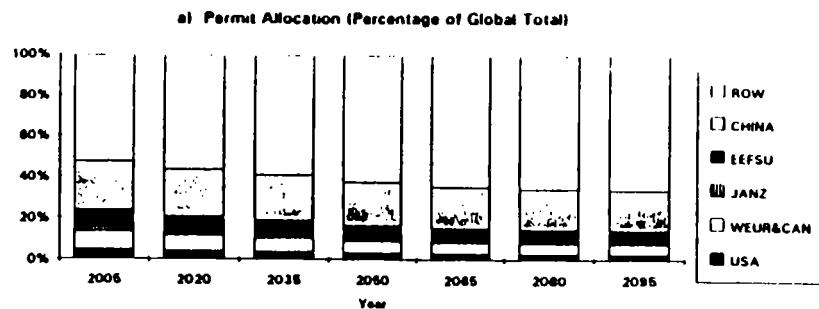
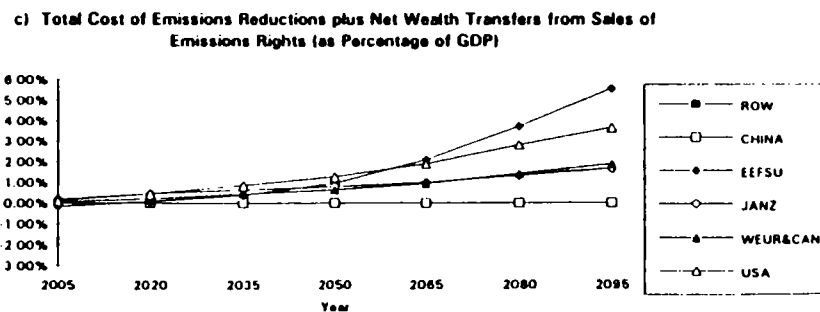
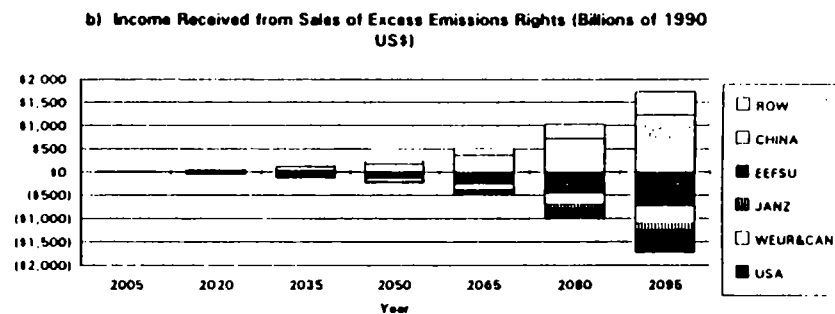
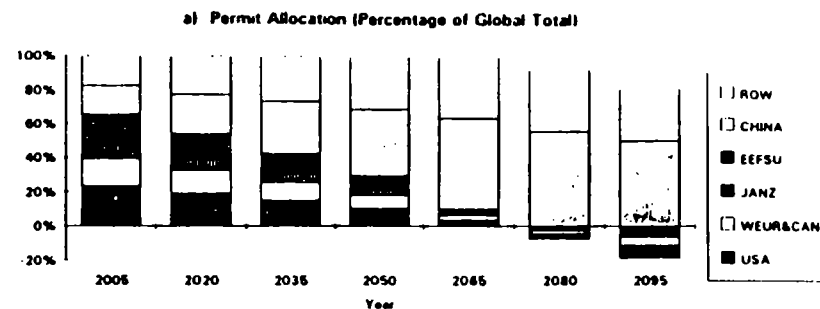


Figure 4.5.6 Grandfathered Emissions Rights Principle



4.5.7
Figure Equal per Capita Emissions Rights Principle



4.5.8
Figure No Net Cost to Developing Nations Emissions Rights Principle

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)	BG (2020)	26%, 45%, 60%	0.6%, 2.0%, 3.2%
Barns et al (1992)	BG (2050)	45%, 70%, 84%	1.9%, 4.9%, 7.5%
Barns et al (1992)	BG (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% ^b
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

4.1.2
Table Models used in Energy Modeling Forum (EMF) Study

Model/Modelers	Model type	Time horizon	Regions
CETA (Lock and Teisberg)	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 Nail)	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
Goulder	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

Table 4.1.3 Description of EMF Scenarios

Scenario	Description
1) Reference	No controls
2) Stabilization	Stabilize CO2 emissions at their 1990 levels by 2000
3) 20% reduction	Stabilize CO2 emissions at their 1990 levels by 2000, reduce by 20% below 1990 levels by 2010
4) 50% reduction	Stabilize CO2 emissions at their 1990 levels by 2000, reduce by 20% below 1990 levels by 2010, reduce by 50% below their 1990 levels by 2050

Table 4.1.4 Comparison of Carbon Taxes and GDP Losses in 2010

Model	Carbon tax (\$ per ton of C)		GDP loss (% of GDP)	
	<u>stabilization</u>	<u>20% reduction</u>	<u>stabilization</u>	<u>20% reduction</u>
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

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%

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	6	1.4	10	
		2030	1.8	3	4.3	1.8	7.1	
National Academy of Sciences, 1991	1990	n/a	-	6				
Office of Technology Assessment, 1991	1987	2015	2.3	-				
US EPA, 1990	1988	2005	2.5	7				
		2010	2.5	7				
SEV/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/a	-	5				
Mills et al, 1991	1988	2000	2.5	6				
Nordhaus, 1990	n/a	n/a	-	-				
Rubin et al, 1992	1989	n/a	-	6				

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Chap 5 Equity and Social Consid.

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D R A F T 1.1

**Intergovernmental Panel on Climate Change
Working Group III**

Equity and Social Considerations

**Lead Authors:
Tariq Banuri
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Michael Grubb
Harold K. Jacobson**

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DRAFT 1.1

**Intergovernmental Panel on Climate Change
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Equity and Social Considerations

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DRAFT 1.1

**Intergovernmental Panel on Climate Change
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Equity and Social Considerations

Lead Authors:

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Michael Grubb, and Harold K. Jacobson**

I Introduction

The first principle in Article 3 of the Framework Convention on Climate Change states:

"1. The Parties should protect the climate system for the benefit of present and future generations of humankind, on the basis of equity and in accordance with their common but differentiated responsibilities and respective capabilities. Accordingly, the developed country Parties should take the lead in combating climate change and the adverse effects thereof."

Because of its inclusion in this principle equity must be a key consideration in all actions taken under the Convention. In common language equity means "the quality of being fair or impartial," or "something that is fair and just." (Flexner, 1987, pp. 656-657)

Science cannot prescribe or decide what would be equitable actions under the Climate Convention. This is the task of the Parties to the Convention. Science can, however, illuminate the meaning of equity and clarify the choices that the Parties face. This is the task of this chapter. It considers concepts of equity, viewing broad concepts within the context of the Framework Convention and the several ways in which this text gives meaning to equity. It then analyses three specific aspects of equity: equity among generations; equity among regions and countries; and equity within countries. Social considerations enter into the discussions of equity in all of the sections.

1.1 Concepts of Equity

Since Plato and Aristotle, theorists who have dealt with economic, political, and social issues have developed and explored concepts of equity. Several broad points emerge from this extensive literature. The first is that equity applies to two separate categories of issues. It applies to both procedural issues--how decisions are made--and substantive issues--the outcomes of decisions.

Procedural equity mandates that similar cases and similarly situated claimants should be treated in a similar fashion. For exceptions to this principle to be regarded as equitable, they must be made on a principled basis. The principle suggests that law should govern decisions, and it provides guidance in how law should be applied. Laws are formulated abstractly, but are applied in specific circumstances. All of the circumstances in which a law would be applied can never be foreseen at the time of the formulation of the law. Starting with Aristotle, theorists have argued that equity demands that law be applied in terms of the intentions of those who established the law, the application should aim at achieving what the legislators would have intended in the specific circumstances or at achieving what would be required by "absolute justice." (Shapiro, 1990, p. 220) Absolute justice refers to a broadly accepted higher notion of what is just. It is in this way that in the Anglo-American common law tradition equity is often introduced into judicial decisions.

Substantive equity has to do with the outcome of decisions, it has to do with the distribution of burdens and the allocation of benefits. There are several broad traditions defining the meaning of equity in this sense. (Young, 1994) They may be summarized in the following categories: parity, proportionality, priority, classical utilitarianism, and Rawlsian distributive justice.

Parity is a formula for equal distribution of burdens or benefits. Parity demands that all claimants be treated equally. *Proportionality* is an Aristotelian principle. Under it burdens or benefits should be distributed in terms of the contributions of claimants. *Priority* argues that those with the greatest need should be advantaged. *Classic utilitarianism* proposes that burdens and benefits should be distributed so as to achieve the greatest good for the greatest number. This Benthanite formula can be expressed mathematically in terms of Pareto optimality. Rawls (1971) carried the concept of utilitarianism a step further, arguing for an equal distribution unless an unequal distribution operates to the benefit of all. *Rawlsian distributive justice* therefore requires that deviations from equality result in overall benefit.

No society has ever regarded any one of these formulae as an adequate criterion for defining substantive equity. None of them have seemed appropriate or practicable as a single standard. Among other reasons, they are not practicable because cases and individuals are rarely identical and burdens and benefits may not be divisible, or if they

are they may not be divisible into shares that are susceptible to precise, cardinal measurement so that it is impossible to apply the formulae directly. In practice, when societies try to achieve equity, they do so in nuanced and subtle ways, applying several criteria and seeking to achieve a balance among them. Nevertheless, the formulae are useful for heuristic purposes. Illustrating the likely consequences of their application can clarify the choices that have to be made in seeking equity in concrete situations such as in the implementation of the Framework Convention on Climate Change. The exploration of the application of these formulae in the following sections of this chapter is for this purpose.

1.2 The Context that the Framework Convention Establishes

The Framework Convention on Climate Change provides guidance as to the relative weight that the signatories would assign to these several formulae. Several other articles, paragraphs, sentences, and phrases of the treaty have implications for the concept of equity as it is used in the treaty's first principle, and they provide a context for the choices that must be made in efforts to achieve the objectives of the treaty. This context should be seen in its entirety before addressing particular issues of equity that will arise. Logic and international law require that particular sections of treaties be interpreted in light of the whole treaty and more broadly in light of general principles of international law not in isolation. (Brierly, 1963) The first principle it should be recalled mentions the concept of intergenerational equity. Many sections of the treaty deal with equity among regions and countries

Beyond the prominent statement in Article 3, paragraph 1, equity is also explicitly mentioned in two other paragraphs of the Framework Convention on Climate Change. Under Article 4, paragraph 2 (a) the developed country Parties¹ to the treaty commit themselves to:

"... adopt national policies and take corresponding measures on the mitigation of climate change. . . . These policies and measures will demonstrate that developed countries are taking the lead in modifying longer-term trends in anthropogenic emissions consistent with the objective of the Convention, . . . taking into account the differences in these Parties' starting points and approaches, economic structures, available technologies and other individual circumstances, as well as the need for equitable and appropriate contributions by each of these Parties to the global effort regarding that objective."

This paragraph indicates the Parties intention that equity should be applied not only between developed and developing countries, but among developed countries as well.

The concept of equity also appears in Article 11, paragraph 2. This article relates to the financial mechanism established under the Convention. The paragraph says that:

"The financial mechanism shall have an equitable and balanced representation of all Parties within a transparent system of governance."

The article seeks to insure equitable procedures and outcomes by mandating rules for the composition of the financial mechanism.

Several other sections of the Framework Convention, though they do not specifically mention equity, are relevant to ways in which equity should be interpreted. The broad statement of the Convention's objective in Article 2 states the goal of stabilizing greenhouse gas concentrations at a level "that would prevent dangerous interference with the climate system." It then goes on to specify a time-frame within which this objective should be achieved.

"Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner."

This stricture bounds the way in which equity should be achieved.

Paragraph 4 of Article 3 proclaims that all Parties "have a right to, and should promote sustainable development." It goes on to say that measures to protect the climate system should be appropriate to each Party's specific conditions. Paragraph 5 of the same article states that the Parties should "cooperate to promote a supportive and open international economic system that would lead to sustainable economic growth and development in all Parties. . . ." In other words, equity is to be achieved in ways that allow all Parties continued economic growth and international trade is to be an essential instrument in this growth. Strategies are to be tailored to the specific conditions of Parties.

The Framework Convention differentiates between developed and developing country Parties. The preamble notes that developed countries have been and are responsible for the largest share of greenhouse gas emissions, and that the share of greenhouse gas emissions from developing countries will grow. As mentioned above, developed country Parties are required to take immediate action to limit greenhouse gas emissions.

The Framework Convention also singles out categories of Parties for special consideration, thus broadly defining how the concept of equity should be applied. Even though they have the obligations of developed Parties, countries undergoing the transition to market economies are allowed some flexibility. (Article 4, Paragraph 6)

Paragraph 2 of Article 3 states:

"The specific needs and special circumstances of developing country Parties, especially those that are particularly vulnerable to the adverse effects of climate change, and of those Parties, especially developing country Parties, that would have to bear a disproportionate or abnormal burden under the Convention, should be given full consideration."

A preambular paragraph notes the particular vulnerability of: small island and low-lying countries; countries with low-lying coastal areas; countries with arid and semi-arid areas; those that are liable to floods, drought and desertification; and those that have fragile mountainous ecosystems. Another preambular paragraph acknowledges the special difficulties that will be faced by developing countries that have economies that are particularly dependent on the production, use, and exportation of fossil fuels as a consequence of limiting greenhouse gas emissions.

The Framework Convention creates obligations and mechanisms for the transfer of financial resources and technology from developed country Parties to developing country Parties to assist them deal with the adverse effects of climate change and in the implementation of measures to mitigate climate change. All of the categories listed in the preceding paragraph and others that are especially vulnerable are singled out as meriting special consideration in the transfer of resources.

As is readily apparent, the Framework Convention on Climate Change has already provided a substantial context for the interpretation of equity in designing measures to attain the Convention's objectives.

II Intergenerational Equity

(First draft. References not included, language not corrected, August 7, 1994 Karl-Goran Maler)

II.1 Equity and the bearing of risk

I. Background

Future climate change may have substantial impacts on the distribution of welfare between different generations. If policies are implemented to reduce the risk of global warming, the burden of abating emissions of greenhouse gases will probably fall more heavily on present generations while the benefits from not having to adjust to climate changes will be incurred by future generations. On the other hand, if climate policies are not implemented, the future generations will bear the burden while the present generations will benefit greatly from continued use of fossil fuels. How should one view this intertemporal distribution of welfare and how should one formulate operational guidelines that would support a more equitable intertemporal allocation of welfare? These are the basic issues in this paper and they are analyzed in the framework of established economic theory.

A discussion of the ethical aspects of climate change would require at least the following steps:

- operationalisation of the theory
- measurements
- ethical values
- conceptual theory of ethics
- policy recommendations

In this paper, I will try to give a sketch of the first item, discuss the operationalisations and in particular for intertemporal equity, and give some hints on the theory of measurements. I will conclude with some aspects on policy recommendations.

II. Ethical theories

What I am going to discuss under the heading of ethical theories is almost completely based on professor Partha Dasgupta's recent book *An Inquiry into Well-Being and Deprivation* (1993). This book gives an excellent original and novel presentation of how economic theories can be used to improve our understanding of basic ethical conflicts and their resolutions. There are basically two types of ethical theories we will consider:

- consequentialism
- deontological

Consequentialism theories look at the consequences from actions and the policies that govern the actions. They are therefore goal-based. Thus, a consequentialist theorist would look at the set of possible states, evaluate these states in terms of their consequences and then recommend that state that is most desirable in terms of its consequences.

One particular set of consequentialism theories we will adopt and discuss in the sequel is the set of utilitarian theories. Here the consequences are described in terms of utilities, which simply is another word for well-being of the relevant individuals. The best known utilitarian theory is the classical theory, going back to Bentham, saying that it is the sum or the weighted sum of utilities over individuals that should matter. This is also the basic theory behind much of established welfare economics. However, there are other utilitarian theories. For example, one such could be the maxi-min theory, that is that society should maximize the utility for the individual with the lowest or minimal utility. In connection with global warming, this ethical theory should give highest priority to the poorest country, and in fact give that country sole right to make decisions! There are also many other utilitarian theories. However, for the present discussion, we will keep to the weighted utility sum as the typical theory. Most other theories can be approximated by this by choosing the weights appropriately.

The deontological theories, on the other hand focus more on the process by which decisions are made and less on the consequences from these decisions. Thus, deontological theories judge action by their rightness or wrongness and not solely on their consequences. In fact, one important strand of deontological theories are those founded on procedural fairness. Here procedural fairness is judged independently of the consequences of the action.

One particular important class of deontological theories deal with rights. Nozick, for example, declares that all individuals have a sphere of moral rights in which no one, including the state, is allowed to interfere irrespective of the consequences for well-being from such an interference. Another example of a rights based theory is Rawls' first principle of justice declares that *Each person is to have an equal right to the most extensive system of equal political liberties compatible with a similar system of liberty for all*, and this second principle states that *Social and economic inequalities are to be arranged so that they are a) to greatest benefit of the least advantaged*.

Implicit in these statements is the notion of primary goods, i.e. those goods or commodities to which individuals have a right. Among them are various liberties, but it could also be argued that basic needs should also be included. This concept was introduced by several individuals in the 1970's, among them professor Graciela Chichilnisky. It corresponds to the idea that individuals have the right to goods and services necessary to sustain their lives at some minimum standard of well-being making it

worth living. It includes potable water, shelter, minimum nutrition, health care and general environmental resources. If there are infringements of these rights, then we should be entitled to claim that a severe injustice is being committed. From the point of view of climate change, the idea of basic needs is worth pursuing. It is very easy to think of scenarios in which flooding or decreased agricultural productivity will bring about such infringements and should therefore not be tolerated. Thus if we accept this approach some rather strict conclusions about climate change policies can be derived. However, I do believe, probably because of the prejudices I have been accustomed to by my training as an economist, that these ideas can be included in a strict utilitarian framework. For example, if we define utility to include basic needs, we would be able to carry out an intelligent discussion, that can be made operational in terms of a utilitarian framework. I will therefore in the sequel use such a framework.

However, before trying to exploit such a framework, let me remind you of one important consequence of a framework based on rights. If all individuals are going to have rights - such as defined by Nozick or Rawls - to their own life, decisions on the climate must be anchored in their own evaluation and their own judgment of their lives. However, climate is what economists call a pure public good. It will affect anyone but in general differently, and there is no way one can get around a change in the climate. The global climate, as it will affect everyone living on this earth, now or in the future, is a truly global public good. Therefore, it is imperative that we can come up with decision mechanisms by which those who are affected also have something to say. We need new international institutions, i.e. new rules of the game, in order to protect the rights of everyone.

III. Climate change impacts

What are the distributive impacts from climate change and policies for controlling the climate? Basically, we can identify two different categories of impacts

- Burden of abatement of green-house gas emissions
- Burden from adjusting to changes in climate

Obviously, these two categories of impact will differ in importance between different nations, between different individuals in the same nation, between individuals living in different time epochs. It seems that a policy like business as usual will not impose high burdens on countries emitting much green-house gases while it will impose possibly high expected costs on countries affected adversely from climate change and expected benefits to countries affected beneficially from climate change. The use of the term expected costs and expected benefits here is crucial. In spite of the deep science used and the highly sophisticated computer models climatologists have constructed, they have not so far been able and because of inherent non-linear dynamics will never be able to come up with predictions that are certain. We must recognize as a fact that we have to make decisions

under uncertainty but that the decisions should be as rational as possible. This means that we need to use a stochastic framework to discuss intelligently the distributive impacts of climate policies. But as soon as we have admitted this, we have to recognize another cost item - the cost of bearing the risk. Thus we could argue that climate change impacts usefully could be categorized into the following four groups:

- The intertemporal distribution of expected utility
- The international distribution of expected utility
- The interpersonal distribution of expected utility within countries
- The distribution of the cost of risk bearing

It should be noted that most of the discussion on the economics of climate change has focused on the first three types of impacts but very little if any has been said on the last - the distribution and the size of the cost of risk bearing. The uncertainty aspect combined with irreversibilities - both in abatement and in impacts from climate change - makes the analysis technically difficult but not impossible. Unfortunately, too little has been done in this area.

Furthermore, the combination of the idea of basic needs and risk-bearing has also some far reaching implications. If we accept that individuals have the right to some basic goods - food, shelter, access to environmental resources - and if action like the emissions of carbon oxides threaten the availability of these basic goods, then those who decided on these action must be prepared to compensate those who have lost their fundamental rights to basic goods. An international climate agreement should therefore resolve this issue of risk bearing.

I will in the rest of this presentation focus on the first item - the intertemporal justice. I have made this choice not because I believe this is the most important of the issues but because that is the item for which I can claim some expertise.

IV. Utility

In order to discuss sensibly a utilitarian framework, we need some measure of well-being or welfare. Here we will follow standard economic theory by postulating the existence of a utility function. Let us imagine a list of all factors that are relevant for determining the well-being of an individual. Such a list would include among other things the amount of goods and services that the individual can use for consumption, different aspects of his physical and spiritual environment and his rights and liberties. In view of our interest in climate change, it seems appropriate for this discussion to limit the list to the goods and services available and to those aspects of the physical environment that are determined by the climate. The other variables affecting well-being may be more important but will hardly change because of climate change or by abating the emissions of green-

house gases, and we can therefore exclude them from our study. Thus we are left with a list of factors that for each time period determines the well-being of the individual. In order to measure well-being, we assume that it is possible to aggregate all these factors into one single variable - utility. Utility is therefore a function of the variables determining well-being and is an indicator of well-being.

We will not go into a discussion of the logical and philosophical basis for such a utility function, the reader is referred to (???). Usually, we will assume that the utility function is defined with respect to a time period - a year, the average length of a generation, etc. For each individual there are therefore different sequences of utilities over time, dependent on policies affecting the emissions of green house gases. This holds true, irrespective of whether the individual is living now or belongs to a future generation. What the idea of a utility function has accomplished is for each individual to aggregate a rather long list of factors affecting well-being into one single measure. There remains the much more difficult task of aggregating these utilities over different individuals. In a sense, this is the real ethical problem in connection with climate change.

Professor Kenneth Arrow addressed this issue in 1951 (Arrow 1951) by asking the fundamental question whether individual preferences - irrespective of what they look - can be aggregated in a reasonable way into a social preference relation. His answer is negative. It is in general impossible to aggregate individual preferences to a social welfare function if we require that the aggregation should satisfy some very natural and reasonable conditions, including that no individual should be allowed to be a dictator. Thus, there is in general not possible to deduct "objectively" the social preferences over distribution of well-being from individual preferences. However, professor Arrow proved his possibility theorem for the case when individual preferences could be completely arbitrary. If it is known that individual preferences are restricted to certain types, then it may still be possible to aggregate individual preferences in a consistent and reasonable way to a social ordering (see Sen 1987). We will argue here that when it comes to the distribution of welfare over time, it could be argued that there is a consensus on what should be denoted an equitable distribution of welfare. This is so because of the apparent agreement on the concept of sustainable development.

The idea of sustainable development was introduced by the World Conservation Strategy (IUCN 1980) but became popular only after The World Commission of Environment and Development - the Brundtland Commission - published its report *Our Common Future* 1987. In that report sustainable development was not rigorously defined, but a number of ingredients in sustainable development were identified (not necessarily consistent with each other). It seems that the main idea in the Brundtland report was that the present generation should not make such changes in the present resource availability so as to reduce future generations possibilities to achieve a comparable well-being. This is, obviously, an ethical norm which, if accepted by most decision-makers, may have far

reaching consequences for how we view intertemporal justice. The main purpose of the rest of this paper is to deduce then consequences.

It should be stressed that we are looking at and will be comparing different utility and not climate consequences as such. What we are interested in is the well-being of the and future generations and this well-being is, as we have already discussed, determined by a multitude of many different factors. Climate factors and costs of abating emissions of greenhouse gases are only a few of these factors. It is fundamentally wrong to limit any discussion of intertemporal justice to climate change, or even to all environmental variables. We need a much broader perspective! On the other hand, it will be seen that environmental and in particular climate variables may have a profound effect on discounting.

II.2 Risk and Uncertainty

V. Risk and climate change

The future climate is far from certain. The IPCC predicts that the average temperature will rise with between x^* and y^* per decade under the emission scenario called business as usual. Although, the expected temperature rise is high, the uncertainty about the future average temperature is also high. However, the future average global temperature means almost nothing as it is local effects that really matter. Unfortunately, the predictions on regional temperature are enormously uncertain and vary substantially the predictions of different climate models. It may even be that in some areas the temperature will go down while it will go up in most others but that we are not able to predict with any greater precision which areas that will experience temperature rise and which will experience cooling. Furthermore, the impact from climate change will surely be affected in a major way by the effects on precipitation and on winds. The climate models predict in general that precipitation will go down in the interior of continents while it will increase elsewhere. However, the precise effects are not known. The sea level is predicted to rise but the amount of rise is course a rather uncertain factor, partly because of the uncertainty in the predictions of average global temperature and partly because of uncertainty about the dynamics of heat transfers in the oceans.

Thus any prediction of the future climate on any scale is subject to great uncertainty. This uncertainty is partly due to our limited scientific theoretical and empirical understanding of the dynamics of the earth's climate system, but also partly because the climate is inherently chaotic. By this is meant that the dynamic system that explains climate variations is highly sensitive to the initial situation. For a popular discussion of dynamical systems and chaos see Gleick (1987) and for a mathematical treatment see for example Devaney (1987). A dynamical system is a system that predicts the state - temperature, population size, GNP etc. in the next period from information of the present state. If these predictions depend non-linearly on the present state (i.e. if an increase in the atmospheric concentration of CO_2 this period with 10% implies a temperature change in the next

period different from 10%), then the system may be chaotic. This means, as was said above, that a small change in the present state will cause great changes in the predictions for the future periods. The models describing climate are highly non-linear and there are therefore reasons to assume that some aspects of their predictions are chaotic. This means in particular that it is impossible to predict with any precision the future! A small change in the assumptions regarding the present state will in the long run cause the system to change substantially. This is the so called butterfly effect: The beats of the wings of a butterfly in Africa may cause a hurricane in the Caribbean!

To this should be added the increase in risk following global climate change due to a more violent weather pattern. It is believed (but not universally agreed) that global warming will increase the frequency of heavy storms and hurricanes, droughts and in general the frequency of violent fluctuations in the weather. These fluctuations will not in general be predictable (except in a probabilistic sense), and will therefore add to the uncertainty. Furthermore, this uncertainty will remain even after climate change has taken place, that is they will tend to be permanent (at least over a foreseeable future)

Traditionally, the situation just described is described both in terms of risk and in terms of uncertainty (Knight 19??). The term risk is used when it is possible to attach probabilities to the various outcomes and the term uncertainty when this is not possible. However, this distinction is to a large extent not relevant for rational decision making. The reason being that rational preferences (where of course "rational" is defined in a special but very reasonable way) always can be represented by subjective probabilities and utilities in such a way that the rational choice is given by the choice that maximizes expected utility. Therefore, we will limit ourselves to the theory of risk.

VI. The expected utility hypothesis

The expected utility hypothesis, either as a norm for rational decision making or as a description of behavior vis-à-vis risk, has a very long history. It goes back to the St Petersburg paradox. Consider a coin throwing game such that if the first time head shows is in n 'th throw, you will win 2^n . How much would you be willing to pay for participating in the game? It is easy to see that the expected win is infinity, but no one would be willing to pay a high amount for the right to participate.

This is the paradox. It was resolved by Bernoulli, who argued that the "real" gains to the player was not the money gains but the utility derived from these monetary gains. Furthermore, he argued that, although the utility increases with the monetary gains, the rate of increase goes down with the monetary gains. Bernoulli postulated a logarithmic utility function, so that the utility of the monetary gain is simply the logarithm of the gain. With such a function it is easy to show that the expected utility is finite and that the player would be willing to pay only a finite amount for the right to participate.

The idea that one could and should use expected utility for analyzing uncertain prospects was introduced into economics (and social sciences in general) by Frank Ramsey (1931). However, it was in von Neuman's and Morgenstern's book *Theory of Games and Economic Behaviour* (1944) that the concept was derived from a small set of axioms describing what has been called rational decision-making. John von Neuman's and Oskar Morgenstern's contribution was so seminal that today we usually use the name von Neuman-Morgenstern utility whenever we discuss the expected utility hypothesis.

The axioms introduced by von Neuman and Morgenstern (the probably best presentation of the expected utility hypothesis is still Luce and Raiffa (1964) characterized preferences over uncertain prospects. A prospect is simply a lottery - a list of prizes (some of which can be negative) and the associated probabilities. One such prospect can be described as $L = (p_1 A_1, p_2 A_2, \dots, p_n A_n)$, where A_i is the prize if the i 'th outcome is realized and the probability for this is p_i . The list of n outcomes is complete, so that the probabilities add up to one. The problem we are going to study is how to choose between different prospects. Let L' be a different prospect $L' = (p'_1 A_1, p'_2 A_2, \dots, p'_n A_n)$. We have here assumed that the second prospect has the same list of prizes. This does not impose any limitation as we can use as the list of prizes the combined list for the two prospects. How should a decision-maker choose between L and L' ?

Von Neuman and Morgenstern introduced six axioms²:

1. The decision maker can rank the prizes $A_1, \dots, A_n$ consistently. This means that we can assume that the prizes are order in such a way that A_n is regarded as best, A_{n-1} next best, etc.
2. A compound prospect, i.e. a prospect in which the prizes are new prospects can be reduced to a simple prospect with prizes $A_1, A_2, \dots, A_n$ with probabilities calculated according to the laws of probability theory.
3. For each prize A_i , there exists a probability u_i , so that the decision-maker is indifferent between A_i and the lottery $((1-u_i)A_1, u_i A_n)$. Let us denote this last lottery with B_i . Then the axiom says that the decision-maker is indifferent between A_i and B_i . This assumption is really an assumption of continuity and is usually interpreted as saying that to each uncertain prospect, there is a certainty equivalent, i.e., we can replace an uncertain prospect with a certain outcome and the decision-maker will be indifferent to such a replacement.
4. In any prospect, if we replace A_i with B_i , then the new prospect will be indifferent to the original prospect.
5. The preference among different prospects is transitive, i.e., if L is better than L' , and L' is better than L'' , then it follows that L is better than L'' .
6. A prospect $((1-p)A_1, pA_n)$ is preferred to a prospect $((1-p')A_1, p'A_n)$ if and only if p is greater than p' .

These axioms seem, at least at a first look, eminently reasonable. However, they are of course open to some severe criticism. We do not have space here to discuss them further but the reader is referred to a number of excellent presentations (Luce and Raiffa 1964, Machina 1987). It is now possible to show that if L is preferred to L' , then

$$p_1 u_1 + p_2 u_2 + \dots + p_n u_n > p'_1 u_1 + p'_2 u_2 + \dots + p'_n u_n.$$

This can then be interpreted as saying that the expected utility for the first prospect is greater than the expected utility for the second prospect. Thus, when analyzing choices between different uncertain prospects could simplify the analysis by using the expected utility hypothesis.

Whatever criticism one could raise against the axioms, one could argue that they include a minimum of conditions that would guarantee rational decision making. Therefore, the expected utility hypothesis is generally accepted as prescriptive device. An individual, an organization or society should behave in a way consistent with the axioms in order to be certain to behave rationally. However, it is a completely different matter whether individuals, organizations or society behave in a way consistent with axioms. Already in the early 1950's, Maurice Allais, Nobel prize winner in economics, constructed an example with a number of prospects and when different individuals had to choose between the prospects, they in general made choices not consistent with the expected utility hypothesis. After that, psychologists and economists have carried out a great number of laboratory experiments, the results of which seem to indicate that people do not behave in a way consistent with the expected utility hypothesis. In order to enable us to predict actual choices between uncertain prospects, alternative theories have been developed and tested. Machina (1987) surveys both the experiments and the recent development of new theories.

Even if experiments indicate that there are deficiencies in using the expected utility hypothesis in explaining individual behavior, it has been used with great success in explaining market behavior. For example, the successes in explaining insurance and financial markets³ as well as some commodity markets⁴ indicate that the expected utility hypothesis has explanative powers in many circumstances. However, more important for the analysis of equity issues in connection with global climatic change is that it is very useful for prescriptive analysis. We will therefore in the rest of the discussion of risk maintain the hypothesis.

VII. Other criteria

However, before continuing, a few remarks should be made on the assumption that there exists probability distribution over the possible outcomes. Although IPCC has

suggested an interval for the predicted future average global warming, it has not quantified the predictions by giving a probability distribution of the global temperature change. Of course, for local climate changes not even averages have been produced. It is therefore not straightforward how one should apply the expected utility framework.

There are a few criteria that could be used in decision-making in case there are no probability distributions over the outcomes. Once again, Luce and Raiffa (1964) gives a modern discussion of the appropriate theory which is still very much up to date. The different criteria respond in the literature can all be related to each other through various systems of axioms. Instead of describing these axioms, it will suffice for this purpose to discuss one particular criteria that is very much related to the precautionary principle. This is the well known maxi-min criteria. If the global community has a number of alternative strategies to choose among then each strategy can be characterized by the worst outcome that is associated with that strategy and the maxi-min criteria then means that we should select that strategy that maximizes this worst outcome. Its basis is the same as Rawls' criteria for equity which we will discuss in a later session. It is clear that it corresponds to the precautionary principle in the sense that it recommends that it looks at the worst outcomes and tries to avoid those strategies that will generate the worst outcomes. It is not possible to apply the criteria to global warming directly, as we must first solve the problems of international equity, i.e. how costs and benefits from different strategies should be shared by different countries. However, if one strategy would be a freeze of carbon emissions while a second would be business as usual, and if the worst outcome of the second strategy is worse than the corresponding outcome with the freeze, then the global community should choose to freeze the emissions. The maxi-min criteria is, however, rather conservative because it takes into account only the worst outcome and not the nature of the other outcomes from a strategy, and it may happen that appropriate concern of these other outcomes would lead to a different choice.

Maxi-min and other criteria are designed to be applied to situations with complete ignorance. In most cases, we are not facing such situations. The climatologist give us some guidelines to what the more likely outcomes will be even if they cannot generate objective probability distributions. That leads us directly to the notion of subjective probability. Savage (1951, 1954) has shown that with axioms similar to the ones used by von Neuman and Morgenstern but with extensions, it is possible to derive the existence of an a priori probability distribution over the sets of outcomes in such a way that the rational decision maker would behave as if he is maximizing expected utility. Furthermore, Savage designed a scheme by which these subjective probabilities could be revealed by letting the decision maker express preferences over a sequence of binary choice questions. Savage's approach has been extended in various directions, for a survey see ??? In view of this, we will in the sequel that the expected utility framework is the appropriate framework for the analysis of the cost of risk-bearing.

VIII. Cost of risk-bearing

From now on, we will assume that the expected utility hypothesis is the appropriate starting point for an analysis of the risks involved in global warming.

In estimating the cost of global warming and the cost of carbon abatement it is usually the expected cost that is estimated. Sometimes it is not even that but the cost associated with some special outcome, for example, the most probable outcome. These estimates are useful but neglect a cost component that may be substantial for some countries - the cost of risk bearing, if the utility is linear in the damage cost, then there would be a one-to-one correspondence between the expected utility and expected cost. However, usually there are no reasons to assume that utility is linear. In fact the St. Petersburg paradox arose from the assumption that utility was linear and in order to solve the paradox a non-linear utility was introduced.

In order to understand the meaning of the cost of risk bearing, consider a very simple case with two outcomes, A and B. In A the monetary gain is M_A and in B the gain is M_B . Let the probabilities for the two outcomes be p and $1-p$. The expected gain is then $pM_A + (1-p)M_B$ which we will denote by M . Is the decision-maker indifferent between the uncertain prospect $(pM_A, (1-p)M_B)$ and the certain gain of M ? If he is, he is said to be risk-neutral and if his utility function is u , it implies that

$$pu(M_A) + (1-p)u(M_B) = u(M) = u(pM_A + (1-p)M_B),$$

i.e., the utility function is linear. However, most evidence indicates that the utility function is concave, i.e., it increases with the gain but the rate of increase goes down as the gain goes up. This has the important implication that

$$pu(M_A) + (1-p)u(M_B) < u(pM_A + (1-p)M_B).$$

The individual would prefer the certain outcome M to the uncertain prospect, although they have both the same expected value. This also means that the individual would be willing to sacrifice an amount in order to ensure a certain outcome. This willingness to pay is defined as the cost of risk-bearing. Let C be this cost. Then it is defined from

$$pu(M_A) + pu(M_B) = u(pM_A + (1-p)M_B) - C.$$

C is the maximum insurance premium the decision-maker would be willing to pay in order to eliminate the uncertainty. If the uncertainty is not eliminated, then it is the cost he has to bear for that uncertainty.

These simple ideas have some powerful implications on equity issues in connection with global warming. There do not exist markets on which individuals or countries could insure themselves against impacts due to changes in climate or due to changes in abatement policies. This means that organizations will have to bear an unnecessary burden corresponding to the cost of risk-bearing. The establishment of global insurance markets would therefore increase efficiency in the global economy substantially. Furthermore, there are good reasons to believe that the distribution of the cost of risk-bearing is very uneven. First of all, industrialized countries have in general better insurance markets. This means that individuals in those countries can reduce their cost of risk-bearing substantially (but not completely, partly because global warming is a collective risk and partly because the incompleteness of markets). These possibilities are not open to most individuals in developing countries, and they have therefore to bear a higher cost of risk-bearing. Secondly, the cost of risk-bearing may be much higher in some developing countries than in industrialized countries because of the nature of the impacts. For example, a range from 20 cm to 60 cm may imply a quite low cost of risk-bearing in a country like USA and the expected damage would be a good proxy for the total cost of sea level rise. For a country like Bangladesh, the difference between 20 and 60 cm may mean a substantial difference in utility, which is not accounted for in the expected damage. For that reason, the cost of risk-bearing in Bangladesh is probably much higher than in other countries. The same holds true for countries that may be threatened by increase in both the frequency and the severity of droughts. The variation in utility will probably be much greater than the variation in actual damages among different outcomes and therefore, the cost of risk-bearing will be high. Unfortunately, there are hardly any empirical studies on the cost of risk-bearing and therefore there is no hard evidence that the hypotheses raised above are correct. But they do seem to be reasonable.

The conclusions to be drawn from this discussion are two

- It is necessary to include the cost of risk-bearing in any equity discussion related to global warming. In particular, measurements of costs of impacts should also include this cost component in addition to expected cost
- It is necessary to establish global markets for insurance against impacts from global warming.

IX Irreversibility

The problem of risk becomes more severe when changes in the environment are irreversible. The reason is that an irreversible change means losses of future options. This was studied by both Arrow and Fisher (1974) and Henry (1974) and they showed that the

combination of uncertainty and irreversibility implied that the expected net benefit is not the correct criteria to decide whether the irreversible change should be undertaken or not. In fact, on average, fewer irreversible changes should be made than what would be implied by the expected net benefits. The correct criteria should include a cost component known as the quasi option value, reflecting the expected value of the losses in options following the irreversible change.

There have been a substantial number of extensions of Arrow-Fisher's and Henry's analysis (Fisher Hanemann (???), Hanemann (???), Maler (?r) etc. etc. However, there have been very few empirical applications of the basic ideas. The best known is Fisher Hanemann (1987) on the quasi option value of extinction of a specific species of Mexican rye. The theory has obvious bearings on the discussion of the economics of climate change, but there are no empirical studies at all.

Intertemporal equity

X. The time horizon

Before continuing the discussion on intertemporal justice, it is necessary to fix the time span in which we are interested. How far in the future should we be concerned with well-being? There are in principle two answers to the question. We could be satisfied with a finite number of time periods, say T years, during which we are concerned with human well-being. But we could also argue that we should look human well-being forever. It turns out that the choice of answer will be of profound importance for how we should look at intertemporal distribution of well-being.

With a finite time horizon, we always end up with the problem on how to evaluate what happens after the last time period. If we take the idea of a finite time horizon seriously we have to admit that what happens after the horizon is of no concern. But that implies that the well-being of generations living after the time horizon will not be accounted for⁵. Thus, the interpretation of the notion of sustainable development we offered in the previous section seems to be contradictory to the idea of a finite time horizon. Logically we should therefore accept the notion of an infinite time horizon. As we shall see in the next section, this will carry with it some interesting and important implications.

We should also point out that this is true even when we take into account uncertainty about a possible end to human life (unless it is known that human life will expire at certain time). This uncertainty will of course affect the way we look at the welfare of future generations, but not the conclusion that we need to consider an infinite time horizon.

XI Impatience

What we now have to do is to find some representation of a social order of an infinite stream of utilities. However, in order to do that we have to make the judgment whether these utilities are bounded or not. This rather abstract, mathematical issue will have some rather important implications for the way we should look at intertemporal justice. Roy Radner (1974) and more lately Graciella Chichilnisky (1994) have argued that bounded utilities have important implications. We will return to their arguments later. For now, we will focus on the case when there are no *a priori* assumptions on the utility stream.

In a remarkable set of contributions, Koopmans (1960, 1965, 1967, 1972a,b) conducted a series of thought-experiments on intertemporal choice so as to see the implications of alternative sets of ethical assumptions in plausible worlds⁶. Underlying Koopman's program of research was the premise that no ethical judgment in such abstract exercises as those involving resource-use should be taken as being, decisive. We should instead play off one set of ethical assumptions against another within plausible scenarios, see what their implications are for the distribution of well-being and then appeal to our varied intuitive senses before arguing policy. For example, he showed (Koopmans, 1965, 1967) that we can have no direct intuition about the validity of discounting future well-beings, unless we know something concrete about feasible development paths. As the set of feasible paths in a world with an indefinite future is enormously complicated, the reasonable thing would be to work with alternative discount rates on well-being and see what they imply⁷. Although seemingly innocuous, this suggestion represents a radical break with a philosophical tradition, stretching from Ramsey (1928) to Parfit (1984), that has argued against discounting future well-beings without first having studied its distributional consequences across generations in plausible worlds. That this tradition is otiose by Mirrlees (1967) and Chakravarty (1969), who showed that in plausible economic models, not to discount future well-beings could imply that the present generation be asked to save and invest around 50 per cent of gross national product. This is a stiff requirement when GNP is low.

For simplicity of exposition, let us assume that population size is constant over time (t), and that generation t 's well-being is an increasing function of its level of consumption (C_t), which we denote by $W(C_t)$. We assume time to be continuous. Let Γ_c be the set of feasible consumption paths - from the present to the indefinite future-, and let Γ_w be the corresponding set of well-being paths. We take it that there is no uncertainty, and that Γ_w is bounded. Imagine that there is an underlying ethical preference ordering defined over Γ_w . Alternative policies are therefore to be evaluated in terms of this ordering. Koopmans (1960) showed that under a plausible set of assumptions, this ordering can be represented by a numerical functional (which we may call aggregate well-being) possessing the "utilitarian" form:

(1) $\int_0^\infty W(C_t) \exp(-\delta t) dt$, where $\delta > 0$.⁸

Now (1) may look like classical utilitarianism, but it is not. There is nothing in the mans axioms to force a utilitarian interpretation upon W . Moreover, (1) involves discounting future well-beings at a constant rate ($\delta > 0$). In short, positive discounting of well-being is seen to be an implication of a set of ethical axioms that at face value at least, would appear to have nothing to do with discounting.

When conducting analytical experiments with alternative assumptions embedded in (1), it makes sense to go beyond the Koopmans axioms and allow for consideration the case where $\delta = 0$. It also makes sense to go beyond the axioms and to consider unbounded well-being functions. This way we are able to test models to see what all this implies for public policy and the choice of discount rates in social cost-benefit analysis. On the other hand, purposeless generality should be avoided. So we will assume that $W(C)$ is strictly concave, to give shape to the idea that intergenerational equity is valued as an ethics goal⁹.

It is as well to begin by noting that discount rates in use in social cost-benefit analysis are 'consumption discount rates'. In first-best situations, they equal 'income discount rates'. (They are also sometimes, misleadingly, called 'social discount rates', and are different from market interest rates in second-best situations; see below.) If consumption is expected to grow, then the discount rate used in cost-benefit analysis would be positive even if δ were taken to be zero. This follows from the strict concavity of $W(C)$. To see this, recall that, in discrete time the consumption rate of discount at time t is the marginal social rate of indifferent substitution between consumption at times t and $t+1$ minus 1. This means that it is the percentage rate of decline in discounted marginal well-being over the interval $(t, t+1]$. Let ρ_t denote this. Reverting to continuous time and the 'utilitarian' form in (1), it is an easy matter to confirm that

$$\rho_t = \rho(C_t) = \delta + \alpha(C_t) [dC_t/dt]/C_t \quad (2)$$

where $\alpha(C_t) > 0$ is the elasticity of marginal well-being at t (see e.g. Arrow and z, 1970). Moreover, along a full optimum-4 the consumption rate of discount equals the productivity of capital (i.e. the social rate of return on investment). This is the famous Ramsey Rule.

Iso-elasticity offers a simple, flexible form of $w(\cdot)$. So let us assume that

$$W(C) = -C^{-\alpha}, \text{ where } \alpha \text{ is a positive constant.} \quad (3)$$

In this case the optimality criterion reflected in (1) depends only upon two parameters: α and δ . Obviously, the larger is δ , the lower is the weight awarded to future generations' well-beings relative to that of the present generation. The moral of Mirrlees's (1967) computations was that introducing this sort of bias would be a way of countering the

advantages to be enjoyed by future generations, should the productivity of capital and technological progress prove to be powerful engines of growth in well-being.

Nevertheless, consider the case $\delta = 0$. As an example, let us assume that $\alpha = 2.5$ (a not implausible figure if $W(C)$ were to be based on revealed preferences). If the rate of growth of optimum consumption at t is, say, 2 per cent, then $\rho_t = 5\%$. It will be noticed that the larger α , the more egalitarian is the optimal consumption path. As $\alpha \rightarrow \infty$, the well-being functional represented in (1) resembles more and more the Rawlsian maxi-min principle w applied to the intergenerational distribution of consumption (and thus well-being). This in turn means that, even in productive economies, optimal growth in consumption is slow if α is large. In the limit, as $\alpha \rightarrow \infty$, optimal growth is zero. From equation (2), we can now see why the consumption rate of discount is bounded (and how it manages to equal the productivity of capital) even in these extreme parametric terrains, (On this, see Dasgupta and Heal 1979, Chapters 9-10.)

Social discount rates are percentage rates of change of intertemporal relative shadow prices. It follows that unless the optimizing economy is in a steady state, social discount rates typically depend upon the numeraire that has been adopted¹⁰. As equation (2) makes clear, the well-being discount rate differs from consumption rates of discount, and it continues to be misunderstood in a good deal of the environmental literature that is critical of social cost-benefit analysis (see e.g. Daly and Cobb, 1991; Norgaard and Howarth, 1991). Modern philosophers writing on the matter make the same mistake and conflate well-being and consumption rates of discount. They argue that δ should be zero and then criticize the practice of discounting future flows of consumption in social cost-benefit analysis (see e.g. Parfit, 1984; Cowen and Parfit, 1992).

Although simple, the Koopmans formulation spans a rich variety of ethical considerations. Among other things, it tells us that consumption rates of discount do not reflect primary value judgments: they are derived notions. They are essential when we try to implement optimal policies by means of cost-benefit analysis of projects.

Notice that in equation (3), $W(C)$ is unbounded below. If $\delta = 0$, this ensures that very low consumption rates are penalized by the optimality criterion reflected in (1). On the other hand, if δ were positive, low consumption rates by generations sufficiently far in the future would not be penalized by (1). This means that unless the economy is sufficiently productive, optimal consumption will tend to zero in the very long run. As an illustration of how critical δ can be, Dasgupta and Heal (1974) and Solow (1974a) showed in a model economy with exhaustible resources that optimal consumption declines to zero in the very long run if $\delta > 0$, but that it increases to infinity if $\delta = 0$. It is in such example that notions of sustainable development can offer some cutting power. If by sustainable development we wish to mean that the chosen consumption path should as a minimum never fall short

of some stipulated, positive level, then it follows that the value of δ would need to be adjusted downward in a suitable manner to ensure that the optimal consumption path meet with the requirement. This was the substance of Solow's remark (see Solow, 1974b) that, in the economies of exhaustible resources the choice of δ can be a matter of considerable moment.

On the other hand, by sustainable development we could mean something else. we could mean that well-being (and, therefore, consumption) must never be allowed to decline. This is a stiffer requirement than the one we have just considered. If δ is less than the productivity of capital, the valuation criterion reflected in (1) ensures that the optimal consumption path will satisfy the requirement. This follows immediately from equation (2) and the Ramsey Rule. We may therefore conclude that the Koopmans program is all-encompassing, and that concepts of 'sustainability' are useful in pruning out of consideration those consumption paths that are ethically indefensible on *prima facie* grounds.

Let me very briefly add to this that one assumption underlying this discussion has been that well-being or utility has not been bounded. If we restrict well-being to be bounded, some other results will come about. This has to do with mathematical properties of the space of bounded sequences, and it turns out that for such sequences the present value calculations are not rich enough to catch all the subtleties of the evaluation of a utility stream. In fact, one has to add to the present value another term. In an ingenious interpretation, professor Graciella Chichilnisky (1994) has suggested that the first term, - the present value term - represents the requirement that the future should not be over the present and that the second term - the new term - represents the requirement that the present should not be a dictator over the future. This second term will in general have the form of a long term average. It could be approximated by minimum requirements for the long run stocks of environmental resources. With regard to climate change, one could imagine that the Chichilnisky criteria would be to minimize the total discounted damage and abatement costs from now and forever under the restriction that in the very long run, the climate must not exceed some bounds. Unfortunately, Chichilnisky analysis does not offer a way of finding these bounds. It is very difficult to have an intuitive appraisal of whether the utility stream should be allowed to be infinite or not when we allow for an infinite time horizon. But it is remarkable that these rather abstract mathematical facets may have an important ethical and economic impact. However, for this presentation, I will remain within the Koopman's framework, that is a present value calculation of the well-being of all generations.

XII. Measurement

From an ethical point of view, the important choice is the choice of δ , that is the pure time preference. How should it be chosen? From a practical and operational point of

view, the important choice is of ρ , the consumption interest rate. Typically, in the literature on cost benefit analysis, the chosen discount rate is based on market rates of interest. The argument being that the market rate will reflect the opportunity cost of capital. Sometimes it is argued that there is a need to correct the market rate because of market imperfections, such as capital income taxes (see Lind 1982, Dreze and Sandmo 1977). The result after these corrections would then reflect the consumption rate of discount. In a perfect world, with perfect markets and in which we are ethically neutral between the well-being of different generations, this will yield an acceptable estimate of the consumption rate. In fact, if the economy is expecting a reduction in productivity because of climate change, then the market rate of interest will also be expected to fall and if the impact from the climate change is serious enough, the return on capital may be negative with the result that we should discount the future with a negative interest rate!

However, we do not live in an ideal world and there are other imperfections that we have to account for. The most important one has to do with missing markets. The market rate of interest is determined through transactions in assets. However, only those assets that have well defined property rights can be subject to transactions and have an impact on the market rate of interest. This has some far reaching implications as most of our environmental resources - including our climate - has no property rights and it is in fact impossible to define property rights for many of these resources. Thus, the productivity of these resources does not directly influence the market rate of interest although in an ideal world they should. If we base our intertemporal equity considerations on the market rate of interest, that is the opportunity cost of real capital, we are excluding the productivity of our environmental resources from consideration.

Referring back to equation 2, we could argue that α may be negative because of deterioration of the environmental resource base - in this case the climate - while this would not be reflected in the market rate of interest. Thus, there is the possibility that the market interest rate gives no guidance at all for making intertemporal choices, but that we need some more elaborate ways of estimating the present and the future productivity of the total capital stock - human capital, real capital and natural capital - in order to make reasonable statements on how to compare future and present consumption bundles. Right now we do not have the data or the techniques available to do that. Undoubtedly, this a terribly important issue to be resolved in view of the possible consequences from climate policies.

The main conclusion is, however, that the choice of the consumption rate of discount is not something one could select independently of ones predictions of the future. If the IPCC predictions for the economic impact from climate change are very gloomy, then a low or even negative rate of discount would be appropriate, where if the predictions are rather optimistic, then the market rate (after corrections for other imperfections) may be the correct choice.

If there would be a perfect global capital market then of course, the same rate should apply in all countries. We do not have such a market. One reason being the lack of insurance, discussed above. This incident of missing market will also have implications for the choice of an interest rate. The market rate will in that country be higher in order to give the investors the necessary compensation for the increase in exposure to risk. However, with perfect insurance markets, the interest rate would be lower. Once again, the lack of insurance markets will have serious implications for the distribution of cost of impact, and it seems as important to address this institutional issue as it is to address the issues related to instruments to control emissions.

III Equity Among Regions and Countries

Draft contribution to IPCC chapter on Equity and Social Considerations

First draft by Michael Grubb

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III.1 Introduction

This part of the chapter considers equity issues between different countries. This has many different aspects, ranging from a variety of philosophical and other theoretical debates about meanings of equity and fairness, through a variety of aspects in which countries differ in practice, to debates about the implications of these factors for international policy towards climate change.

Various philosophical and other theoretical and definitional issues have been discussed earlier in this chapter [Jake]. The main focus in this section is upon the ways in which countries differ in ways that are relevant to the question of equity between countries in responses to climate change. The following section then reviews some of the issues and conclusions that writers have drawn concerning implications for policy towards climate change.

Equity is not the same thing as equality, but issues of international equity are clearly related to a variety of differences between countries. This review looks at five aspects which are of greatest relevance and which feature most in the literature, namely:

- Wealth and consumption
- Social considerations and institutional capabilities
- Emissions - past, present and future
- Impacts - the distribution of and vulnerability to climate change
- Endowment with resources that may be affected by responses to climate change

III.2 Wealth and consumption

Wealth is one of the most obvious and pervasive differences between countries. Much of the literature on international equity starts from this issue, and the statistics need little elaboration. Figure 1 shows the distribution of average per-capita income between

[countries/regions. best source: WDR?] on convention [&/or PPP?] exchange rates. On this basis, the one-fifth of the world's population in the richest countries account for XX% of the world total GNP; the poorest one fifth account for XX%.

In human terms these differences have a direct bearing upon the issue of climate change in various ways. Activities of the poor that result in emissions of greenhouse gases are mostly those that relate most closely to "basic needs" often at little more than subsistence levels - energy for cooking or keeping tolerably warm, emissions from agricultural activities, perhaps energy for light to enable reading, and occasionally for travel by public transport. Emission from the rich tend to be dominated by activities such as driving private cars, home central heating, and energy embodied in a wide variety of manufactured goods and the use of such goods. The welfare impacts of cutbacks of greenhouse gas emissions may thus differ greatly according to the level of personal wealth [Ref. Basic Needs literature (Chichilnisky, others? Agarwal, etc.)]

Obviously there are great variations within countries, but in aggregate the same broad issues apply concerning wealth disparities between countries. The aggregate relationship between wealth, consumption of a variety of natural resources, and emissions of various pollutants have been explored methodically by a number of authors. Using cross-sectional data [expand?], Parikh shows that consumption of a wide variety of resources - many of which involve emissions of greenhouse gases in their extraction, processing and application - is closely related to the level of wealth [Figure?]. Williams [+ others] argues that in many developed economies, a decoupling of wealth from material consumption has occurred since the 1970s and that this will accelerate, though others have disputed this []; but the aggregate relationship at middle and lower income levels seems undisputed. The 1992 World Development Report notes that direct emissions of many pollutants declines beyond a certain stage of economic development, but considers that this point has not been reached for most greenhouse gases, particularly CO₂ and (to a lesser extent)

CH₄ from sources other than land use.

Wealth is thus not only one of the most important determinants of greenhouse gas emissions (at present). It also has a very important bearing upon vulnerability to climate change. [expand here, or below]

Poverty also has an important bearing upon national priorities and the time scales considered in policy. Economists have long noted that personal discount rates decline with rising income (is there standard ref?). Richer people can afford to look further ahead, have greater security, and can afford to invest more for the future. Poor people are focused more upon short-term concerns, including those of striving to ensure that they can meet

basic needs. This has important implications for the potential equity impact of policies to address climate change within countries [as noted above - Tariq?] and the same applies at the level of national economic and political systems.

Thus, in poorer countries interest rates tend to be higher, capital is scarcer, and the whole focus of policy and politics tends to be upon meeting pressing short-term needs ranging from poverty alleviation and employment generation to the management of fiscal crises, often driven partly by the needs of debt repayment. At the industrial level, the focus may for example be upon the scramble to construct infrastructure and capacity fast enough to meet rapidly rising demand, rather than the more considered examination of optimal investments over longer periods that may be possible in richer countries. Thus the context both for actual investment behavior and broader public policy is strongly affected by national wealth in ways that are directly relevant to the climate problem (Mathur, others..).

III.3 Social considerations and institutional capabilities

The importance of social considerations and institutional capabilities has been considered in the previous section. The important point here is to note the extent to which countries differ in these respects.

III.4 Patterns of greenhouse gas emissions

Discussion of patterns of historical, current and projected emissions, based on my co-authored "sharing the burdens" paper review and some more recent work (IPCC?), and noting Agarwal, Meyer etc. points about ways of presenting.

III.5 Impacts of climate change

Focusing upon:

- distributional nature of physical impacts (sea level, storms, drought etc.)
- differential susceptibility
- differential capability to adapt Concluding with discussion of:
- time lags involved
- implications for damage evaluation

III.6 Resources that may be affected by responses to climate change

III.7 International equity considerations in responding to climate change

III.7.1 Introduction

The previous section has addressed the principal differences between countries that are relevant to the subject on international equity: differences in wealth, institutional capabilities, emissions, resource endowments, and vulnerability to climate change. This section considers the implications that these differences, when combined with various principles of equity, may have for international responses.

In addressing these questions, several points need to be made at the outset. No international agreement has ever been founded purely on a logical consideration of equity issues, a whole range of other factors, ranging from basic economic and political power structures to accidents of timing and personalities, influence the outcome. Yet nor is the converse - the cynical view that equity considerations play no role at all in the real world of international politics - true. Analysis of possible agreements based upon game theory (especially "single shot" or non-repetitive games), conducted purely from the point of view of maximizing self-interest, point towards outcomes with little or no explicit equity content, but often do not explain agreements that have been reached.

Furthermore, a broader view of self-interest often point towards more explicitly equitable outcomes because of the longer-term risks that grossly inequitable behavior may pose to stability and cooperation in the international system. This chapter however is not concerned directly with such broader conceptions of self-interest, but rather with equity per se.

Second, there are many inequities in the world, between and within countries, and it is no more realistic to suppose that climate change can be a vehicle to resolve all the international inequities than to suppose that it can resolve all the inequities within countries. But there is an important difference. Within countries, institutions exist to address a wide range of issues of common interest to members of that society. The institutions have developed in part to provide a way of taking decisions about constitutes acceptable behavior, and decisions about the distribution of wealth and resources - in most countries, through regulation of market structures backed by legal codes and with progressive taxation as a way of redistributing resources to common goals.

Equity - in the form of views about what constitutes social justice - is an important influence and measure of the legitimacy of these institutions and their decisions. The actual strength and perceived legitimacy of these institutions varies widely, but policies to

address climate change at the level of national implementation fall clearly within the remit of these institutions and processes.

The institutional parallels at the international level are weak or non-existent. Yet in responding to climate change, humanity faces unavoidable decisions about the distribution of effort and burdens, and what constitutes acceptable behavior, in circumstances where the internal activities of one country may directly impact upon all others. Whilst on a modest scale there are precedents (e.g. with ozone depletion, commodity cartel pricing decisions etc.), climate change is wholly unique in the scale and scope of its potential implications. Whether or not countries seek to use climate change to try and resolve inequities in other areas, therefore, the relative weakness of international institutions may need to be compensated by great explicit emphasis on considerations of equity. Climate change and responses to it should at the very minimum not worsen existing inequities (Shue, the Unavoidability of Justice).

Finally, it should be noted that the applied research literature on these questions - relating specifically to climate change policy - is limited compared to that on climate science, impacts or the economics of responses. There are of course many short articles and statements of positions made in newspapers, newsletters, 'non-papers' at negotiating sessions, etc.; and also some important official declarations developed through extensive discussions to reflect consensus positions among groups of countries (e.g. the Beijing Declaration, and various regional statements). Also, the UNCED agreements themselves contain innumerable references related to equity. Most of this is cast in North-South terms, with important additions concerning the interests of particular groups.

The following section attempts to reflect this material, whilst recognizing the impossibility of ensuring comprehensive coverage, and drawing heavily upon the limited deeper analysis of international equity issues in the more conventional academic literature of books, substantive reports and articles in peer-reviewed journals. Interestingly, of those that have contributed such analysis, few are professionally employed as academics in the discipline which might seem to be of greatest direct relevance - moral philosophy. In structuring the remainder of this chapter we draw upon the observation by one such philosopher (Shue, 1992) that the equity issues comprise at least four distinct questions:

- distribution of the costs of coping with climate change
- distribution of future emissions
- distribution of the costs of measures to limit emission
- the background allocation of resources and capabilities and consequent basis for fair bargaining

All these questions are interrelated. For example, a "fair" distribution of future emissions may depend somewhat upon how much countries help others with the costs of coping, a

fair distribution of abatement costs depends upon various background circumstances; and debates about joint implementation and tradable emission quotas highlight a potentially strong link between ii) and iii). Few authors in fact have distinguished these different components, but they are distinct and it is useful to address the equity issues each raises in turn, even if two or more of them may in practice be tied or even addressed through the same instruments.

III.7.2 Who should pay for the costs of coping?

If there are no international transfers or other assistance connected directly with the measures to cope with actual or potential impacts of climate change, each nation in effect is expected to cope using its own resources. The available literature appears to be unanimous in considering this inequitable, for two main reasons.

The first arises directly from the observation above that poor countries are likely to be much more vulnerable to climate change. Climatic change is thus likely to exacerbate existing inequalities. Most ethical systems would anyway expect richer parties to contribute more to addressing a common problem; the rationale is much stronger still when the cause is shared but the impacts are disproportionately large on the least well off parties.

The second factor, which applies irrespective of this inequitable distribution of impacts (but is much reinforced by it) is the direct causal link: the fact that the actions of some people (emitting greenhouse gases) may directly harm others. There are few if any ethical systems in which it is acceptable for one individual knowingly to inflict potentially serious harm upon another and not accept any responsibility in helping or compensating the victim, or to pay in some other way. None of the literature attempts to present reasons why the same principle should not apply concerning transboundary impacts potentially arising from climate change.

Indeed, this is a point which was formally accepted at the intergovernmental level in Principle 21 of the Stockholm Declaration, and more explicitly in Principle 13 of the Rio Declaration. [XX] This 'fault-based' rationale aligns closely (though not perfectly) with that arising from the likely distribution of impacts: poorer nations tend to be more vulnerable, and richer nations tend to be greater past and current emitters of greenhouse gases. It is also an issue for which historical emissions are of direct relevance, since climate impacts are a function of atmospheric concentrations which depend strongly upon the cumulative emissions.

There are three broad kinds of costs that may be incurred in coping with climate change:

- i) preparation (or protection) to minimize the potential impacts of climate change, for example through the construction of sea defenses, improved water storage or water transfer capabilities, or changing the kind or diversity of crops;
- ii) costs arising directly as a result of changes in the resource base (e.g. loss of land to the sea, other loss of agricultural land), and the social costs that may follow from this (ref Suleman above?);
- iii) costs caused directly by extreme events, such as freak storms and droughts

Although the underlying equity issue of who should pay is similar in each case, some of the practical issues differ. Even if there is agreement on the underlying equity principles, major practical differences and disputes may arise because of all the uncertainties surrounding climate change. General protection measures (I) have multiple benefits, views will differ on the extent to which they should be funded primarily on the basis of concerns about climate change. It is likely that victims of both underlying climatic changes (ii) and extreme events (iii) will attribute their suffering to human-induced climate change more readily than those responsible for the emissions. Insofar as international help is based on the second 'fault-based' rationale, this raises important issues about fair processes for deciding about the probability of events being tied to human-induced climate change, which none of the literature addresses explicitly.

The different nature of these costs has also led to different proposals about how to tackle them. Notably, there have been suggestions [detailed references sought Beijing Declaration?] for a "climate fund" to help developing countries pay for protection measures (i), whilst the small island states have proposed creating an insurance pool to provide some cover against the costs of extreme events (iii)

The proposal for an insurance pool against the impacts of sea-level rise and associated salt intrusion and storm surge damage - put forward as an Annex to the draft Climate Convention but removed at a late stage under pressure of the Rio deadline - appears to be the most developed proposal. Wilford (1993) notes several reasons why commercial insurance markets cannot adequately cover against such risks and even to the limited extent they can the insurance premiums would presumably fall primarily upon the potential victims and thus represent an inequitable burden. Consequently, AOSIS proposed that an insurance pool be created with international funding from governments. Two precedents are noted:

- The 1971 International Convention on the Establishment of an International Fund for the Compensation for Oil Pollution Damage, which is funded by agreed levies on oil importers; and
- the 1963 Brussels Supplementary Convention (an OECD agreement, amended by 1964 protocol) to the 1960 Paris Convention on Third Party Liability in the field of Nuclear Energy. This is funded half on the basis of GNP, and half on the basis of nuclear capacity.

The draft Insurance Annex to the Climate Convention proposed, by analogy with the nuclear precedent, funding through a combination of GNP and CO₂ emissions, the latter component suggested both on grounds of responsibility and to give an incentive to limit emissions.

The main criterion for entitlement to claim was proposed as proved loss attributable to sea level rise, including storm surges. However, discussion of the proposal does not attempt to explain why the principles involved should be restricted to the case of sea level rise; it would appear more equitable to extend the scope of such a fund to insurance against all kinds of climate impacts. The literature does not appear to explore this issue, nor does the question of compensation or other support for other kinds of climate coping appear to have been explored more fully.

III.7.3 Abatement equity in the absence of substantive and separated international transfers

III.7.3.1 Introduction

Issues of how future emissions (or abatement efforts) should be allocated, and who should pay for abatement, form some of the most contentious equity issues in climate policy. As noted above, the two questions are closely intertwined. This section considers questions of fair distribution of emissions - and by implications abatement effort - separated from any substantive financial transfers related to climate change. The distribution of emissions / abatement effort then directly determines the payments, and any abatement-related transfers would be similarly determined directly by the initial emissions allocation, through the mechanisms of joint implementation or by more formal emissions trading. The subsequent section then considers other approaches which consider directly the question of 'who should pay' abstracted from the question of distribution of emissions.

There are three reasons for dividing the issues in this way. First, it provides a useful way of classifying the literature: although much of the general writing does not explicitly distinguish issues of who should pay from emissions distribution, most of the

more analytic material in practice focuses upon one or other as the "output". Second, it provides an analytically clear delineation which may help to remove some of the confusion in understanding the literature.

Much of the economics literature assumes that an international market - mediated by large international transfers to produce a global least-cost response - exists or will naturally come into being. This debatable assumption explains much of the division between economic and other perspectives. Third, by the same token it provides a politically useful clarification; many are skeptical of the prospects that an international fund, with payments though it on some equitable basis on support of a globally optimal response, will in reality ever be created, and this explains much of the fear about inequitable global responses. Focusing initially upon allocation in the absence of big international transfers helps to clarify these issues.

It is also useful to distinguish short-term from long-term allocation issues. In the long term, decisions will have to be taken - by design or default - about the overall allocation of greenhouse gas emissions. The appropriate allocation depends upon the conception of equity, and different ethical approaches may have very different implications. But in the short term, the position is simpler. All ethical systems, and all the applied literature, appears to point in the same direction (Shue, 1991):

'Even in an emergency one pawns the jewelry before selling the blankets... whatever justice may positively require, it does not permit that poor nations told to sell their blankets [compromise their development strategies] in order that the rich nations keep their jewelry [continue their unsustainable lifestyles].'

This much has been formally agreed in the Framework Convention on Climate Change 'developed countries shall take the lead...' [get full cite]

The observations about what is not fair in initial distribution of emissions obligations extends to other measures of abatement effort. Notably, some earlier and overly simplified economic studies assumed that a uniform carbon tax, as an indicator of abatement effort, would distribute the "burden" equally, fairly, and efficiently. None of these three suppositions have stood up to closer scrutiny in the literature.

- A uniform carbon tax would not impose equal burdens upon different countries because of differences in existing tax structures (Shah and Larsen; OECD; etc.), resource endowments (Whalley and Wigle; others?), and stages of development;

- even in a scheme involving "equal burdens," most observers argue that this would not be fair because of the many differences outlined in the previous section, notably differences in historical and current emissions and current wealth and consequent priorities;
- a uniform tax would also be Pareto-inefficient in the absence of optimal international lump-sum transfers, because of the differing marginal utilities between countries at different stages of development (Chichilnisky 1993a).

The literature thus demonstrates a degree of consensus about relative responsibilities and equitable directions of response in the short term, and some elements of what would not be equitable in longer term allocations. Beyond this, and in the attempt to develop more precise allocation principles, there is a far wider range of perspectives, which derive from a range of ethical approaches. These may be classified in three broad categories: ad-hoc proposals; general distributional principles; and specific allocation proposals. These are considered in turn.

III.7.3.2 Ad-hoc allocation schemes

Various ad-hoc allocation schemes have been proposed. Krause et al (1993) suggest that an overall cumulative limit for emissions of 300GtC over the next 100 years be established and divided equally between the current industrialized and developing countries. The general characteristics of this allocation are argued to be ethically appealing - it requires substantial cutbacks from the industrialized world and allows for some interim growth from developing countries - but no more detailed division is offered and no more formal justifications for a 50:50 aggregated division of future emissions are presented. Westing (1989) suggests land area as a basis for allocation, but without any particular justification and with some perverse consequences (Grubb et al, 1992).

More widely suggested is some proportion of GNP; Cline (1992) [others?] for example suggests that this could be a component of an allocation on the grounds that carbon emissions are partially tied to economic activity. But the relationship is quite variable between countries for a variety of reasons, and pure GNP allocation faces the objection that on its own it would directly reward riches, thus exacerbating inequalities - especially since poorer countries generally have lower GNP/carbon ratios (there could also be technical difficulties associated with definitions and manipulation of GNP comparisons).

III.7.3.3 General distributional criteria

Proposed general principles for emissions allocation appear to fall into three broad categories.

Rawlsian criteria

One approach derives directly from the philosophical approach developed by John Rawls (1971). This considers the allocation that an observer might propose before knowing which country he or she belonged to (the "veil of ignorance"). For many, this leads to the principle that allocation should seek to most improve the position of the least well-off. At a minimum this would suggest that developing countries be left at least as well-off under an emissions control regime as they would be in its absence. A stronger interpretation would be that the regime should be used to seek to improve their position. [ref Knordsvel]

A related version of this is to place the emphasis upon basic needs, or defining a "reasonable level" of emissions for each country - a level that would support a consistent, modest standard of living, given the national climatic or other conditions. Allocations would be granted for emissions at this level, but not for those "luxury" emissions exceeding this. The actual level - presumably somewhere between survival emissions and reasonable comfort - and the extent to which it might vary between countries if at all, is of course somewhat ambiguous.

Comparable burdens

Another general approach to emissions allocation is the sentiment, frequently stated but not subject to more detailed analysis, that allocation should affect all countries similarly or involve "comparable burdens," or "sharing the effort equally." This is not to imply that countries should incur the same monetary costs (e.g. per capita), some conceive of it as a fixed proportion of GNP, others in terms of a more general measure of ability to pay, including more complex measures (e.g. the Human Development Index - see below). A strictly economic interpretation of "comparable burdens" can also arise from purely economic considerations in terms of Pareto efficiency. Chichilnisky (1993) demonstrates that if there are no big international transfers and each country has the same, convex utility function, at a Pareto-efficient allocation, the fraction of income which each country allocates to carbon emission abatement must be proportional to that country's income level, and the constant of proportionality increases with the efficiency of the country's abatement technology. This is the only distribution of abatement effort, for a given global total abatement, in which no country can be made better off without making another worse off.

Willingness to pay

Another principle is simply that countries should bear costs based upon what they are - or objective "should" be - willing to pay, give the potential damages they face from climate change. According to this principle, contributions should be determined by a combination of ability to pay (reflecting current wealth) and, national benefits gained in terms of reduced climatic stresses, and level of general concern about climate change. This approach reflects the principle of welfare economics that subjectively perceived

benefits ought to affect the distribution of burdens (and hence allocations). Dorfman (1991) draws the important distinction that for a common property resource (degradation of the atmosphere), willingness to pay should be based not on how a country values a given reduction in its own emissions, but instead, how much it would value a reduction in worldwide aggregate emissions. Presumably those valuing such reductions to a greater extent should be more willing to abate. One concern is that this could lead to a situation of "victim pays," though in the greenhouse case the wealthiest countries are likely to be both the greatest polluters and the most willing to pay. At present an intractable difficulty is the lack of knowledge concerning the regional impacts of climate change, and in practice such a criteria would imply piecemeal negotiations in which each country had an incentive to underestimate the potential damages from climate change, and overestimate the costs of abatement, so as to obtain a lax allocation for itself.

These various principles can be extended to incorporate some differences other than those arising from differences in wealth, for example those arising from different resource endowments.

III.7.3.4 Specific equity-based allocation proposals

The approaches outlined in the previous subsection offer general criteria, but do not give specific rules that could determine a unique allocation of emission entitlements. The number of such specific, equity-based proposals is in fact very limited.

Equal per-capita entitlements.

The most widely cited specific proposal for allocation in the literature is that derived directly from egalitarianism, suggesting that all human beings should be entitled to an equal share of the atmospheric resource. This takes two general forms, with minor variations.

Equal contemporary entitlements - allocation in proportion to national population - is proposed by Grubb (1989), Bertram (1989, 1992), Epstein and Gupta (1990), and Agarwal and Narain (1991), among others. To prevent this providing an inducement to population growth, Grubb (1989) suggests that it should be restricted to adult population; Grubb et al (1992) note a wider range of possibilities for such decoupling including allocation tied to population a fixed period earlier, apportioned to a fixed historical date, or including an explicit term related inversely to population growth rate. The net effect in all cases would be to give developing countries, with much lower per-capita emissions, a substantial excess entitlement, whilst the industrialized countries, with emissions well above the global average, have a deficit.

This effect is much stronger still in proposals for equal historical or stock entitlements. Fujii (1990), Ghosh (1991) and Meyer (1992) propose that everyone should have an equal right to identical emissions regardless of country and generation, and develop detailed systems of accounts involving intergenerational transfer of the responsibility for past excess per-capita emissions by the industrialized countries.

Egalitarian allocation, in either form, would be compatible with some of the more general principles noted above (such as Rawlsian) but not others (such as comparable burdens and willingness to pay).

Status quo.

At the opposite end of the spectrum, an alternate principle for emissions allocation has been suggested - but not necessarily advocated - for example by Young and Wolf (1992) as "status quo" - not only that past emitters should be held harmless but that their current rate of emissions constitutes a status quo right now established by past usage and custom especially since past carbon emissions were not generally regarded as damaging. Analogies are drawn with the common law claims of "squatter's rights."

A strict status quo allocation - proportionate to current emissions - would violate all the more general principles outlined in the previous section. In fact, none in the literature appear to advocate strict status quo as an equity principle in its own right. It has however received widespread reference as a basis from analysts taking a pragmatic or game-theoretic approach (e.g. Barret, 1991), in that it is the default allocation that would arise in the absence of agreement (and hence a focal point), and the only specific allocation basis which does not automatically impose big burdens upon the industrialized countries. In such treatments the ethical basis, where considered, is usually referred back to concepts of equal burdens. It should be emphasized that in this context 'status quo' is not a static concept, but rather refers to starting from a baseline of what emissions would have been in the absence of abatement, and thus would allow for more rapid growth from developing countries.

Mixed systems

An alternate form in which historical contributions are considered as a determinant of emissions allocation, other than historical egalitarianism, is a scheme examined by Grubler and Nakicenovic (1991) in which countries have to cut back from current levels in direct proportion to their responsibility for past increases. In a sense therefore this is a mixed system. In requiring cutbacks from all countries - albeit more from the richer countries - it is probably inconsistent with the other principles sketched in the previous section.

Cline proposes an alternate mixed allocation which combines population, GNP and current emissions. Grubb and Sebenius (1992), supported by Shue (1993) suggest an allocation which combines egalitarian and status quo / comparable burden principles, as a weighted mix of population and current emissions, and argue that the weighting accorded to population should increase over time.

III.7.4 Distributing costs with international transfers

The discussions above have focused upon the equity issues raised by different possible approaches to distributing emission "entitlements," irrespective of international transfers. In practice, most analysts suggest that both equity and efficiency considerations suggest a case for large international resource transfers as part of any regime for substantial reductions in greenhouse gas emissions.

Three main approaches have been taken to consider how, and how much, such transfers might occur.

III.7.4.1 Basis of the Climate Convention

One is based upon the principles in the Climate Convention, which states that [incremental costs]

This effectively divides the world into three groups. [Expand convention Annex I & 2 & developing countries / GEF / Joint Implementation]

III.7.4.2 Transfers determined by emission allocation and tradable entitlements

A second approach to international transfers is to let them be generated directly by determining a fair initial allocation, and allowing these entitlements to be traded (UNCTAD study). Since most of the allocation proposals noted above would give poorer countries entitlements greater than their needs, and leave richer countries with a deficit, this would generate a transfer of resource to the poorer countries. The initial allocation would be the principle means of determining resource transfers.

A number of concerns have been raised about practical aspects of such systems, including their possible fairness in operation without institutional safeguards. Several analysts, including both those supporting and opposing tradable entitlement schemes, have raised concerns about the equity implications of allowing countries to sell the "right" to emit. For this reason, it has been proposed that entitlements should be either leasable (Grubb 1989; Agarwal and Narain 1991), or issued with a finite lifetime (probably overlapping)

and reissued periodically according to the agreed allocation scheme (Bertram 1992, Grubb and Sebenius 1992). III.7.4.3

Polluter pays principle and historical responsibility

Bring in Natural Debt here

III.7.4.4 Ability to pay proposals

Smith / Hayes proposals on HDI index here

III.7.4.5 Mixed systems

Smith / Hayes 50:50 payment matrix here.

III.7.5 Process fairness in climate change negotiations

This is the section I most wanted to complete before going away for comment - but as you can see I haven't managed it. The main references I have to go on seem disconcertingly dated, and are:

Millennium special issue 19:3, Winter 1990

Policy Studies special issue 19:2, 1991

For Earth's Sake - report of Commission on developing countries and global change
Global Accord (Choucri, editor) 1994

I will insert box on Joint Implementation as a focus and illustration of equity issues.

Concluding section? Pointing towards process of building international rules?

One thing I haven't brought into this is the issue of "free riding" which initially we were asked to address, unless in the simplistic sense I have indicated in iv) above; I am not clear what else it might encompass that we should address?

IV Equity Within Countries

To be supplied by Tariq Banuri.

V Conclusion

To be supplied by the lead authors.

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Notes

1. The article refers to "developed country Parties and other Parties included in annex I Annex I lists the European Community and 35 states, the 24 members of OECD in 1992 (Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Japan, Luxembourg, Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, United Kingdom, and United States of America) and 11 European states that are undergoing the process of transition to market economies (Belarus, Bulgaria, Czechoslovakia, Estonia, Hungary, Latvia, Lithuania, Poland, Romania, Russian Federation, and Ukraine).

2 The number of axioms differ between different presentations, but they all are essentially equivalent.

3 See Copeland and Weston (1983) for an introduction to financial markets and Borch (1977) for a discussion of insurance.

4 Newbury and Stiglitz (1987) is good example of this.

5 The idea of an infinite time horizon has a long history in economics from Ramsay (?), Samuelson, Tinbergen, Koopmans...

6 For an account of this programme, see Dasgupta and Heal (1979, Chapters 9-10).

7 Dasgupta and Heal (1974) and Solow (1974a) provide exercises of this sort in economics with exhaustible resources.

8 Koopmans's theorems were proved under the assumption that time is discrete. In Koopmans (1972a,b) the ethical axioms are imposed directly on T_c , and $W(\cdot)$ is obtained as a numerical representation.

9 For simplicity of exposition, we will begin by focussing on a full optimum. In Section 9, when commenting on cost-benefit analyses of policies to combat global warming, we will look at second-best situations. Social cost-benefit analysis in second-best circumstances was the subject of discussion in Dasgupta, Marglin and Sen (1972) and Little and Mirrlees.

10 Therefore, unless the numeraire has been specified, the term 'social discount rate' is devoid of meaning.

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

Table 4.4.4 Key elasticities in reference and abatement scenarios for 1990 to 2020/30.

Country	Energy/GDP	REFERENCE		ABATEMENT		
		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.

(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.

Unnumbered studies were part of the UNEP GHG Abatement Costing project.

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.

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
Venezuela	Total CO ₂ reduction	30	
	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	

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.

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.

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Divider Title: _____

Real transfer / absolute

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How much you are willing to pay

response time

Optimal clearance

Δ w.

Decision-making Framework to Address Climate Change

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6.1 Decision Criteria

This section investigates some of the basics of decision making and gradually introduces the new ground broken by climate change.

It first presents the criteria of choice in relation to standard economic situations as well as with respect to decisions that are taken beyond individual choice-like situations. Then, it delimits choice variables like certainty, risk, uncertainty and ignorance, and catastrophic risk. Finally, it indicates the variations to the decision making scheme that climate change might lead to.

The next section is devoted to the factors that affect decision making (e.g., time, information, irreversibility, attitudes, and value) whether generally or with respect to environmental concerns.

6.1.1 Criteria of Choice

Main concepts underlying decision making are presented to familiarise the reader with the criteria for choice and standard decision approaches. Many questions arise.

What is choice? On which criteria do individuals make choices in economic contexts? Do choices with respect to environmental problems convincingly differ from choices in economic situations? Is the economic foundation supporting decision making enough robust to address climate change related decision problems? Finally, what are the decision rules we already have at hand to respond to risk, uncertainty, near ignorance, or catastrophic risks, and to which extent do we need to forge new rules and/or variations to old ones? For instance, this might be the case for insurance in the sharing of climate change associated risks.

Though economic requisites are not a priori in dispute, classical formulations of such criteria and variables in economics might no longer suffice because of the existence of some disturbing amount of unpredictability with regard not only to the accuracy of either climate changes or economic forecast, but also with regard to the natural (sea-level rise, ice-sheet melt, coastal erosion) and man-induced (enhanced greenhouse effect) sources of environmental variability, and thus to the evolution of nature-economy joint systems (Vercelli, 1991, Pillet, 1993, Chichilnisky, 1993, Tooley, 1994). It is therefore our ambition, initially, to stick to the current status of choices in economic situations, as we ordinarily understand that expression. And then to consider decision making situations to address climate changes. This will help us thinking and assembling the pieces the building of an adequate decision making framework presumes.

6.1.1.1 What is choice?

What do "economic situations" mean? On which criteria do we make choices in economic contexts?

The general picture of the *theory of choice* is as follows. The individual can take a limited range of actions that have attached consequences. He or she "has in mind an ordering of all possible consequences of actions". Among the actions actually at hand, "that action is chosen whose consequences are preferred to those of any other available action" (Arrow, 1951).

Together with the relevant settings of some central conditions as well as of the criteria of choice, such situations constitute the reference framework in which economic choices apply.

Central conditions are, for example, a theory of market interactions and clearing as well as any coherent theory of reactions to the economic stimuli (prices, in essence). Assumptions also compose the economic framework. For instance, a decision-maker's beliefs can always be represented by a unique probability measure; economic agents are said to be perfectly competent to deal with the difficulty of the processes involved in the decisional situation. More radically, economic situations (and theory) are based on *rationality*, as a matter of principle.

On the "apparatus" side, economic criteria of choice rest upon representations and orderings of consequences of actions by means of the assumption of a *utility function*. A utility function renders intelligible with regard to observable situations the ability of the consumers to rank their preferences in a consistent order (in like manner, entrepreneurs will prefer more profit to less if each is equally risky). The assumption of a utility function, therefore, postulates a *consistency* of human choice—in short, *rationality*. From a decision analysis viewpoint, this postulate places the focus on the decision to reach, not on the process per se. Verily, inasmuch as individuals are assumed to be perfectly knowledgeable and rational, the most valuable option—in terms of utility, or human wishes—is always chosen (Price, 1993).

Yet, will *rationality* and attached economic criteria of choice still play the same pivotal role in climate change-oriented decision making processes as in economic situations? This might not constantly be the case. Decision makers must initially be aware of the following differences.

With respect to the climate change perspective, choices will be of collective and of longer-term view nature—they will no longer be individual and fixed choices (for instance, one cannot make the hypothesis that, in as far as global environmental concerns call for international agreements and actions, individual nations might act as individual economic agents do). Choices will not be made

with respect to a fixed set of alternatives, either. In addition, they will not be confined to market related decision situations, but will also be concerned with non-market related decision situations (including issues of ethics, equity, poverty, and fragility of natural ecosystems and species).

Last, introducing these specific factors into decision making problems along with key man-induced and natural sources of change will inevitably disclose uncertainties and risks that were not previously recognised. This will reveal less dependable probability distributions, lack of data and knowledge, stronger uncertainties, highly specific risks, irreversibilities, gaps between competence and difficulty (are agents able to figure out all of the complexities of a nature-economy system?), small contributions of information from a number of diverse sources, unpredictable situations, intertemporal perspectives, and scientific controversies.

In spite of these circumstances, economic choice situations and criteria constitute useful benchmarks for making decisions. Consider them in a practical way.

6.1.1.2 Maximising something

For the classicists, rationality had the (limited) meaning of preferring more to less (for instance, capitalists choose to invest in the industry yielding the highest rate of return, landlords rent their property to the highest bidder, and so on). Being rational merely meant making decision.

Today, economists do not assert that human agents are "rational" by definition. Rationality appears as a lawlike refutable statement which "simply means behaviour in accordance with some ordering of alternatives in terms of relative desirability" (Arrow, 1951, Blaug, 1992). In this respect, it designates a "maximisation of something" (Arrow, 1987); in other words the maximisation of the expected value of a given utility function (Savage, 1954). *Maximising something* is the basal economic criterion of choice (minimising chance of adverse effects belongs to the same criterion). Note that subjective arguments are compatible components of the assumption of a consistent utility-maximising behaviour and profit-maximising conduct.

Main economic choice criteria are utility-based ones (cf. Table 6.1). Other, "weaker" choice criteria are rights-based ones (see Table 6.2).

■ *Utility-based* criteria are prime choice criteria in economics. They mean maximising the expected utility. They entail decisions that are based on the valuation of outcomes—wealth levels, time streams of consumption, etc.—(Morgan and Henrion, 1990).

Table 6.1—Examples of some utility-based decision criteria

Source: Alter Morgan and Henrion, 1990: 26

Benefit-cost: Estimate the benefits and costs of the alternatives in economic terms and choose the one with the highest net benefit.

Maximise multi-attribute utility: This is the most general form of utility based criterion. Rather than use monetary value as the evaluation measure, MAU involves specifying a utility function that evaluates outcomes in terms of all their important attributes (including uncertainties and risks). The alternative with maximum utility is selected.

Cost effectiveness: Select a desired performance level, perhaps on non economic grounds. Then choose the option that achieves the desired level at the lowest cost.

Minimise chance of worst possible outcome ... maximise chance of best possible outcome, etc.: Political and behavioural considerations frequently dictate the use of such criteria.

Maximum budget (bounded cost criterion): Set the maximum budget to devote to risk management activity.

Minimise maximum regrets: Choose measures of "regret" and minimise the maximum regret.

Minimax criterion for catastrophic risk: For each decision alternative find the loss associated with the extreme event. From among these losses find on with the maximum loss and try to minimise it. This a conservative criterion.

For example, they would involve a balancing of benefits and costs in a benefit-cost analysis framework (Table 6.1).

A more general formulation has been set up in terms of *maximising a multi-attribute utility function* (Table 6.1) for situations where options involve "collections of attributes that are incommensurate" (Keeney and Raiffa, 1976, Morgan and Henrion, 1990). The resulting decision models can thus avoid the dilemma of converting each attribute to an equivalent monetary value.

Variations to utility-based decision criteria are available. A *cost effectiveness* criterion (Table 6.1) can be used where the value of benefits cannot be estimated—but a choice must be made between alternatives (Morgan and Henrion, 1990). A *maximum budget* can be set to devote to risk management activity (bounded cost criterion). Finally, measures of "regret" can be chosen and the maximum regrets minimised (Table 6.1).

Economic criteria of choice don't have to be maximisation-related, utility-based criteria definitely. For instance, addressing climate change might mean international and intertemporal cost sharing, common but differentiated responsibilities, self-constrained risks, North-South financial transfers, specific commitments, and so on.

Table 6.2—Examples of some rights-based criteria

Source: Morgan and Henrion, 1990: 26

Zero risk: Independent of the benefits and costs, and of how big the risks are, eliminate the risks, or do not allow their introduction.

Bounded or constrained risk: Independent of the costs and benefits, constrain the level of risk so that it does not exceed a specific level or, more generally, so that it meets a set of specified criteria.

Approval/compensation: Allow risks to be imposed only on people who have voluntarily given consent, perhaps after compensation.

Approved process: Not strictly a decision criterion for analysis, but widely applied in risk management decision making. If all relevant parties observe a specified set of procedures (e.g., under some international convention), then any decision reached will by definition be acceptable.

Other criteria can be postulated, as for example equity, a satisfying strategy (Simon, 1987), ecological sustainability rules, minimum surprise. Outcomes can also be applicable to changes in natural ecosystems. And regional distribution can be at issue.

■ **Rights-based criteria** (Table 6.2) have been thought to deal with processes and constrained actions or activities (Morgan and Henrion, 1990).

As Morgan and Henrion argue, some of these criteria are not adequate to deal with exogenous, naturally occurring risks as for instance the *zero risk* criterion which simply does not allow the introduction of the risk. Nevertheless, this criterion and the like are appropriate with respect to "new" human risks, including climate change associated risks once these can be understood as endogenous occurrences. For instance, the *approved process* criterion insists "that all the relevant parties observe a specified set of procedures" such as some internationally signed convention defining a due process.

But don't let's look too far ahead. To the point, let's recall that standard economic choice criteria are supported under restrictive assumptions such as perfect rationality, information and knowledge, finite time horizon, etc.

6.1.1.3 Bounded rationality

As already explained, rational behaviour is a "first approximation" to actual behaviour. For instance, as soon as one faces either imperfect forms of competition or non-market resources allocation decisions, the knowledge requirements radically shift and are prompt to exceed those usually required for the price system. It is, therefore, accepted that (economic) rationality hypotheses be supplemented by

assumptions of a different character (e.g., information-gathering ability and limitation of both knowledge and computational capacity). It is accepted that rationality, obviously, is bounded (Simon, 1957, Arrow, 1987). Basically, these cognitive difficulties are connected to decisions that lie far away from individual-related, standard economic situations; they are relative for example to decisions that must be reached through international conventions, or to decisions that, *independently of the valuation of the outcomes*, are destined to eliminate risks.

As a concept, "bounded rationality" has been coined to name rational choice that takes into account the "cognitive limitations of the decision-maker" (Simon, 1987). This makes bounded rationality much more concerned with *the ways in which the actual decision-making process influences the decisions that are reached* than with reaching decisions assuming the maximisation of something, as we are used to consider from a standard economic viewpoint. This concept designates a different type of rationality, namely procedural rationality. Incidentally, a decision which optimises the expected value of utility will possibly be in opposition with a decision which optimises cooperation because the former places the focus on *the decision to reach* while the latter puts the emphasis on *the decision process in itself*.

6.1.1.4 Procedural kind of rationality

The former cognitive limitations may break usual limits on specific information. In the words of Simon, they are almost always limits on the adequacy of the scientific theories that can be used to predict the relevant phenomena (Simon, 1987). Meteorology and atmospheric chemistry, on the one hand, as well as economics, on the other hand, openly leave large bands of uncertainty in reference to climate change. In addition, lack of knowledge about fundamental mechanisms that equations cannot currently master represents limits to computer models in both domains.

These difficulties typically occur with respect to decisions that are taken on a national or international scale when governments negotiate some form of agreement and countries differ in their economic wealth, reliance on fossil fuels, endowment of alternative resources and technical capabilities. For instance, the need for an equitable distribution of tasks both at the national and international levels is the cornerstone of the 1992 Framework Convention on Climate Change (FCCC). While all the Parties are required to contribute to the collective effort by elaborating a national programme, the application of the principle of "common but differentiated responsibilities" implies

that the industrialised nations must assume the prime share of the effort—first by adopting specific national measures to stabilise greenhouse gas emissions, second by promoting the transfer of financial resources, know-how and/or technologies to developing countries, in particular the least developed countries (FCCC, 1992, BUWAL, 1994).

Specifically, "procedural" rationality designates the rationality of a decision in terms of the manner in which it is made while economic—also called "substantive"—rationality names the rationality of a decision considered independently of the manner in which it is made (in the case for substantive rationality, rationality evaluation refers exclusively to the results of the choice, not to the decision-making process in itself—Faucheux and Froger, 1994).

Which kind of theory can better predict and explain the decisions at issue? Shall we place interest in the decisions to be reached only, or shall we focus attention on the (international) decision-making process as such? Answering to these questions and the like would command the choice between substantive and procedural rationality frameworks (Simon, 1987). From an economic standpoint, unfortunately, the fact that the manner in which the decision is made—and not the result of the choice—is at issue in the decision evaluation makes the procedural kind of rationality mostly undetermined. Reasonably, procedural rationality can be at work for setting norms or institutional arrangements as a framework for further economic choices.

Since the *Framework Convention on Climate Change* (FCCC) came into force in March, 1994, further choices vis-à-vis climate change are supposed to be economically sounded choices.

6.1.1.5 Accommodating the added uncertainty attached to climate change

The cognitive and computational limitations that have been pointed out by the concept of bounded rationality make sense with respect to climate change concerns. Economic-oriented decision making is also concerned with these limitations. Accordingly, devices exist that can help to some extent at solving predictions where new information is needed to reduce uncertainties.

Climate change prospects also reveal—besides cognitive limits—that data one should use to make long term decisions "is weaker than we had imagined when climate change was overlooked or disregarded". Ignoring climate change would simplify decision making, but it would be irrational to return to our previous lower level of uncertainty awareness. We thus have to accommodate the added uncertainty attached to possible changes in climate (Caselton and Luo, 1994) and to make decisions.

As a consequence of insufficient knowledge and data, predictions of the rate and extent and timing of climate change and their effects have been made in terms of scenarios rather than in usual statistical terms. In particular, this situation reflects a gap between the information that is available on climatic processes and the one that would be relevant to statistical prediction—and consequently to the standard economic, namely “Bayesian”, framework—and that is in short supply at present time.

What is at stake? Within the economic rationality framework, decisions are based on the valuation of outcomes and/or of alternatives. The valuation procedure focuses on a *quantity* that is known as a “state of nature”. Standard decision making is served by the Bayesian statistical approach which represents any information or knowledge concerning this state of nature by assigning *probabilities*. In this respect, the representation of information in the form of conventional, necessarily precise, probability distributions has been developed in the statistical literature for well over 100 years.

In view of the climate change concerns, and lack of knowledge and data, we undoubtedly have to address decision situations under “strong uncertainty” and even “near ignorance” in addition to those concerned with conventional levels of uncertainty or risk (see Table 6.3). How to treat information sources (these are diverse with respect to climate change, each of which providing only a small component of the total information), and how to allow probability assignments to which subsets is going to be of paramount importance. This means that decision making to address climate change appears as a category of decision making which must envisage shifts to the traditional Bayesian scheme (Paté-Cornell, 1992, Caselton and Luo, 1994) when confronting to strong or even extreme uncertainties created by climate change¹.

The information and data issue brings us to better introduce the nature and representation of uncertainty, risk, and ignorance, first in economics, then with respect to climate change prospects.

¹ In decision making under “weak” uncertainty and risk, the analyst is provided with precise, either objective or subjective probabilities. When it is not possible to arrive at such a unique probability distribution for an event, one tries to construct it from more fundamental events. Such a procedure is known as the Bayes’ rule. Suppose the hypothesis B is true and that an event A has occurred. Then, the probability of hypothesis B given that event A has taken place is given by $p(B|A) = p(AB)/p(A)$. $p(B|A)$ is known as the posterior probability and depends upon $p(A)$ which is known as the a priori probability. How do we obtain the prior probabilities? If there are past empirical evidences one can obtain the priors from them. But if there is no evidence available to us about, say, whether global warming or climate change of unacceptable level is going to occur or not, then, according to the “principle of sufficient reason”, one has to assign equal prior probabilities to all the mutually exclusive events (or to forget about the Bayes’ rule if climate change simply does not allow to make prior probability assessments—Heup et al., 1992). In the first case, if new scientific information is forthcoming, one can use that information to update the prior probabilities or beliefs using the Bayes’ rule to get the posteriors. In summary, the Bayesian theory yields instructions on how to use new information to update beliefs “rationally” in certain circumstances.

6.1.2 Decision Problems under Uncertainty and Risk

Climate change concerns give ground to a new situation with respect to uncertainty and risk. This means that responses will vary either. Here is a quick overview of the current responses to risk and uncertainty.

6.1.2.1 Standard responses to uncertainty and risks

Consider first *uncertainty*. The classical ingredients of a decision problem under uncertainty are a set of feasible acts (A), a set of consequences (C), and a set of states of nature (S). The decision-maker does not know for sure which consequence will result from a chosen act (probabilities for the events are not known in advance). The role of the states of nature is to indicate the matching of feasible acts to consequences, thus resolving the uncertainty which relates acts to consequences. This makes states of nature exogenous (uncertainty becomes in like manner exogenous, too) so that probabilities can be computed. As a result, the decision-makers basically have to assign utilities to the consequences (utility U assigned to each consequence c in C) and probabilities to the states (probability p assigned to each state s in S) (Schmeidler and Wakker, 1987).²

In choosing between acts, the decision-makers will elect that one with the highest “expected utility”—that is, the one with the highest sum of the products of probability and utility.

Second, consider *risk*. A decision making under risk introduces a special formulation of the decision problem to the extent that probabilities for the events are known in advance. In other words, the decision problem includes the probability distribution of an act over the consequences. Accordingly, decision-makers only have to determine utilities of consequences before choosing between acts. Typically, however, reducing risk entails a reduction of benefits (Starr, 1989).

6.1.2.2 Uncertainty and Risk Decision Rules

First, *uncertainty* approved collective/individual decision rules can be outlined as follows (MIT, 1986):

² A specific way allowing to cover the case for uncertainty—originally about the availability of resources and about consumption and production possibilities—is the idea of *contingent commodity* introduced by Arrow (1953) and developed by Debreu (1953). This device is added to the current specifications of the commodity such as its physical characteristics and location to make the availability of the commodity contingent on the occurrence of some (uncertain) environmental event such as weather conditions.

- 1 **Maximax** The decision maker should opt for that course of action which yields the
 2 highest pay-off (net benefits, or whatever) *regardless* of any view taken
 3 about which state of nature will occur. It's the optimistic rule.
- 4 **Maximin** ...We should first observe all the minimum pay-offs and then select the
 5 highest of these.
- 6 **Minimax regrets** ...We should select measures of "regret" (i.e., the difference between an
 7 actual pay-off and what the pay-off would have been if the correct strat-
 8 egy had been chosen). This is a cautious principle and ensures that, if the
 9 worst happens, we make "the best of a bad job".
- 10 ...We should seek to minimise the maximum regrets.
- 11 ...We should seek to minimise maximum loss (Dowlatabadi and
 12 Morgan, 1992).
- 13 Second, *risk* basic collective/individual decision rules can be outlined as follows (MIT, 1986):
- 14 **Risk aversion:** Higher expected return as compensation for an increase in risk. A risk
 15 averter can be a diversifier and spread his *portfolio* over different
 16 assets—or a "plunger" and invest wholly in bonds and money.
- 17 **Diversifier:** Risk is likely to be the cause of *portfolio* diversification: if risks increase
 18 then the diversifiers will move back to holding wealth in the form of
 19 money.
- 20 **Risk lover :** A risk lover accepts a higher level of risk for a given expected return.
- 21 **Risk neutral :** A risk neutral individual would be indifferent whether or not he
 22 accepted "fair" insurance.

23 6.1.3 Uncertainty and Risk Revisited in the Context of Climate Change

24 A useful four-part classification of choice variables is to consider decision making under certainty,
 25 risk, uncertainty, (Luce and Raiffa, 1957), and catastrophic risks. A classical description is given
 26 below while attention about climate change is gradually introduced.

1 6.1.3.1 Certainty

2 Certainty refers to situations in which chance is excluded because knowledge is sufficient. With
 3 sufficient knowledge, in other words, there would be no probability distributions, only certainty
 4 (Fisher, 1930, Arrow, 1951).³ Only simple cases and those treated in a perfect-information equivalent
 5 context fall into the certainty category.

6 6.1.3.2 Risk

7 Basically, risk refers to situations in which chance is included in the form of known probabilities. In
 8 other words, risk refers to situations where probabilities are knowable (Johansson, 1993), or where
 9 the size of the event has a probability distribution (MIT, 1989). Individual insurance decisions and for
 10 instance technical situations usually fall within the risk category.

11 In economic situations, risk is exogenous and individual. It is for instance expressed by a set of ex-
 12 ogenous states of nature whose values are random. At the beginning of our understanding of
 13 economics, risk was thought as unimportant because of our capability at hedging and diversifying and
 14 since risks could be perfectly insured (Knight, 1921, *see* Bray, 1987). Knight's criterion was that
 15 "risk" was insurable while "uncertainty" was not inasmuch as the scientific method—namely the
 16 Bayesian scheme—could not be applied. This distinction has been since denied by many leading
 17 economists. The point is that from a Bayesian standpoint, a subjective probability can always be
 18 formulated "as a bet on a certain event" and a decision-maker's beliefs can always be represented by a
 19 unique probability measure (Vercelli, 1991). Therefore, to the extent that agents have fully reliable
 20 information about a unique probability distribution, the scientific method can still be applied and
 21 uncertainty is reduced to "risk"—reciprocally, risk applies to any kind of uncertainty.

22 The climate change context makes risk endogenous and collective (Chichilnisky and Heal, 1993).
 23 Risk cannot anymore apply to any kind of uncertainty with respect to the global environment. Indeed,
 24 climate-related risks cannot be expressed in a classical statistical sense (numerical probabilities) be-
 25 cause of a lack of experiments, poor data and/or diverse data sources. For the insurance industry it-
 26 self, circumstances have changed "in ways that mean traditional practice and the old statistical
 27 methodologies are no longer adequate"—"past experience is no longer a safe guide to the far future"

³ To formalise the conditions of certainty (and later on, of uncertainty), it is convenient to refer to Arrow's concept of *state of the world*, a description of the world so complete that, if true and known, the consequences of every action would be known. The meaning of certainty is that the agent *knows* the state of the world.

(Ayres and Weaver, 1994). Climate change implies a certain degree of irreducible unpredictability beyond the economic category of risk like uncertainty. This unpredictability arises in two ways. On the one hand, it appears with regard to the future structure and outcomes of any nature-economy joint system. On the other hand, it exists with regard to the characteristics of the evolution (rate, abruptness, etc.) of the processes involved.

In total, the "unpredictability" of climate changes gives rise to a kind of uncertainty which might not be straightforwardly reduced to Bayesian risk (see Tables 6.3 and 6.4).

6.1.3.3 Uncertainty

Uncertainty proper, contrary to risk, has always been thought of having an important effect on the workings of the economy. It refers to situations in which chance is included but knowledge is insufficient: Probabilities cannot even be defined (Johansson, 1993). In other words, the likelihood of an event occurring is *not known at all* (MIT, 1989) and the events upon which decision outcomes depend are not controlled by the decision agent—consequently, they are only known after the decision is made (Fishburn, 1987)—though any actual decision creates a new starting point. In decision makings under uncertainty, therefore, no probability distribution can be attached to the outcomes—e.g., conceivable outcomes will be known, but their probability of occurrence will not. According to the concept of state of the world, the meaning of uncertainty is that the agent does *not* know the state of the world (Arrow, 1971, 1984).

Yet, in the conjunction of utility theory and decision theory, probabilities of the events are considered as assessable although with reference to personal judgement. In this case, indeed, the criteria for choice are to be based on numerical representations of the decision agent's preferences and values. The condition for making uncertainty computable is that agents at least believe that they know, even approximately, the relative frequencies of the states of nature. As a consequence, the Bayesian scheme applies to uncertainty situations as it does with respect to risk situations. This risk-like kind of uncertainty is generally referred to as "weak" uncertainty while "strong" uncertainty indicate uncertainty proper—in other words situations for which probabilities cannot be defined.

6.1.3.4 Catastrophic Risks

The risks may be substantial. Climate changes have the potential to alter the natural setting of the earth through droughts, productivity of forests, coastal erosion, to name a few outcomes. Climate

changes can induce non-linear, abrupt, and high impact consequences: Change in ocean circulation patterns, liberation of methane in currently frozen sediments, melting of Antarctic ice sheet. Catastrophic risks break a new ground in the analysis of nature-economy systems because (a) the scope is global on the nature side, and (b) the change in circumstances is man-induced.

These risks are however still depicted as surprises and/or as natural hazards (extreme weather events). They are characterised as low(er) probability – high impact scenarios (Fankhauser, 1994). Nevertheless, extreme-event probabilities associated to coastal inundations have been underestimated. In this case, the reason is that data from the recent past showed insufficient variability to provide guidance on possible rates and extents of sea-level change (Tooley, 1994).

Like severe industrial hazards, environmental hazards are not straightforwardly defined. Querner (1993) defines a severe hazard as a public, physical risk: (a) with a very low probability of the adverse event (unlikeliness); and (b) a possibly very large death toll (catastrophiness). Compared to "normal" physical risks, catastrophic hazards are characterised by (a) an extremely small expected number of accidents (EA), (b) a very high expected number of fatalities per accident (EFPA), (c) still constituting only a very small average individual death probability μ , which equals $EA \times EFPA$ over the number of people exposed to the hazard (Querner, 1993).

Getting back to global environmental hazards, they also are considered as unforeseen environmental and economic losses (the ones for which the insurance and reinsurance sectors have been forced to take the "hit" despite their short-term vision on the future and their fixed contracts policies). *One cannot rely upon commercial assurance neither to compute nor to cover catastrophic risks associated to climate change.* These losses are not so readily quantifiable. In order to assess such catastrophic risks, society basically needs better information on the resilience of the environment, the rate of environmental change, the probabilities of extreme events, and vulnerability (INSEAD/SANDOZ, 1994).

6.1.3.5 How to address uncertainty and risk associated to climate change?

It is usual to alternatively speak of risk, uncertainty and even ignorance (incomplete information).

Climate change, however, suggests that we clarify the distinction between risk, uncertainty, and ignorance, and that we consider its implications in relation to the decision making framework.⁴

⁴ Other important factors such as time, information, discounting, irreversibility, fairness across generations, and scientific results—which all affect decision making under risk and uncertainty—will be introduced and developed in section 2.

Table 6.3—Climate change related uncertainties

The rise in the accumulation of greenhouse gases is agreed upon though, basically, uncertainties are attached to energy-related carbon emissions, to regional carbon emissions as well as to the range of cumulative energy-related global carbon emissions and associated variables such as population, and economic growth (see Chapter ...). What is then uncertain are the pace and extent of climatic impacts such as rise in temperature, rise in sea level or abrupt changes as well as occurrence of extreme events and thereby changes in ecological balances of biosphere. It is expected that efforts to contain these impacts and offsetting them would have significant economic costs (with costs in front and benefits being heavily discounted).

Uncertainties that are associated with potential climate changes can be categorised into the following groups:

- (a) Scientific uncertainties associated to the effects of emissions of greenhouse gases on climate change:
 - mean temperature rise
 - sea level rise
 - reduction of moisture, precipitation changes
 - pace/abruptness of changes.
- (b) Scientific uncertainties attached to how much impacts different levels of climatic variables might have:
 - biomass productivity, e.g., that of agriculture and forests
 - species loss (terrestrial and marine)
 - other discomfort and damage costs (replacement costs, e.g., cost of increased air-conditioning, etc.)
- (c) Economic uncertainties about the extent and nature of the economic impacts caused by these physical impacts:
 - effects of global warming on per capita, national and regional incomes
 - efficiency of actions designed to mitigate/adapt/control/understand human environmental loading, the climate system, and its interactions with the biosphere (Dowlatabadi and Morgan, 1993)—for instance as unit of income per unit of impact
 - possible benefits of abatement actions, if taken to avoid global warming (costs, because they are in front, are known with more certainty than future benefits); costs per ton of Carbon will vary, beyond the carbon savings target, with the extent by which damage due to climate change, on the one hand, and benefits, including side benefits, on the other hand, are internalised.

Figure 6.1 shows a schematic linkage between scientific uncertainties and impacts uncertainties.

To say the least, if the occurrences facing an agent can be expressed in terms of specific numerical probabilities, or if the agent knows or believes that he or she knows—at least approximately—the relative frequency of the states of nature, then the situation can be said to be a risk-like situation. In other words, if the parties believe that the relative frequencies of the events at issue are at least approximately known, risks can potentially be allocated (Chichilnisky and Heal, 1993). It turns out that uncertainty, as defined with respect to such situations, is reducible to risk. As a consequence, this “weak” form of uncertainty can be dealt with according to the scientific method and the expected utility maximisation scheme.

Conversely, if one cannot assign actual probabilities to the relative frequency of the states of nature, or does not know it at all, or does not at least believe in any probability distribution, the situation can be said to involve uncertainty proper. In these circumstances, society is facing true uncertainty.

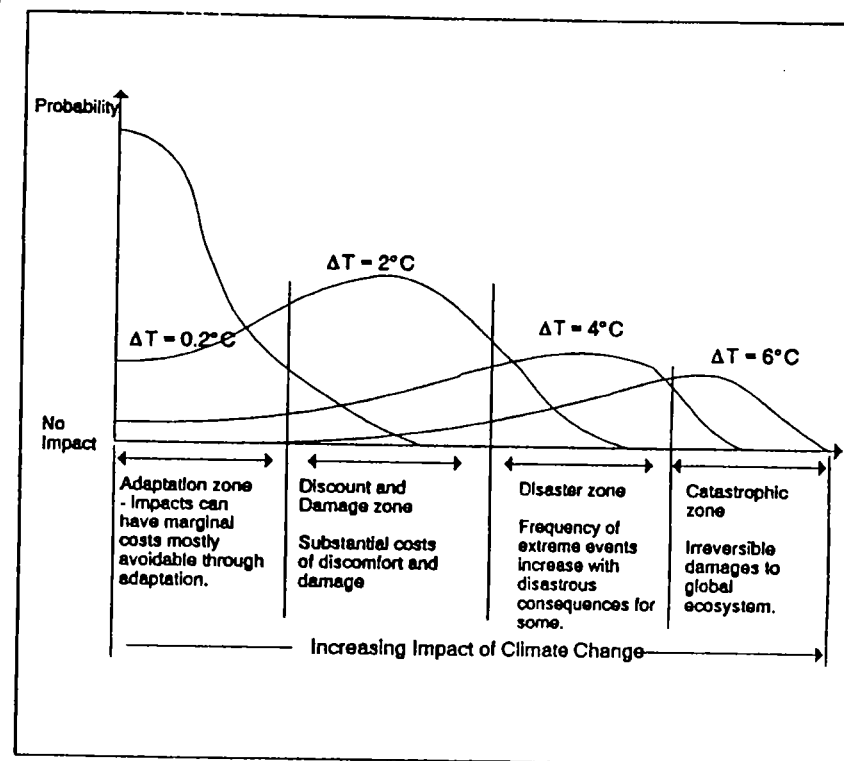


Figure 6.1: Schematic linkage between scientific uncertainties and impacts uncertainties
Area under each probability distribution curve is 1 (probabilities are thus additive to simplify matters, although “strong” uncertainties should require non-additive probabilities—Beltratti, 1994). At $\Delta T = 0.2^\circ\text{C}$, the probability that there is no impact is much larger than at $\Delta T = 6^\circ\text{C}$. Reverse is the case for the catastrophic zone. Similar relationships may be plotted for different levels of sea level rise. After Parikh et al., 1994.

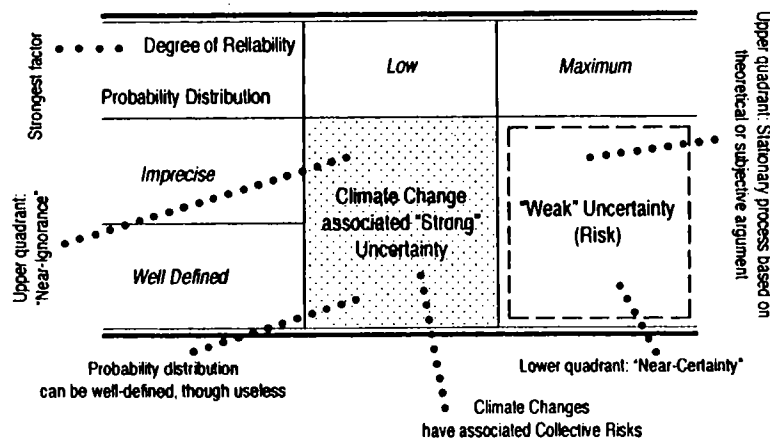
Accordingly, “strong” uncertainty would be characterised by the absence of reliability with respect to some existing probability distribution, if any, while near-ignorance would be characterised by lack of information and absence of believability as well (both suppose a weight of argument). The existence of “strong” uncertainties implies to consider at least two different issues at two different levels; that is, (a) the existence and reliability of statistics and/or probability distributions (Vercelli, 1991), and (b) present versus distant future preferences (Chichilnisky, 1993).

The concern about the existence and reliability of statistics and/or probability distributions designates a reconciliation framework for risk and uncertainty (see Table 6.4). According to various contributions, let's define the case for "weak" uncertainty (risk) where only one probability distribution is possible (even on a theoretical basis) and its degree of reliability is the maximum, and the case for "strong" uncertainty (near-ignorance) where, even with regard to a well-defined probability distribution, the degree of reliability is low because of the existence of an unavoidable gap between competence (of the agent or of society) and difficulty (of the problem)—to illustrate, learning should be assumed to be successful to generate a convergence towards a fully reliable probability distribution.⁵ Under "strong" uncertainties, however, we don't know the full range of possible outcomes: To know it, we would have to know the future growth of knowledge, and how this will affect the world (Heap et al., 1992)!

The present versus distant future issue addresses social choice via maximum utility and fairness across generations. Chichilnisky's (1993) axiomatic construction requires an equal (or non-dictatorship) treatment of the present and of the future. This eliminates pure (discounted) maximisation of utility. In future, *sustainable preferences* will constitute the welfare—or, social choice—criterion.

Table 6.4—A Climate Change Related Risk versus Uncertainty Framework

Source: Adapted from Vercelli (1991), Faucheux and Froger (1994), Froger and Zyla (1994), and Pillet (1994)



⁵ By way of illustration, 50 years of data collection about floods in Southern France can be treated as a probability distribution though it is useless with respect to the global time scale associated to changes in climate (Tooley, 1994).

According to a model by Heal (1993) and subsequent developments by Chichilnisky and Heal (1993), Beltratti (1994), and Pillet (1994), the reaction to "strong" uncertainty translates into a consumption increase. Interestingly, this effect—or, "strong" uncertainty aversion—indicates that in the short run – long run trade-off, consumption today dominates the equation, which is similar to the discounted utilitarian perspective, but sets in contrast to the precautionary principle that is supposed to satisfy the long-run future.

Table 6.5—Risks Associated to Climate Change

Climate change associated risks are:

- *endogenous*—they are affected by our actions
- *correlative*—they are not statistically independent risks.

They are defined as affecting large numbers of people in the same way. Think for instance about a 10 percent chance that 90 percent of the population will be harmed by global warming, a 25 percent chance that 50 percent of the population will be harmed, etc. After Chichilnisky (1994).

Climate change risk positions might be traded on the international scene (cf. 6.3.3).

Regarding decision criteria and standard responses to risk and uncertainty, the shift to "strong" uncertainty from standard risk-like situations has different implications. In particular, this must lead to revise the atemporal repertoire of the ready-to-use decision rules if one wants to address decision making with respect to climate change. This also has implications on how to make decisions in the sense that this is also a shift to options making (equal sensitivity to the present and to the future, insufficient knowledge and insufficient competence and statistics) from standard decision making (sensitivity to the present, sufficient statistics, knowledge, and competence).

Last, other factors that are specifically connected to climate change will influence decision making. Basically, one must consider that beyond the global character of climate change prospects, different countries are facing different risks and their perceptions also differ. In addition, if one cannot arrive at a global welfare function for a country by aggregating individual utility functions, one cannot infer some global welfare function from individual countries' ones, either. Section 6.2 is a step towards alternative factors that affect decision making for countries that have different capacities, welfare, and attitudes towards climate change "strong" uncertainties and collective risks.

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6.2 Factors that Affect Decision Making

As seen in Section 6.1, responses to uncertainty and risks associated to climate change might shift from standard decision rules based on sufficient statistics, knowledge, competence, and sensitivity to the present to rules that would accommodate to insufficient knowledge, competence, statistics, and symmetric sensitivity to the present and to the future. Section 6.2 is devoted at actualising this by looking through main factors that will influence climate change related decision making. To simplify matters, these factors have been arranged into three categories: first, factors that are linked to temporal economic analysis such as information, irreversibilities, and discounting; second, socio-economic considerations of equity, poverty, and attitudes; and third, scientific insights that are emerging with respect to the behaviour of the climate system.

6.2.1 Time

We have presented decision making as a one-shot process. In reality, however, one needs to make a series of decisions. For instance, the International Negotiating Committee might be willing to wait for more information before deciding which levels of global carbon emissions are desirable. Before the information succeeds, one might have to take decisions regarding other issues (Parikh et al., 1994).

In particular, risks associated with such cases is known as temporal risks. In such *temporal situations*, as Machina (1984) pointed out, risk aversion is higher compared to the case of atemporal choices, and events with low probability (unlikeliness) and a possibly very large death toll such as catastrophes become more important compared to "normal" physical risks (see 6.1.3.4, *supra*).

Risky elements also lead to the role of interest for discounting. Basically, climate change is long-term oriented and is very large on the scale of the economy. It cannot be dealt with by private actions on this scale. Therefore, governmental actions are required, which are risky ones, and which consequently call for considerations about discounting, and other issues such as irreversibilities, insurance, and so on.

6.2.1.1 Information, value of information

Will information, will more knowledge resolve uncertainty? Conventionally, improving information and knowledge should resolve uncertainties. As a practical consequence, learning strategies are included in decision making in the form of sequential decision processes (Hammit et al., 1992).

For instance, learn-then-act strategies can be balanced against act-then-learn options (Manne and Richels, 1992, Peck and Teisberg, 1993). In addition, there is a fairly agreement on improving our understanding of the climate change problem (Peck and Teisberg, 1993). This led to the analysis of the *value of information* about global warming.

According to Peck and Teisberg (1993), a resolution of uncertainty has high value relative to current research budgets.¹ Moreover, Peck and Teisberg (1993) points out two interesting results. On the one hand, they found that there was *not a high premium on immediate resolution of uncertainty* in as far as this would occur within, say, twenty years. On the other hand, they found that "if the real world political process would result in a suboptimal control policy being chosen under uncertainty, and this choice could be prevented by early resolution of uncertainty, the *benefit of early resolution* may be as much as three orders of magnitude greater". This constitutes a fair criterion if one wants to look into alternatives to current policy responses that could override both suboptimal policies and the difficulty at solving *now* "strong" uncertainties.

The decisions we make as well as the results of the simplest models we run to simulate the outcomes of decision-makings are contingent upon the level of information we possess—e.g., about climate change prospects and impacts—or that is assumed to be produced with time. As a matter of fact, progress in knowledge will have much influence on the decision to reach as well as on the decision process itself. This will for instance update the distribution of probabilities for the subsequent years (Peck, 1994). As one another example, the possibility of future learning will influence current period decisions: facing a project which is reversible, learning leads to a lower value of the current period decision. Learning more about the net benefits of the investment at a future date will still allow subsequent investment decisions to be made (Ulph and Ulph, 1994).

A widespread assumption is that scientific knowledge will linearly increase with time, and give a perfect information after n years. This analysis proceeds as if we had—in principle and at any step—the opportunity to learn the state of the world before taking action (Manne and Richels, 1993). No information is forthcoming once the decision is taken; e.g., by the next period. This analysis is typically shared by deterministic models, which assume that all uncertainties are resolved *prior to* decision making.

¹ And "resolving uncertainty about the cost of warming is nearly as important as resolving uncertainty about the extent of warming".

The most plausible assumption, however, is that uncertainties *will not be completely resolved with time*. This leads to integrate information in decision making under uncertainty and risk by incorporating the opportunity for learning into the decision making framework; that is, by making the decision process an ongoing, for instance an "act—then learn" process (Manne and Richels, 1992, 1993). In other words, incorporating information means making uncertainties endogenous and, therefore, entering a sequential-decision process. This also means that learning will be endogenously used to revise the distribution of probabilities for the years to come. Such a strategy come into play in as far as we know that any action set up now will need to be revised later (Hammit *et al.*, 1992). On the one hand, as scientific understanding of climate change improves and, on the other hand, as economic actions evolve and uncertainties are nearly resolved.

Finally, one must recognise that not every progress in knowledge is synonymous of reducing uncertainties. For example, the ozone layer issue has shown the contrary (Mégie, 1992). In many cases, progress in knowledge can even stress uncertainties because of the circular causality and non-linear cause-effect relationships in science (Gassmann, 1994).

Incorporating information into decision making and thus entering a sequential decision making process means that forthcoming information carries a value. In other words, waiting for information bears a value which can be computed as the option value of preserving an environmental asset. This "option value" can be defined as the gain from retaining the option to preserve or develop an area in the future (Krutilla, 1985); in other words, the gain from being able to learn about future benefits of not developing that area initially. A quasi-option value is defined as the increase in expected net benefits of not developing the area initially when the decision maker can make the decision after uncertainty is resolved (Johansson, 1993).

Basically, this value is born from the existence of uncertainties around the future benefits associated to the action taken now and the uncertainty about future generations and preferences. This refers to the cases for leaving more resource to the next generation, for conserving an ecological asset, when consumption is an irreversible depletion of a stock, and when emissions affect the global climate (for preserving the atmospheric environment). Indeed, the benefits from the preservation of the (natural) asset will accrue in the future and—similarly for future preferences—are yet unknown. As a rule, waiting for information will save the option of reconsidering the decision about to preserve

the resource when improved information becomes available. In other words, economists allow for a future reduction of uncertainty by incorporating option value.

Preventing climate change—what acting strongly now would depict—should thus be credited with an option value, the value of waiting for scientific knowledge about the greenhouse effect. In a development versus conservation context, if the decision maker does not anticipate for better information (does not allow for a future reduction of uncertainty), first-period development could be too great (Krutilla and Fisher, 1975, 1985). There is some controversy about expanding this result to the class of global warming problems (Ulph and Ulph, 1994).

Yet, option value is not identical to the value of information in a development decision problem. On the one hand, option value is conditional on a particular choice of first-period development whereas the value of information, which basically is the expected value of perfect information, is unconditional. Option value is thus connected to contingent decisions. On the other hand, the former can be equal to or greater than the latter.

Last, a good number of authors have established that option value was identical to a risk premium, and that it could be negative because preservation, and not only development, can bring risks.

In sum, incorporating information into decision making processes makes subsequent decisions *contingent* upon future resolution of uncertainties and upon attitudes toward risk.

Yet, it might appear in the interval that increasing scientific insights would also result in a decreasing capability in establishing climate change forecasts (see 6.2.3, *infra*). In other words, more knowledge might mean more uncertainty instead of inferring more certainty.

What in fact happens is that, on the one hand, by additional knowledge, we realise that our view of climate dynamics was too simple being too much influenced by classical linear systems. So, the new results widen the spectrum of possible reactions of the global climate system to the anthropogenic CO₂-input and clearly, this widening results in an increased uncertainty. On the other hand, however, by anticipating more possible reactions, the surprise potential is reduced and so is the probability of unfavourable response strategies. This new view about the relationships between knowledge and uncertainty rests on the assumption of a shift to abrupt—either regional or global—climate changes (see 6.2.3, *infra*). Therefore, response strategies and decision processes that want to address *abrupt* climate changes should be robust enough to be supportable even once some unforeseen abrupt climate change happened.

1 "Waiting for information" has also been explored on a more substantial basis in the context of the
2 Arrow-Fisher-Henry irreversibility effect (1974)—see infra.

3 6.2.1.2 Irreversibilities

4 Irreversibility has come to be known as an important choice variable in decisions that have uncertain,
5 though not reversible consequences.

6 This decision factor evolved from economic-like situations dealing with special environmental
7 features as for instance unique natural environments and wildlife resources. These situations led to
8 identify a new approach for making allocation decisions because of the existence of resources with
9 no, no adequate, or at least a few substitutes (uniqueness does not need to be absolute for the
10 argument to hold). The features that Krutilla (1967) identified are multiple. One of them is this: in
11 this category, the (natural resource) allocation decisions are irreversible.

12 This conclusion gave rise to a conservation versus development debate. One noticeable con-
13 sequence has been that efficient control policies might mean some restriction of the activity.

14 According to Arrow and Fisher (1974) irreversibility can be alternatively defined as follows: "A
15 technically irreversible development could be characterised as one that would be infinitely costly to
16 reverse".

17 With respect to climate change/technology linkages, the state of the world beyond ten or twenty
18 years from now cannot be carefully thought about as independent from today's decisions. The
19 consequence of this non-independence is the formation of irreversibilities (basically, the fact that
20 there is no possibility of "negative emissions", that there is no process for removing CO₂ emissions
21 from the atmosphere once emitted, makes the emissions of CO₂ irreversible).

22 In other words, this non-independence is responsible for the existence of irreversible or quasi-irre-
23 versible trends in technology because of lock-in effects for example in consumption and land-use
24 patterns (Hourcade and Chapuis, 1994).

25 On the decision making side, irreversibility predominantly leads to risk averse type decisions (e.g.,
26 portfolio diversification, no-regret policy, minimum surprise). Note that there is some controversy
27 about expanding development versus conservation results to global warming problems. Conven-
28 tionally, the belief is that if the decision involves irreversibility, then current period decisions should
29 involve less irreversible commitment (one should undertake less irreversible investment) if there is

1 the possibility of future learning than if there is no such possibility. Although irreversibility and
2 learning seem to have opposite effects on the current decision period, "whether there is learning or no
3 learning, there will be less investment when investment is effectively irreversible, than when
4 investment is reversible" (Ulph and Ulph, 1994). Does this mean that irreversibility requires lower
5 current emissions of greenhouse gases?

6 6.2.1.3 Discounting

7 In conjunction with uncertainty, risk, and the need for capturing forthcoming information, time
8 also introduces the discounting of future benefits and costs.

9 Abatement as well as adaptation strategies are costly. Uncertain benefits are attached to such ac-
10 tions. Long-term costs and benefits are uncorrelated to national incomes.

11 Climate change, as already said, is big at the scale of the economy. Therefore, actions are re-
12 quested from governments (no private action can be a key action on this scale). These actions are
13 risky. The risk might be that you don't abate enough. Or too much. Discounting costs and benefits
14 becomes of paramount importance in the valuation of outcomes.

15 At which rate do you have to do that? The overnight rate of interest, as business does? Bond rates?
16 The pure rate of interest? A discount rate below the pure rate of interest? Or do we have to favour a
17 zero discount rate?

18 Let R be the current rate of interest. Basically, R is a mixture of pure rate of interest (r) plus some
19 allowance for risk. In other words, $R = r + \text{some risk premium}$. In this respect, we actually buy some
20 insurance because of aversion to risk (because we expect to lose money) (Arrow, 1994). Now, this
21 aversion to risk also means a preference for the present. In other words, the preference for the present
22 translates into heavily discounting the future.

23 Which discount rate to choose is an important question since the result of any cost or benefit
24 calculation over time is highly sensitive with respect to the discount rate's value. Schmalensee (1993)
25 points out that in an example that in order to pay a US\$1 billion damage in the year 2200, one has to
26 spend in 1992 US\$ 126 million on basis of a 1% discount rate of US\$ 32,000 on basis of a 5% dis-
27 count rate. Cline and Nordhaus present similar examples (Cline, 1992, Nordhaus, 1991). To illustrate,
28 the present value of \$ 1 obtainable in 200 years from now amounts to \$ 1 if the discount rate is zero,
29 to \$ 0.14 if the discount rate is 1%, to \$ 0.000058 for a 5% discount rate or to \$ 0.0000000527 for a

1 10% discount rate. These examples indicate that a moderate change in discount rate results in a
2 significant change of the evaluation of spending amounts over time (see Schubert, 1994).

3 The argument that the discount rate should be greater than zero is usually based on the assumption
4 that it represents individual's time preferences which should not be denied. The value of this
5 argument depends on the interpretation of the meaning of "discount rate"; i.e., on the answer to the
6 question "what is to be discounted?" (Broome, 1992). In general, two different interpretations of
7 "discount rate" are of special importance; that is, the social time preference and the opportunity cost
of capital. Whereas the first one represents the marginal utility of today's consumption as compared to
future consumption, the second one indicates the profitability of private investment. Usually, this
second rate is significantly higher than the first one. The reason is that for private investors the rate of
return on the best alternative project that is displaced by the investment under consideration depends
on various capital market imperfections whereas the time preference reflects the interest rates
available to consumers. Since consumers are net savers, the interest rate they have to pay (R) is less
exposed to risks (the risk premium is lower) and therefore lower than the real net rate of return of
producers.

16 For calculating the social time preference, typically two aspects are taken into consideration
17 (Pearce et al., 1990). The first one is that individuals are impatient and prefer the present to the future.
18 Their exposure to a limited life span might underline such preferences. If society is taken as the sum
19 of its individuals, it also prefers the present to the future. Such temporal preference leads to a positive
20 discount rate. The fact is, however, that climate change is away from the scale of private, individual
21 actions.

22 Indeed, there exists a variety of arguments against this aspect of social time preference. Nearly all
23 of them go back to Jevons' argument that impatience is irrational and therefore in contradiction to the
behavioural assumptions used for explaining choice behaviour (Jevons, 1871, Böhm-Bawerk, 1884,
25 Ramsey, 1928, Pigou, 1932). Nevertheless, impatience is observable so that this aspect should not be
26 fully denied. One another implicit argument against impatience has been forged by Chichilnisky
(1993). One can summarise this argument through the twin axiom of non-dictatorship of the present
and of non-dictatorship of the future. While non-dictatorship of the future eliminates deep ecological
29 "long-term average" solution, the non-dictatorship of the present eliminates discounting.

1 As suggested by Schubert (1994), one also has to take into consideration empirical studies on the
2 existence of discounting. According to these studies one can show that, in general, consequences
3 expected to occur later in time are regarded as being less important (Björkman, 1984, Jungermann
4 and Fleischer, 1988, Svenson, 1991). Two explanatory cognitive patterns have been identified (Van
5 den Berg et al., 1993). One is that more remote consequences will be judged as being less serious
6 (i.e., value discounting). The other is that such consequences, if a certain controllability is perceived,
7 will be thought of as less probable to occur (i.e., probability discounting).

8 As a consequence, whatever the explanation may be, empirical and especially experimental studies
9 seems to support clearly the discount rate greater than zero position. In conjunction with economic
10 analysis, it seems that, in principle, a low rate of discount is advisable (Arrow, 1994). As determined
11 by Cline, a discount rate of about 2% should be used for evaluating projects that are directly thought
12 for fighting global warming. Why (World Bank's statements are in favour of an effective discount
13 rate of about 8%)? Cline correctly assumes that 80% of project's resources come from consumption
14 and 20% from investment expenditures. Indeed, recall that, in principle, R is lower for consumers
15 than for producers. The fact is that governments must take actions, but that these actions are going to
16 be fuelled much more through withdrawals from consumption than from investment expenditures.

17 Conversely, the main reason for a relatively high discount rate would be that any project directed
18 to fight global warming should yield at least the same project profitability as any other (World Bank)
19 project (i.e. 8%). The point is that this would be valid only to the extent that, in order to allow an
20 equal treatment to different projects, negative externalities (which, indeed, are connected to climate
21 change) be included in any project's calculation (Pillet, 1992, Broome, 1992, Schubert, 1994).

22 6.2.1.4 Costs, benefits

23 Costs and benefits refer to the valuation of outcomes (alternatively of decision or response options).
24 In the climate change context, there exists not only economic outcomes, but also ecosystem out-
25 comes. The former are for instance world income losses, costs of delay, cumulative social costs. The
26 latter are made of losses to the unmanaged ecosystems, including species and habitat loss. Potential
27 benefits of slowing down climate change have to be assessed, too.

28 How one values these outcomes, including benefits—particularly economic ones as opposed to
29 ecosystem ones—, how this valuation depends on the uncertainty, and how averse one is to risk, will

influence the decision to reach as well as the process which will optimise expected value (Peck, 1994).

[to be completed by J. Parikh]

6.2.2 Attitudes

While the picture of division of responsibilities for global warming is known (for example, OECD was responsible for nearly 50% of gross global CO₂ impact in 1990 while Africa for nearly 2% only—Meyer and Sharan, 1994), the picture of vulnerabilities is known with much less certainty. In addition to economic parameters, the decision making framework must thus address questions like equity, poverty and ethics.

6.2.2.1 Equity, poverty and global warming

Generally speaking, the poor are more vulnerable to any calamity compared to the well off. For instance, while the Netherlands can build more dykes, nearly half of Bangladesh could be expected to submerge due to possible increased floods and sea level rise, increasing poverty and homelessness. Some island states face the fear possibility of disappearing from the map of the earth.

Large scale out-migration from coastal zones is expected due to sea level rise. More than seven million persons may be displaced from coastal zones in India. Large cities like Bombay, Calcutta and Madras are on the coast (Parikh et al., 1994).

Intrusion of sea water in the ground water and changes in temperature can reduce agricultural incomes everywhere, if any. In Bangladesh, the share of GDP due to agriculture is 38% compared to only 3% of GDP in the USA (World Development Report, 1992). Share of population depending on agriculture is also more than 60% of the population in Bangladesh.

One can therefore envisage that the impact of climate change on the poor of the South could be relatively more destructive than in the North. This raises the question of compensations, for instance in the form of insurance contracts, to be provided by the North. Immigrations rights might also be provided by the developed countries.

"While the rich can argue about whether to enjoy more now or pay more in the future, and what discount rates to use, this is not the issue for the poor, many of whom on the margin of subsistence have no option but to reduce their current consumption" (Parikh et al., 1994).

In sum, on the one hand, the poor might bear a disproportionate burden of changes in climate primarily caused by the lifestyles and consumption patterns of the rich (Parikh et al., 1994). On the other hand, conversely, one cannot isolate poverty from political, social, regional, cultural, demographic, and environmental factors. Some regions of the world already are overpopulated in terms of the maximum population that can be supported indefinitely in a given environment. In this respect, climate change would increase the pressure on the limits of the conditions on which life can be supported in some fragile life-support systems (Pillet, 1991). Losses in terms of natural capital in these regions would inevitably make the poor poorer. What is to be first addressed under these circumstances is the threat to the natural carrying capacity of such regions, which of course is not independent from local and regional economic and life-style options to make for the future.

6.2.2.2 The ethical problem: anthropocentric vs. ecocentric evaluation

As vulnerable as poor people are, the natural capital may be affected by global warming even before mankind notices the change. The earlier IPCC impact assessment indicates substantial pressures on biosphere and biodiversity due to climate change. For example, bleaching of coral reefs is expected due to upward movement of temperature zones. Within the rest of the ecosystem, loss of species is also indicated (Parikh et al., 1994).

Loss of species or damage to biodiversity has been traditionally ignored in the decision making framework. Only recently researchers have started developing tools for valuing the environment. Efforts to value species are mostly anthropocentric evaluations (economic valuation methods "value" the preferences of individuals or society for the environment, not the environment per se—Pethig, 1994). In other words, values refer to the pleasure and service of *mankind*, be it for recreation, medicine, education, research, chemicals, biochemical and other ingredients or to derive raw materials for a variety of purposes (Parikh et al., 1994).

An ecocentric view, on the other hand, views mankind as *one* of the species on the planet earth expected not just to live in harmony and balance with other species but also to share the biosphere including oceans, atmosphere, rivers, and so on which provide sustenance to other with other animals and plants. It does not make a judgement on other species but judges itself from the view point of others. To put it sharply, mankind's abrogation of decision making powers regarding nature is questioned; the ecocentric approach proposes to curtail such decision making power. The link

1 between the existence of other species and that of human beings should be kept in mind while
 2 making any decisions regarding the activities of mankind which will adversely affect the environment
 and other species (Parikh et al., 1994).

This is an issue of values. We raise it here to emphasise that whatever decision making framework
 is adopted, the value judgement implicit in it should be made explicit.

6.2.2.3 *Distributional aspects: Interregional and intergenerational equity*

[To be completed according to Parikh et al. and Shlyakhter et al.]

6.2.3 *Scientific Results (Gassmann, 1994)*

The anthropogenic nature of CO₂-increase found wide acceptance in the scientific world and caused
 public concern. However, this acceptance does not yet mean an acceptance of anthropogenic climate
 change.

6.2.3.1 *Climate change: Waiting for observation or learning from the past?*

Many scientists, politicians and the public have a deep natural belief in the stability and robustness of
 the climate system by trusting yet unknown negative feedback-loops guaranteeing homeostasis.

Indeed, our Holocene climate showed a seemingly convincing stability and steadiness over the last
 10'000 years with fluctuations of only plus minus half a degree (global average temperature) as de-
 rived from the most recent Greenland ice core (Dansgaard, 1993). Slow variations of unknown origin
 as the "Little Ice Age" or the medieval optimum, modulated with irregular variations with periods of
 the order of 30-100 years, do not substantially disturb this trustful view because of their small ampli-
 tude. The well-known interannual variability due to the evolution of high and low-pressure cells and
 also by other dynamical processes with inherent irregularity as "El Niño" (Graham and White, 1988)
 are not taken into account in the framework of the climate discussion by defining climate as the aver-
 age state of the atmosphere over an integration period of 30 years. Other causes of such short term
 fluctuations are the regular 11-year sunspot cycle or irregular volcanic eruptions. However, these
 short term variations can hide continuous anthropogenic climate changes over several decades. If the
 prognosticated anthropogenic trend of +0.3 K per decade (Houghton et al., 1990) would be reality,
 the global temperature signal will be clearly out of the noise level by the years 2010-2020. It is a
 cheap and therefore widespread excuse against taking measures to reduce greenhouse gas emissions,
 delegating any decision to the next generation that will better see what happens.

1 On the theoretical side, the important processes influencing the global climate are identified and
 2 can be understood at least in principle. Very detailed knowledge is available concerning long- and
 3 short-wave radiation transport through the atmosphere. Especially, gases influencing the greenhouse
 4 effect are analysed in detail (absorption bands, infrared emissions, diffusion) and so, its anthro-
 5 pogenic modification can be rather exactly calculated. However, the basic assumptions made in such
 6 calculations are that the structure of the climate system remains unchanged. Especially, atmospheric
 7 and oceanic circulation patterns and cloud formation, in many models, are assumed to remain quali-
 8 tatively the same, at most being quantitatively slightly affected and so contributing to a positive or
 9 negative feedback, amplifying or damping anthropogenic climate effects respectively. Easy to under-
 10 stand, that the prognosticated anthropogenic warming is gradual without discontinuities (the above
 11 mentioned +0.3 K per decade).

However, the picture drawn by the newest ice core results (Anklin et al., 1993) emphasises
 variability and instability in a surprisingly unexpected way. Not only shows the last ice age a big
 number of sharp transitions between a glacial and an interstadial climatic regime (what has been
 known before) but also reveals the last interglacial "Eem" as being composed of a series of sharp
 climatic transitions. The largest uninterrupted interval of Eem climate optimum (roughly 2K warmer
 than our Holocene level) encompasses only ca. 2500 years and at least 20 very important abrupt
 transitions between different climate levels can be observed. The most catastrophic fluctuation yet
 analysed happened towards the end of the Eem interglacial (115'000 years ago), where the climate
 changed into a glacial regime within about 15 years, to make the same abrupt change back to the
 original warm climate only 70 years later (Anklin et al., 1993)!

The discrepancies between the paleoclimatic observations of abrupt changes and the smooth grad-
 ual warming prognosticated by today's models could not be more pronounced. They are the result of
 the fact that the models simulate climate changes as marginal variations around a stable basic climate
 mode. That the dynamics of this basic mode could dramatically change, being replaced by a different
 one, is out of the scope of most of today's models. Consequently, they are not able to simulate ice
 ages as a whole nor the numerous and important climatic fluctuations within the last ice age or the
 Eem. From a general theoretical point of view, however, the observed step-like behaviour of the cli-
 mate system is to be expected, as will be shown in the following paragraph.

6.2.3.2 Behaviour of systems with non-linearities and feedback-loops

In the natural sciences, a slow but nonetheless deep and fundamental revolution is taking place that started in the sixties in mathematics, physics and chemistry and now comprises all other disciplines of natural sciences. It is centred around the seemingly contradictory notions of chaos and self-organisation that lead to a fundamental change of paradigms and offer a new understanding of nature.

Up to now, no general rules could be indicated that would guarantee that a given system will display chaos or self-organisation. However, necessary conditions enabling a system to make phase transitions into a chaotic or a self-organised state are circular causality (feedbacks) and non-linearity. To illustrate this point, the behavioural change of a chemical system resulting from non-linearity will be shown.

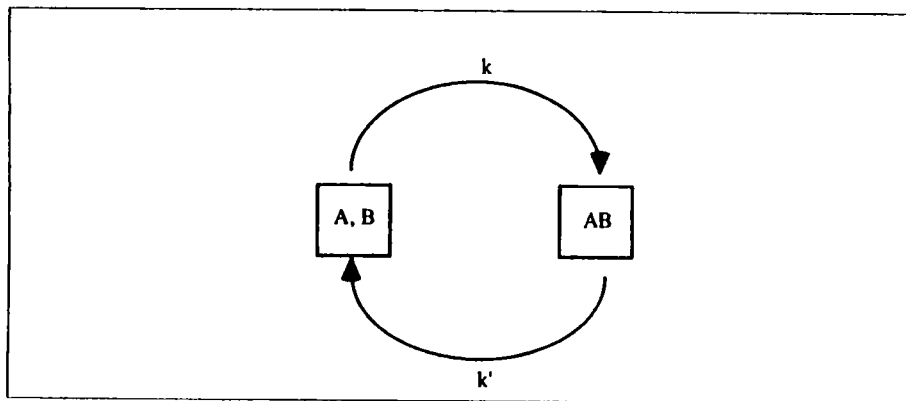


Figure 6.2: Circular causality in a bilinear system leading to a stable equilibrium concentration $[AB] = K [A][B]$ with an equilibrium constant $K = k/k'$ (k, k' = reaction rate constants)

6.2.3.2.1 A linear chemical system tends to the classical thermodynamic equilibrium

One of the most obvious examples of a feedback-system is the basic chemical reaction that combines two educts A and B into a product AB. Because of the decay reaction due to the thermal vibrations AB disintegrates into A and B. Based on the bilinear kinetic equations, it can be shown that an asymptotically stable equilibrium concentration $[AB]$ develops gradually, being determined by the bilinear product $K[A][B]$. $[A]$ and $[B]$ are the concentrations of the educts that, in many industrial processes are held constant by continuous supply and K is the equilibrium constant, defined as the ratio of the kinetic reaction rate constant k for the combination-reaction ("forward reaction") and the re-

spective constant k' for the decay reaction ("backward reaction" or feedback reaction). The system-inherent circular causality is schematically shown in figure 6.2.

A physical example of such a decay-dynamics is heat exchange between two masses with initially different temperatures. Also here, an asymptotically stable thermodynamic equilibrium state is gradually approximated that is defined by equal temperatures of both masses.

6.2.3.2.2 A non-linear chemical system can be found in different self-organised or chaotic states

If the two properties mentioned above, namely non-linearity and circular causality are combined, new qualities different from equilibrium can arise: self-organisation or chaos (Gassmann, 1993). In chemical systems, the most simple form of non-linearity comes from an auto catalytic reaction, where an intermediate product X is necessary for the synthesis of itself as shown in figure 6.3.

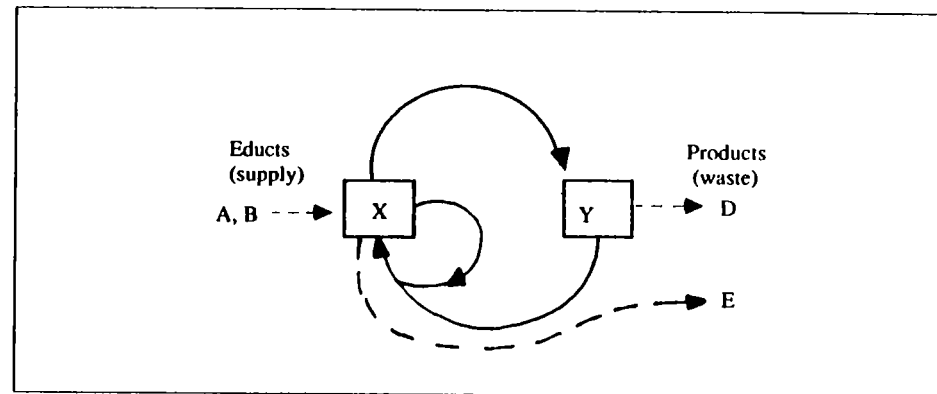


Figure 6.3: The most simple form of non-linearity in a chemical reaction arises from auto catalytic reactions.

The intermediate products X and Y show patterns in time or space maintained by the flow of mass and energy through the system (open, dissipative system). The uninteresting products formed are normally called waste.

Such open, dissipative systems (Prigogine, 1980) driven by a throughput of mass and energy (or energy alone) are numerous in physics, chemistry, biology and the earth sciences (physics of the atmosphere, oceanography, ecology, etc.). The most important behavioural characteristics shared by all these systems are :

- chaos: small differences in initial conditions are amplified making a prognosis exceeding a limited time horizon impossible (weak causality, "butterfly-effect") (Lorenz, 1963);

- 1 • self-organisation: macroscopic coherent structure in space or time being stabilised by dissipation
- 2 (Haken, 1977).

The transitions between different self-organised states or between chaotic and self-organised states are abrupt: The old structure disappears as a whole in a short time and is replaced by a new one.

- 3 These phase transitions occur at exactly defined values (critical values) of some system control pa-
- 4 rameters.

7 6.2.3.2.3 *The possibly big effects caused by small stochastic fluctuations*

- 8 In the framework of the basic properties of non-linear systems with circular causality, small
- 9 stochastic fluctuations can become important factors influencing the time evolution of a system. As
- 10 soon as the system approaches a critical value of a control parameter, an unpredictable fluctuation
- 11 might be the cause triggering an abrupt phase transition into one of several possible nearby states.
- 12 Even if all the critical values would be exactly known, neither the transition time nor the follow-up
- 13 state could be predicted due to the uncertainty coming from stochastic fluctuations and weak
- 14 causality. Thus, in the optimal case of complete knowledge about the system, the spectrum of
- 15 possible metastable states could be described, but no time evolution could be predicted.

16 6.2.3.3 *Different climate change scenarios to be considered*

- 17 The main characteristics of the global climate system is its structure consisting of many interlinked
- 18 feedback-loops, some of which being highly non-linear. Especially the hydrological cycle shows
- 19 strong non-linearities: exponential saturation pressure curve for water vapour versus temperature,
- 20 phase change from water to snow or ice at 0°C leading to abrupt surface albedo increase, critical sea
- 21 surface temperature of 27.5°C for dramatic increase of deep convection and thunderstorms etc. An
- 22 important property of the climate system is the strong coupling between different regions of the globe
- by atmospheric or sea currents. Furthermore, different important delays complicate the dynamic re-
- 23 sponse of the climate system. Examples are: heat capacity of the sea-surface layer (ca. 70 m deep),
- 24 time for melting snow, ice etc.

- 25 A system with intensive non-linear feedback-loops is a good candidate for self-organisation and
- 26 whence abrupt changes at critical values of control-parameters or even for chaotic behaviour above a
- 27 certain threshold. As the past 200'000 years including the last two glacial times as well as the Eem
- 28 interglacial show everywhere abrupt changes and climate instabilities, it is indeed a so far unsolved
- 29

- 1 problem why the past 5% of this time, the Holocene, showed a practically stable climate. As long as
- 2 this question cannot be answered, this comfortable climate stability must be considered as exceptional
- 3 and probably fragile. The most natural behaviour to be expected is not a gradual warming but rather
- 4 an abrupt phase change, a transition to another climate regime (i.e. the Eem optimum regime with
- 5 roughly 2K higher temperatures).

- 6 It turns out that global change scenarios must be revised according to these emerging scientific in-
- 7 sights. In addition to the "classical" scenario characterised by gradual warming, two "abrupt change"
- 8 scenarios are proposed:.
- 9

- 10 • The "classical scenario" with a gradual warming of 0.3 K per decade is not yet ruled out but has
- 11 to be considered as the exception rather than the rule. As it would be a reliable global long term
- 12 process with rather unpredictable but continuous regional evolutions, it would fall into the cate-
- 13 gory of "weak uncertainty".
- 14 • The "abrupt global change" scenario with a sudden important temperature increase within a
- 15 short period (1-10 years) seems to be a natural candidate based on theoretical reasons as well as
- 16 new paleoclimatological results. The time point where the abrupt change will take place as well
- 17 as the amplitude of the step and the regional responses will be unknown, so leading to "strong
- 18 uncertainty".
- 19 • The "abrupt regional change" scenario with sudden important climate changes in certain regions
- 20 is a possible combination of the above described scenarios. While the global average tempera-
- 21 ture increase would be rather continuous and reliable, it would be unknown which region will be
- 22 next for what change. We would face a "globally weak but regionally strong uncertainty".
- 23

- 24 These scenarios characterised by "weak" and "strong" uncertainties (see reconciliation framework,
- 25 Table 6.4 in Section 6.1) call for response strategies that are robust enough against abrupt regional or
- 26 global changes.
- 27

Section 6.3

Contents

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6.3 Approaches to the Formulation of the Climate Change Decision Problem

"Prior judgements that decision makers bring to the problem, and the decision rules they employ [for example maximising expected value *versus* minimising maximum loss *versus* observing a specified set of procedures given by some international convention], could be far more important in controlling the policy conclusions that they reach than are the results of scientific discoveries" (Dowlatabadi and Morgan, 1992).

Although confined to the short run, this statement is not at all in contradiction with what has been previously said. This simply fairly means that we cannot forget the normative dimension of economics when dealing with decision making frameworks. Accordingly, we shall begin by identifying the decision makers' questions before considering various strategies (this Section) and then giving precedence to decision making representations and methods (next Section).

6.3.1 Identifying the Decision Makers' Questions

Identifying decision makers' questions does mean developing policy questions. This means elaborating a set of key questions without prejudging the answers—in other words, without any assessment of whether science could provide results (Joint Climate Project, 1992). These questions echo and extend the analytical framework elaborated through the previous Sections 6.1 and 6.2.

6.3.1.1 Key questions

Decision maker's key questions are (after Joint Climate Project, 1992: 29-34):

- What are the major sources of uncertainties regarding the climate system, impacts of climate change, and potential responses?
- What uncertainties can be quantified (and with what degree of reliability)?
- When will key uncertainties be significantly reduced (and to what extent)?
- How could or should scientists provide information to decision makers (the latter want to know that the information they receive is reliable and accurate)? Observe that in this respect, "open reviews, consensus-identifying exercises, and comparisons of results would assist decision makers in evaluating the reliability of information". This means that the *decision process related information assemblage* is significant.

These key questions lead to policy-relevant concerns which are expected to designate the forcing framework within which answers are to be refined.

6.3.1.2 Policy-relevant concerns

Main policy-relevant concerns are (after Joint Climate Project, 1992: 29-34):

- Global climate change policy is currently driven by an *international perspective* (1994 validated Framework Convention on Climate Change, basically). Information is needed for follow-up.
- *Decision making is driven* by concerns about the potential impacts of changing climate at the regional level, rather than predictions of changing global mean values of climate variables (in other words, decision maker's concerns are effects driven, but research emphasises atmospheric sciences).
- Decision makers need *interim information* and iterative assessments to be provided by scientists and researchers. These "breakthrough" reports should be thoroughly explicit about the inherent *uncertainties*.
- Resolution of the uncertainties related to the policy-relevant questions is *not a prerequisite* for action. Decision makers *will determine* how much uncertainty they judge is enough to take a given policy action!

There is a need anyway to define better the sources, implications, and estimate time frames for the resolution of *policy-relevant scientific uncertainties*.

6.3.1.3 Climate change-related risks

One another set of decision makers' questions is relative to the possible ecological and human risks of climate change (arranged after Joint Climate Project, 1992: 29-34):

- How can human activities influence climate and what mechanisms of climate change are beyond man's control? This question deals with the endogeny *versus* exogeny of uncertainties, risks, and probabilities. In fact, decision makers would like to avoid ineffective research on climate mechanisms that are exogenous (that man cannot control).
- Decision makers want to know what is *at risk* and what is not, which (natural and human) systems are the most sensitive/the most resilient to climate. The same is true for regions.

- Can reliable anticipations of these risks and other impacts of climate change be made *in the next five to ten years*? When can further improvements be expected? What resources and tools are needed?

6.3.1.4 Decision options

Decision makers want information on possible options and their relative costs and benefits. They want information on possible mitigation and adaptation options. In addition, they say that "only by assessing their relative merits and effectiveness can the appropriate mix and timing for implementing response strategies be determined". This interestingly suggests a bias for prominent options and decision criteria.

Questions are (arranged after Joint Climate Project, 1992: 29-34):

- A more thorough understanding of the impacts of *existing environmental and energy*—though also economics, population, forestry, etc.—*regulations* is needed before examining new approaches for addressing potential climate change.
- What are the *possible response options (mitigation and adaptation)* and their associated costs; benefits; level of effectiveness; and their social, economic, and technical barriers?
- Decision makers want information on the evaluation of different options over various time frames. "For example, a particular option may delay the onset of climate change by 20 years if implemented now, but by only two years if action is postponed for a decade."
- Last, though a very important question: How do possible initial actions influence future response options—as well as the ability of decision makers to pursue beneficial measures in other domains?

In sum, decision makers want

(a) to better know, quantify onto a reliable extent, and reduce key policy-relevant uncertainties and risks with respect to impacts of climate change that make sense on a regional, economic, and ecosystems basis primarily—though resolution of uncertainties is not a prerequisite for action;

(b) they want possible policy options to be assessed, and benefits and cost to be balanced—they have a bias for prominent policy options such as, namely, mitigation and adaptation strategies, as well as for utility-based decision criteria;

(c) decision makers want a mix and timing to be elaborated to allow for effectiveness of measures to be duly checked—they also want a better understanding of the impacts of existing environmental, energy, and economics regulations;

(d) they want information to be produced and peer reviewed, not only in order to meet points (a) to (c), but also for fulfilling in the field international conventions related needs;

(e) last, they want various time frames to be evaluated together with possible sequential actions to be set up in order to make future response options matching initial response options consequences.

These decisions options lead us to proceed now with strategies and analyses that have been thought to deal with climate change main issues.

Traditional climate-related uncertainties are exogenous: climate as such still is unpredictable. Yet, the potential climate changes we are today used to consider are global in scope and appear to be driven by human activity. Taking account of these two most recent concerns is not without repercussion on climate-related uncertainties, be it qualitatively or quantitatively (Chichilnisky and Heal, 1993).

If, from a scientific viewpoint, uncertainty about global mean temperature matters, from a socio-economic perspective, it is future climate, with associated wind patterns, humidity and rain patterns, regional and particular ecosystems impacts, conceivable change trails and pace (see 6.3.1.2, *supra*)—together with future emissions of greenhouse gases—, that matters. By turn, in as far as precarious greenhouse gases emissions are man made emissions, and hence can be driven by economic activity and policy measures, faced uncertainties and associated risks become endogenous. *The fact is that they can be altered by agents.*

By way of illustration, this would mean with respect to a standard decision making framework that the states of nature were now endogenous, and thus would have attached computable probabilities. This would be however feasible as long as uncertainties were "weak" uncertainties only. Actually, "strong" uncertainties are in front, with unpredictability attached to basic scientific relationships between climate (link between gaseous emissions and global mean temperature, regional impacts, abrupt changes, and so on) and economic (future emissions, effectiveness of economic instruments, welfare losses, etc.) systems.

In principle, society can respond in two standard ways to such uncertainties and associated risks, depending on the comparative weighting of these two choice variables, and notwithstanding the diffi-

1 culty at assessing and quantifying climate-related risks. One way is mitigation. One another is insurance (Chichilnisky and Heal, 1993).

3 A third way would be through negotiation and/or procedural rules. To date, however, international negotiation and procedural rules can be considered resolved through the 1994 validated Framework Convention on Climate Change.

6 Let's consider mitigation and insurance in turn. Decision making representations (like sequential analyses and hedging strategies) and methods (e.g., portfolio analysis analogies) will be introduced in the next section.

9 6.3.2 Mitigation Strategies

10 Mitigation is the prominent policy option. It first means abating; that is, taking measures to slow down climate changes and thus reduce the potential impacts. Continued intensive science research to reduce climate and impact uncertainties, development of new supply and conservation technologies to reduce abatement costs, and immediate emissions reductions (abatement as such) in order to slow down climate changes are examples. Adaptation, which means taking measures to internalise consequences of changes as they appear, is not in opposition to mitigation. Building dikes to protect low lying coastal areas from sea level rise is an example. In principle, mitigation and adaptation are long-term issues whose outcomes range well into the next century (see Fig. 6.1).

18 6.3.2.1 Abatement and adaptation

19 Generally speaking, mitigation consists in taking steps that reduce the incidence of harmful events (the probabilities of adverse side effects) or that minimise the damage if such events take place (mitigating the adverse side effects). More strictly speaking, one way is the curtailing of emissions (mitigation as abatement strategy). An alternative way is the lessening of the harm or the increasing of the benefits of climate change (mitigation as adaptation strategy). There is a variety of empirical studies that assessed potential damages from climate change and costs of different mitigation options. There are only a few studies on the comparative assessment of mitigation and adaptation costs, and the potential benefits of these measures (Kaya et al., 1993).

27 Attitudes are being changed, but there still is an implicit line of division in economic analysis of global environmental problems. By way of illustration, a 1992 statement says this: "mankind as a whole or individual societies may decide to undertake various sorts of actions to mitigate greenhouse

1 gas emissions at any level of costs they find affordable, but proponents should, at least at this point, not rely on economic analysis to supply ammunition": mitigation strategies don't pass the benefit-cost test (Toth, 1993). As a consequence, actions that are based on other concerns might be legitimate (e.g., ecological concerns or moral principles) though they suppose not to constitute optimal strategies.

6 Where is the trouble?

7 One approach is rooted in neo-classical mainstream economics and attempts to make policy measures pass a benefit-cost test (which is not well adapted for analysis of long-term, large-scale and complex climate change prospects). Indeed, depending on one's views of control costs, a case can be made either for or against emission cuts. A reduction in emissions is not the sole policy response that is available. There is a point at which further reductions could become so expensive that it would be preferable to shift to other options, such as adaptation to climate change—though it is not clear whether adaptation really is such a long term option. Without careful analysis, it is difficult to know where that point might be (Manne and Richels, 1992). A benefit-cost analysis is designed for a "go/no go" decision on a well-defined project. With respect to climate change, the objective is to move away from the standard benefit-cost decision-making framework. In particular, decisions should be adjusted over time as better data become available.

18 The other approach derives hard constraints (climate change must be mitigated) from the (incomplete) understanding of ecological systems and put them on the economy with little respect for the relative costs and benefits. As a consequence, the economic analysis is "restricted to finding the least expensive policy instrument to reach this objective" notwithstanding the enormous uncertainties that remain in our understanding of the greenhouse effect, its likely consequences, and the possible effectiveness of various countermeasures and that will not be resolved for decades.

24 Reaching the decision, therefore, radically differs between the tenants of each approach. In principle, whereas the first approach, according to the need for passing a benefit-cost test, might wait for some resolving of the various uncertainties, the second approach, according to the precautionary principle, would call for early action.

28 These two viewpoints clearly depict the differences in the climate change perceptions in the early nineties (Kaya et al., 1993). Today, if the two viewpoints don't definitely meet, they are reconciliated into a broader context of long-term evolution of efforts to mitigate climate change and with a view to

new results in atmospheric sciences and economic analysis (FCCC, 1992, Cline, 1993). The point, however, still is that if climate change must be prevented, "reduction of our vast ignorance might profoundly change both terms in the benefit-cost balance" (Nordhaus, 1993). This for instance will depend on the link between the value of information (the possibility of learning)—including ecosystem outcomes valuation (Pethig, 1994). This will also heavily depend upon the recognition of the endogenous character of uncertainties and risks associated to climate change.

As said before, key policy-relevant uncertainties and risks are endogenous. For instance, once we take steps to reduce the risks of climate change, these risks become determined by our policy measures, and can be treated as endogenous risks. Mitigation acquires a new meaning when risks, along with uncertainties, are endogenous. Ideally, this would mean that agents might be able to know the state of the world. Accordingly, making this information available today—or prior to decision making—would lead to better decisions; in other words, this would allow decision makers to chart the best course of immediate action.

The question is: How much accuracy is needed in order to improve decisions on carbon reductions? and on adaptation measures? With perfect information today, there would be "no need to hedge bets". "By contrast, the less faith we have in the possibility of near-term research accuracy, the greater is the need for precautionary actions", that is for implementing mitigation strategies (Richels, 1994). In addition, Peck and Teisberg (1993, 1994) have shown using the Carbon Emissions Trajectory Assessment (CETA) model that when policy under uncertainty is arbitrarily chosen (as it would be through any of the two above-mentioned viewpoints) the value of resolving uncertainty now instead of twenty years from now is much greater than when policy under uncertainty is optimal. "Specifically, if the arbitrary policy under uncertainty were to be no emissions reduction, the benefit of resolving uncertainty is an order of magnitude greater; and if the arbitrary policy were to be an emissions limit at the 1990 level, the benefit is three orders of magnitude greater".

This, however, does not mean that there is no value of information attached to an optimal policy used under uncertainty. It is large enough to justify current research efforts, and perhaps to justify increased emphasis on research into the impacts of warming and cost of adaptation to warming (Peck and Teisberg, 1993). This merrily means that if the political process will choose any arbitrary (or, suboptimal) policy, and if this choice could be prevented by early resolution of uncertainty, the urgency of resolving uncertainty is dramatically increased (Ibid.).

The climate issue entails high stakes. Waiting leads to the risk of irreversible damages. Immediate action leads to the risk that large costs will be incurred in the near future, and there is considerable disagreement on how these actions will eventually affect the world's climate and generate future benefits. Let's consider risk economics.

6.3.2.2 Risk-reduction activities

To illustrate, risk-reduction activities would classically need a decision framework made out of three steps, as follows (risk management principals—adapted from Querner, 1993):

(a) Technical risk analysis

"Technical" probabilistic risk-assessment covers the determination of possible physical consequences and their probabilities; that is:

- stochastic prospects (recall, however, that the description of climate change is limited to the setting-up of scenarios), and
- probabilistic risk assessment (occurrence and consequence of climate change; possible catastrophic events, risk exposure per geographical zones by applying anticipated frequency of hazards, total exposure per country for any particular risk scenario, associated probabilities).

(b) Normative risk analysis

Normative risk analysis covers the ranking of individual preferences (and the framework for doing that) over an "as wide as possible range of conceivable probability distributions, including not only financial pay-offs but *also* physical [environmental] outcomes" (Querner, 1993).

Frameworks to accompany normative risk analysis are:

- standard preference models (regarding not only financial pay-offs but also physical outcomes) such as Expected Utility and other approaches.
- tentative application of Willingness to pay approach (money/wealth/assets - individuals relationships) and of option-price for catastrophe-reduction.
- optimal risk (analysis of the aggregate risk reduction cost).

(c) Risk management

Risk management deals with the search for an optimal allocation of resources into risk-reduction activities. Strategies that stimulate an optimal allocation of resources into risk-reduction activities (together with decision making under uncertainty, hedging strategies, etc.) would have to:

- 1 • check the market for systematic market-failures according to risk vs. wealth rate of substitution (a special case would be that of non-market goods and services associated to climate);
- 2
- 3 • evaluate governmental (local/global) counter-measures toward optimal risk-reduction activities (emissions reduction and other options such as adaptation to climate change);
- 4
- 5 • address the case for possible cumulative (regional) severe catastrophic events relative to potential climate change.
- 6

7 6.3.2.3 Prospects for new supply and conservation technologies

8 Decision options are sensitive to the prospects for new supply and abatement/conservation technologies. This is concerned with the value and timing of research and development aimed at improving
9 the cost-effectiveness of greenhouse gas mitigation technologies such as energy efficiency and non-
10 fossil energy sources.

12 Consider two alternative energy futures. In the optimistic scenario, there are abundant low-cost,
13 carbon-free supply alternatives and highly efficient end-use technologies. In the pessimistic scenario,
14 it is more difficult to adapt to a carbon constraint. If one is a technology pessimist, it makes sense to
15 shift more of the burden of emissions abatement from the future era to the present time. For the op-
16 timist, the story is reversed: the far-future will need less help in adapting to a carbon constraint, so
17 there is less pressure for immediate cutbacks (Richels, 1994).

18 The price tag for a carbon constraint is also sensitive to the date and pace of its implementation.
19 The shift to a less carbon intensive economy cannot happen overnight. The time scale for large-scale
20 deployment of new supply technologies is typically measured in decades. Widespread adoption of
21 highly-efficient end-use technologies also takes time. Energy efficient systems are often embedded in
22 long lived durable goods (automobiles, housing, equipment, structures), and these will not be re-
23 placed instantaneously. The process can be accelerated, but at a cost (Richels, 1994). Flexibility in
24 managing the transition to a less carbon intensive economy is required, and appears to be a mix of
25 policy options, including the buying of insurance policies. [To be completed by Parikh]

26 6.3.3 Insurance Analysis

27 By contrast with mitigation strategies—which consist in doing something to slow down climate
28 change and reduce its effects and/or adapt to the its possible consequences—, insurance basically
29 does nothing to reduce the chances of damage due to climate change (Chichilnisky and Heal, 1993):

1 in essence, it only arranges for those who are adversely affected to receive compensation after the
2 event. In reality, the insurance industry is well used at addressing risk reduction and consequently
3 managing risk. With respect to adverse natural events, measures typically include setting total expo-
4 sure limits for a specific high risk zone to avoid the cumulation of risks (e.g., Eastern coast of US,
5 Japan, Australia and other countries with low lying coastal areas, etc.). In addition, the underwriting
6 guidelines of a company may be modified by setting restrictions on coverage (exclusions) or improv-
7 ing overall risk exposure by selective underwriting (Weilenmann, 1994).

8 Yet, can the insurance industry provide adequate insurance cover to those at risk from climate
9 change?

10 6.3.3.1 Purchasing a "greenhouse insurance"

11 A first, global view on climate change insurance is that of buying an insurance policy in the precau-
12 tionary sense of spending some money on alternatives to mitigation strategies that would be aimed at
13 reducing uncertainties and abatement costs by learning and acting.

14 If there are great risks from global warming, the "insurance premium" would be very expansive. In
15 these circumstance, as Manne and Richels (1992) argue, it may be worthwhile to pursue alternatives
16 to cutbacks on emissions. The related "forms of insurance" would be, roughly, as follows:

- 17 • continued intensive science research to reduce climate and impact uncertainties;
- 18 • development of new supply and conservation technologies to reduce abatement costs;
- 19 • immediate reductions in emissions in order to slow climate changes.

20 As a consequence, policy makers should decide how to divide greenhouse insurance dollars
21 among these competing needs. What portion goes to resolving climate uncertainties? What portion
22 goes to technology development? And what portion goes to immediate abatement of emissions? In
23 this respect, devoting a few percent of world GDP to cutting back carbon dioxide emission may emi-
24 nently be justifiable as an insurance policy (Chichilnisky, 1994).

25 6.3.3.2 Insurability of risks associated to climate change

26 The insurance issue can also be accorded our attention in contrast with mitigation strategies.

27 Basically, in view of uncertainties about consequences of carbon emissions, the question is: Is it
28 worth taking costly and disruptive measures to reduce levels of emission far enough to stop the build-
29 up of CO₂ (Chichilnisky, 1994)? Next, should you consistently decide to wait until more is known

and better estimates of the consequences are available, would it not be cautious to insure against harmful events even if the chance of their occurring is small and not immediate?

Further questions to rise are : "Can the existing and very extensive private sector organisations provide those at risk from climate change with adequate insurance cover? If not, why not? What changes in market institutions might be appropriate in this case?" (Chichilnisky and Heal, 1993). Is a trading of risk positions between regions of the world conceivable? Essentially, then, on which ecological-economic basis a trading of such climate change risk positions/insurance contracts would be secured (Pillet, 1994)?

Climate change associated risks are first difficult to quantify (in a classical statistical sense, the probabilities describing them are unknowable). They are then endogenous (once steps have been taken toward reducing climate associated risks), correlated (which demands complex analysis to assess probabilities), and collective (by which the uncertainty about the relative frequency of harmed agents is meant). In principle, however, once frequencies are at least approximately known, actuarial calculations can be set up, and the problem can be conceived as insurable.

This suggests that it is "frequently prudent to insure against harmful events" even with low probability of occurrence: "Thus, most house owners insure their houses against fire, even though the chances of them being burned are less than one in one thousand. Similarly, most Americans who can afford to do so, insure themselves against catastrophic medical expenses even though the chance of them making claims on this insurance are very small. These examples illustrate the prevalent philosophy of allocating some of one's income to insuring against major damage, even though such damage is unlikely to occur. Developing the point to climate change, this is a potentially harmful event which is probably much more likely than your house burning down. It may therefore make sense for humanity to insure against harmful climate change" (Chichilnisky, 1994).

The aim hereafter is to address the insurance issue beyond the dedication of a few percent of GDP to cutting back carbon dioxide emissions; that is, as a way to deal with climate change induced risks.

For instance, to the extent that carbon emissions lead to uncertainties about climate change and the corresponding damage that such changes cause, it can be said that the uncertainty is induced by the industrial countries, and born by the world as a whole. The available data also indicates that developing countries are much more vulnerable to climate change (also see Section 6.2). Any insurance scheme must take this distribution of causes and risks into account". On the other hand, managing

climate risk is not a new activity. In medieval England, a peasant farmer's land was broken into many widely-dispersed parcels. Economic historians interpret this as a way of hedging climate risk. Land at different locations would be affected differently by droughts, floods and frosts. By spreading land holdings over different locations, as well as by organising agricultural cooperatives and buying insurance, farmers have managed climate risk for many centuries (Chichilnisky, 1994).

Chichilnisky's (1994) position is that today's concerns about global climate change break new ground in two ways. One is the global scope of the potential changes considered. The second is that these changes appear to be driven by human activity, which has now reached levels at which it can affect the global climate (Chichilnisky and Heal, 1993).

The floods of 1993 in the US, in Bangladesh, and in Europe (France, Switzerland) have reminded us of the profound vulnerability of human settlement to climate.¹ There is considerable natural variation in these phenomena, although climate scientists expect that variation induces by human activity will soon come to exceed the natural variation (Chichilnisky, 1994). Correspondingly, one must bear in mind that before 1989, natural disasters caused by storm events with insured losses greater than one billion dollars were unknown (Weilenmann, 1994). For insurers, the most costly storm event to date has been 1992 hurricane "Andrew" with insured losses of US\$15.5 billion (see Table 6.6; cf. Weilenmann, 1994; see Pillet, 1994). This kind of losses has become more frequent and a clear potential rise is predicted. However, the causes for that trend are not clear. They also depend upon the increasing concentration of people and insured economic values in areas of high risk.

Table 6.6—Natural Events and Attached Insured Losses

Event	Date	Insured Losses (in billion US\$)
Hurricane Gilbert	September 1988	0.05
Hurricane Hugo	September 1989	5.8
Winter storms Europe	January/February 1990	10.0
Colorado storms	July 1990	1.0
Hurricane Bob	August 1991	0.62
Hurricane Andrew	August 1992	15.5
Hurricane Iniki	September 1992	1.6
East coast storms US	March 1993	1.6
Midwest floods US	Summer 1993	0.75

Source: Weilenmann (1994)

¹ Climatologists link these to El Niño, the ocean current off the coast of Chile, confirming the global linkages within the earth's climate system (Chichilnisky, 1994; also see Folland, Parker and Palmer, 1986).

6.3.3.3 The value of insurance

What a society believes it to be worth paying to reduce the risk of climate change depends *inter alia* on two key characteristics of that society: its *degree of risk aversion* and its *discount rate*.

The degree of risk aversion is a measure of how much an individual or group is willing to pay to avoid a risk.² The discount rate is a measure of the value of the future relative to the present (see 6.2.1.3).

"The more risk averse is a country, the more it should rationally be willing to spend on insurance (or mitigation) against climate change. And the higher its discount rate, the less it should rationally be willing to spend—because the consequences of climate will largely occur quite well into the future, and with a high discount rate, the future is relatively unimportant" (Chichilnisky, 1994)

It consequently turns out that different country's positions with respect to measures to restrict greenhouse gas emissions depend on their discount rates and degrees of risk aversion (even if there were complete agreement about all of the scientific aspects of the global change problem, there could still be disagreement about policy responses). The US, for example, has been against global abatement agreements, while Germany—as a leader in Europe for environmental policy—has been in favour (Chichilnisky, 1994). "This fits with the conventional wisdom that the financial and industrial community in the US has both a higher discount rate and a lower degree of risk aversion (greater willingness to take risks) than that in Germany. The differences in policy positions could then be attributed to differences in discount rates and degrees of risk aversion rather than, or in addition to, different interpretations of the current scientific evidence" (Ibid.).

Yet, different perceptions of the risk involved do not however preclude efficient solutions. Differences in attitudes toward risk could merrily lead to the introduction of new markets in which different risk positions are traded, with efficiency gains. Economics is about differences in preferences leading to trade (Chichilnisky, 1994). Betting on climate states could be envisaged. Not only because insurance can be provided within a market framework, but basically because there exists an

² An indication of the degree of risk aversion can be obtained by the following exercise: offer a person the choice between either \$0 if a tossed coin comes down heads and \$100 if it comes down tails or \$ 50 with certainty. Most people will choose \$50 with certainty, even though on average they will get the same by choosing to bet on the tossed coin and they stand some chance of doing better (and some chance of doing worse). In fact most people will choose \$45 with certainty to a bet on a tossed coin giving \$0 for heads and \$100 for tails. Suppose that \$45 is the smallest amount for which this is true. Then the difference between \$45, the reward in the risk less situation, and \$50, the average reward in the risky situation, is a measure of the person's risk aversion. *The more risk averse you are, the more you will insure* (Chichilnisky, 1994).

ecological-economic ground for the use of financial instruments in addressing climate change collective risks induced by uncertainty about the overall/regional distribution of adverse effects.

6.3.3.4 An ecological-economic basis for betting on climate states

The Arrow-Chichilnisky-Heal idea is then to settle a framework involving securities whose pay-offs depend on which description of the (collective) risk is correct (Pillet, 1994).³ The existence of financial markets⁴ is only half way an explanation. The question to pose is: How to interpret the trading of climate risk positions from a global ecological-economic viewpoint?

The most interesting interpretation is based on the disparity between ecological and economic systems. On the one hand, ecosystems are driven by forcing functions, the ultimate one being the sun. On the other hand, conversely, economic models work according to some objective function from which prices are computed out. In short, ecological models are energy oriented models whereas economic ones are based on the behaviour of individual agents and groups. Under the case for climate change prospects, the behaviour of the agents contributes to make particular energy profiles to appear and develop, with unknown feedbacks on future economic outcomes (Pillet, 1994).

Consider Figure 6.4 where environments and the economy are jointly though coarsely plotted. One typical feature this figure brings forth is the *disconnectedness* of the two blocs: All seeming connections do have ends that are irreconcilably set apart. Indeed, many tentative reconciliation frameworks have been explored, but no one can be considered as being ecologically and economically validated.

This is stressed by Figure 6.5 which opposes matrix (Daly, 1968) and systems (Odum, 1983) views over joint environmental and economic representations. The matrix perspective conventionally plots separated fields of study. From a systems viewpoint, conversely, economies (the left-hand circle) may appear as catastrophes for ecosystems with respect to energy use and concentration, time, etc. These man-induced climatic linkages add to the interest of trading risks from climate change.

³ "This amounts to allowing agents to bet on which model of the risk is correct. Betting on which of several alternative descriptions of the way the world works is correct, is in effect what one does when choosing one research strategy over another. (...) For example, a market for the securities of high-technology firms pursuing different research strategies towards the same goal is a financial market in which these bets are made" (Chichilnisky, 1994).

⁴ For example, Chicago Board CAT Futures (for Catastrophe Futures) are securities which pay contingent on the frequency of the occurrence of a major weather risk such as earthquakes in the West Coast of the US, tornadoes in the East Coast of the US, and floods in the Midwest of the US. "They can be used to hedge the scientific uncertainty about the incidence of environmental risks as they are traded by insurance companies to hedge against their exposure to major climate risks" (Chichilnisky, 1994). This financial instrument was first proposed by Chichilnisky and Heal (1993). It has been since introduced and traded at the Chicago Board of Trade. To illustrate, an insurance company which offers insurance against floods may buy a contract which pays US\$5 billion if the frequency of floods in the US Midwest exceeds a given agreed number over the calendar year 1994 (see also Table 6.6).

Figure 6.4: Ecological-economic Overview Diagram
Pillet, 1993

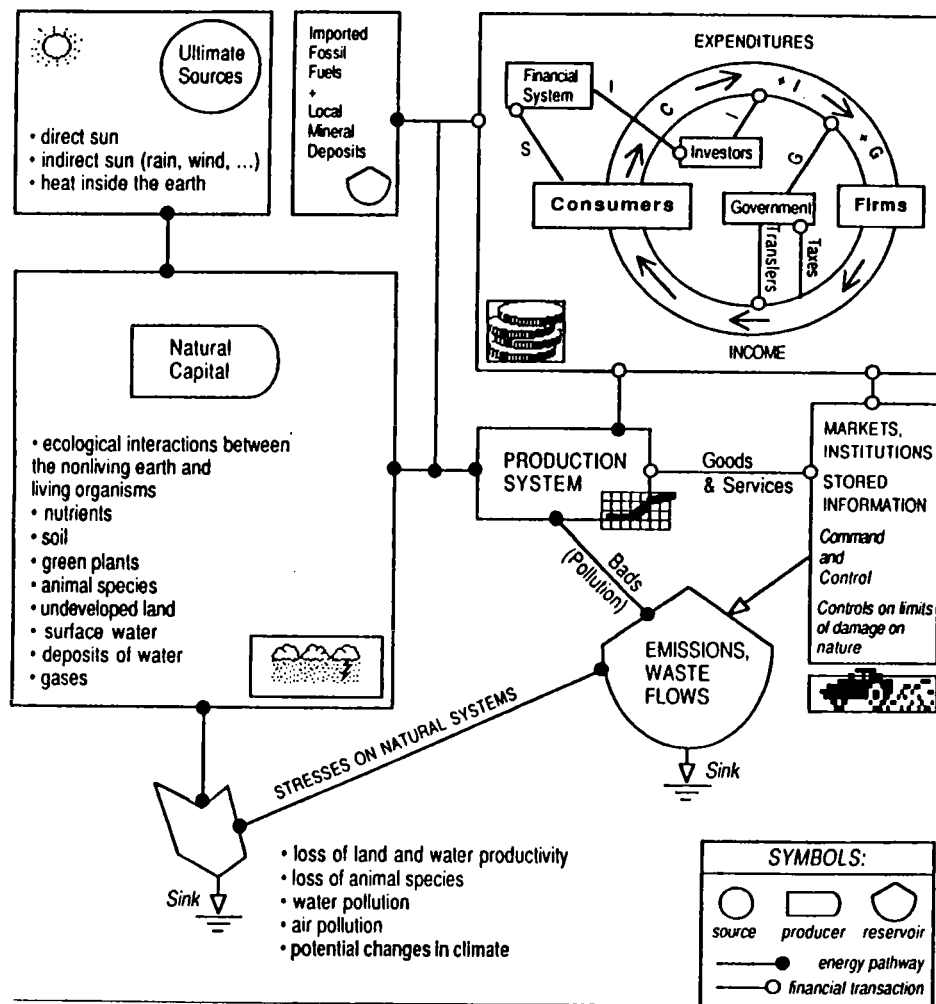
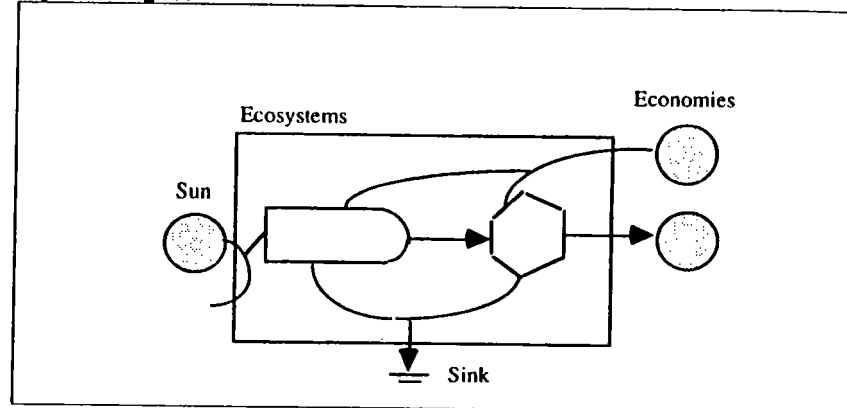


Figure 6.5: Matrix and Systems Diagrams
Pillet, 1994

Matrix Diagram

From \ To	Economy	Environment
Economy	Mainstream Economics	Environmental Economics
Environment	Resource Economics	Systems Ecology

Systems Diagram



Under this perspective, one definitely cannot develop global environmental systems into economically sounded systems. One better has to place the focus on the various matching and diverging points that dynamically occur; that is, on what will possibly emerge, on what will possibly pop up from such interconnections.

This amounts to allowing agents to identify the set of possible descriptions of the risks that humanity faces and to bet on which model of the climate change related risk is correct.

Global environmental systems (assets) cannot be allocated on the marketplace. Therefore, instead of either *laissez-faire* or to let suboptimal policies being implemented—which for sure are biased against the ecological-economic long run—, trading climate change risk positions that are contingent on which model of the change is correct would *interlace* systems that basically are highly differentiated ones (Pillet, 1994). In addition, this ultimately would oblige countries to reveal their true positions on ecological prospects their economies face and want to address (they will basically not be allowed to elude their publicly-professed positions on the global environmental risk, and thus for

instance to free ride on CO₂ abatement strategies) (Chichilnisky, 1994). The existence of markets for the risks from climate change would thus make a country's beliefs consistent with its public positions. This country would not be able without generating some cash cost to sell securities that pay off in the event of climate change not being serious, and buy those paying off if it is serious where this is not its true beliefs (Chichilnisky, 1994, Pillet, 1994). This is an example on how markets for the risks of climate change can make the link with countries' efforts to reduce greenhouse gas emissions.

6.3.3.5 A market framework to respond to collective risks associated to climate change

A market framework with new financial institutions and the trading of risks has been introduced by Cass, Chichilnisky and Wu (1991), Chichilnisky and Heal (1992, 1993) and Chichilnisky (1993b, 1994). It is aimed at addressing two levels of uncertainty in facing the risk of climate change. The first level is world-wide: "What will be the overall impact of climate change on the earth, in terms of how much of the population of the earth is made worse off, and by how much? What is the distribution of agents who are harmed in the economy? Will 60% be harmed, or only 30%? This is a question about the aggregate incidence of damage over the population as a whole". The second level of uncertainty is regional; it is about whether a given community or region is harmed or not by climate change. "It devolves about questions such as: given that 60% of the population will be harmed, will a particular region be harmed or not?" The main reference here is Chichilnisky (1994).

The institutional structure to be developed would use two types of financial instruments in order to deal with the two above-mentioned aspects of the problem. The aim is to obtain an efficient allocation in the face of those risks. One instrument is a *mutual insurance contract* which is tailored to deal with the risks faced on a regional basis by communities contingent on the distribution of harmful effects world-wide. The other one related to *Arrow securities* because we need such securities to deal with these collective risks induced by uncertainty about the overall distribution of adverse effects.

A *mutual insurance contract* is an agreement between parties subject to similar risks that those who are harmed will be compensated by those who are not.⁵ In the climate change context, one can think of groups of communities subject to the possible impact of that change, with those unharmed compensating the others. To illustrate, the Alliance of Small Island States (AOSIS) has proposed that

⁵ Examples are agricultural cooperatives of the type recorded in Europe at least since the fifteenth century, and the nineteenth century UK workers' associations and friendly societies. These involved agreements between a group of workers that if one were sick and unable to work, he or she would be compensated by the others.

an "International Insurance Pool" be established to cover climate change impacts. The Pool would take the financial burden suffered by affected developing countries and distribute it amongst the industrialised countries. The members of the Pool would be divided into two groups. The first group would consist of low-lying coastal countries and small island states that would receive insurance coverage from the fund. The second group would include industrialised countries who would contribute funds (after IUCC, 1993).

Mutual insurance contracts would mean making transfers, the size of the latter depending on the overall level of prosperity, and the transfer per se being contingent on the overall incidence of negative effects (in the sense of high or low overall incidence of negative climate change-related events in the population and in ecosystems).

The AOSIS proposal calls for Pool contributions to be collected in 2004, ten years after the Climate Change Convention enters into force—provided the rate of global mean sea-level rise has by then reached an agreed figure. This ten-year delay has been thought to give the funding countries sufficient time to make their initial investments. If sea-levels have not risen too much by the time the ten-year period expires, a review of conditions would be undertaken.⁶

The securities we would need to deal with collective risks induced by uncertainties about the overall distribution of adverse effects would pay out if and only if there were a particular frequency of damage in the world as a whole. This would involve identifying the set of possible descriptions of the risks that humanity as a whole face, which are called here collective risks. Climate-related events such as floods, tropical storms or certain temperature patterns are examples.

Introducing, therefore, securities whose payoffs depend on which description of the risk is correct would allow agents to bet on which model of the risk is correct. A similar financial instrument is already in use to hedge environmental uncertainties and risks: *CAT Futures* (for Catastrophe Futures). This instrument is a security which pays contingent on the frequency of the occurrence of a major weather risk, such as earthquakes in the West Coast of the US, tornadoes in the East Coast, and floods in the Midwest. CAT Futures are traded by insurance companies to hedge against their exposure to major climate risks.⁷

⁶ Others would say: the island countries would have to contribute some funds to the Pool. Note that the AOSIS proposal was presented to the negotiators of the Climate Convention but was not included in the final treaty.

⁷ See footnote # 4.

1 Yet, would insurance companies be able to address climate change risks? Currently not. A new
2 financial structure has to be set up.

3 For the insurance industry, which is used to drive fixed, short-term contracts, climate change intro-
4 duces new circumstances "in ways that mean traditional practice and the old statistical methodologies
5 are no longer adequate". Climate change implies a certain degree of irreducible unpredictability be-
6 yond the category of risk-like uncertainties. For insurance companies, "past experience is no longer a
7 safe guide to the far future" (Ayres and Weaver, 1994; see also Table 6.6 and comments).

8 To conclude, the markets just described can provide a natural mechanism for reconciling differ-
9 ences in assessments of the likelihood of important climate changes between countries, and for testing
10 the conviction behind publicly-stated positions (Chichilnisky, 1994). Accordingly, this could be help-
11 ful in advancing negotiations between industrial countries with different perceptions of the risks, such
12 as the US and the EU (also see Pillet, 1994)⁸ as well as in correcting the North-South balance
13 between the causes of climate risks, which are the industrial countries emissions of carbon, and the
14 ecological-economic impacts of the risks, which are believed to be more serious in developing
15 countries.

16 Now, risks induced by strong uncertainties from climate change are to be assessed before giving
17 precedence to risk management and the selection of policy options.

⁸ Suppose for example the US believes it most likely that there will be little climate change, and the European Union believes otherwise. Then through the market for securities whose payoffs depend on which description of climate change is correct, the US will naturally sell insurance to the EU. The US would wish to be a seller of securities which pay if climate change is serious, because of its belief that this event will not occur, and a buyer of securities that pay if it is not, because of its belief that this will be the outcome. The EU would be on the opposite sides of these markets. (Chichilnisky, 1994).

Section 6.4

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6.4 Risk Analysis of Climate Change

So far, we have dealt with climate change globally. We now want to address the subdivision of the problem of global climate change into independent parts, thus leaving basal economic views for a more practical analysis of the risks induced by strong uncertainties from climate change. This means addressing quantitative climate change risk analysis. We will then give precedence to risk management and public decision making as such.

Although it is usual to separate risk assessment from risk management (National Research Council, 1993) and normative risk analysis (see 6.3.2.2, supra), risk assessment must contain enough information for the manager to appropriately decide at what point on the probability distribution of the final answer of an assessment he should take an action (Shlyakhter et al., 1994). This section is devoted to the analytic approach to the risks from climate change. By showing how the problem "can be decoupled into discrete, separable modules that can receive individual attention", and using a general layout of the progression of the physical processes involved with respect to the potential risks from global warming (Shlyakhter et al, 1994, Kates et al., 1985), it will further make the analysis malleable for the decision maker.

The key views in this section are, therefore, (a) to move beyond globally considered climate change (as well as beyond isolated studies of the various parts of the problem), (b) to propagate uncertainties through the analysis and to reflect them in the conclusion, (c) to express reliability with which the various pieces of the climate puzzle are understood—and uncertainties are propagated (Dowlatabadi and Morgan, 1993). This will be accompanied by decision making representations, sequential decisions strategies, anticipatory behaviour exploration, and portfolio analysis analogies.

6.4.1 Integrated Climate Change Risk Assessment

An integrated analysis "should be done in such a way as to enable all aspects of a problem to be considered simultaneously" (Shlyakhter et al., 1994). This does not mean that such an integrated assessment ought to incorporate *all* the elements, processes, and feedbacks that are likely to be important. "In an ideal world, where computers are infinitely fast and cheap, an integrated assessment would incorporate the most detailed available representations of each element of the climate problem. It would incorporate a calculable general equilibrium model of the world economy, three-dimensional models of atmospheric chemistry and dispersal, a coupled ocean-atmosphere global circulation model, gen-

eral coupled ecological systems models, and models of social preferences and dynamics. Each of these represents the holy grail of a particular discipline. To date, none has been attained with sufficient satisfaction" (Dowlatabadi and Morgan, 1993; see also Table 6.7). Simply, this is basically concerned with the old paradox of the map and the territory: the map will never be as detailed as territory is; indeed, to the limit, the territory per se is *the* ultimate map, or the map, the territory.

Table 6.7—Climate Change Integrated Assessment Main Models to Date*

Name, Authorship	Background	Comment
IMAGE, Rothmans et al. (1990)	Edmonds-Reilly model (1984)	Rich description of the physical world
ESCAPE	IMAGE	Great deal of details; no characterisation of uncertainties
DICE, Nordhaus (1992)	Economic estimates, cost-effectiveness	No estimates of non-market benefits
GLOBAL 2100, Manne & Richels (1992)	Energy model, regions of the world	Uncertainty is addressed
CETA, Peck & Teisberg (1992)	Global 2100	Based on Nordhaus' estimates; value of information addressed and computed; characterisation of uncertainties
PAGE, Hope et al., 1993	Costs, market damages; economic activities not modelled	Problem of scientific and economic uncertainties recognised
ICAM-1, Carnegie Mellon	Stochastic simulation in the DEMOS modelling environment	Uncertainties processed through the model; major feedbacks integrated

*Established from various sources. Note that, typically, models are used to use a single impact metric.

Nevertheless, it is of paramount importance to recall that, faced with similar problems, the policy research community has usually, and typically, *modelled what was understood*—and "waved their hands at the rest". "The result has often been that the policy discussion has focused on what we know, rather than what is important" (Dowlatabadi and Morgan, 1993). For instance, to avoid this difficulty, subjective expert judgements about poorly understood parts of the problem are being integrated in new policy models that currently are developed at several institutions.

We will now focus on a climate change integrated risk analysis proposed by Shlyakhter et al. (1994). The view here is to show important problem linkages between the different parts of the climate change problem, and to find how they may be decoupled into discrete, separable modules while paying special attention to the cascading of uncertainties.

Then, policy alternatives will be checked.

6.4.1.1 Analysing the risks of global climate change

For the assessment of the potential risks of global warming, Shlyakhter, Valverde Jr., and Wilson (1994) use a general layout of the progression of the physical processes involved (see Figure 6.6).

The processes leading to global warming are divided into a sequence of roughly independent steps. The diagram on Figure 6.6 is simplified for clarity. The steps of the main sequence run from top to bottom by the numbers 1 to 6 referred to in the text.

The equation below Figure 6.6 represents the outcome as the product of the six factors that correspond to those steps.

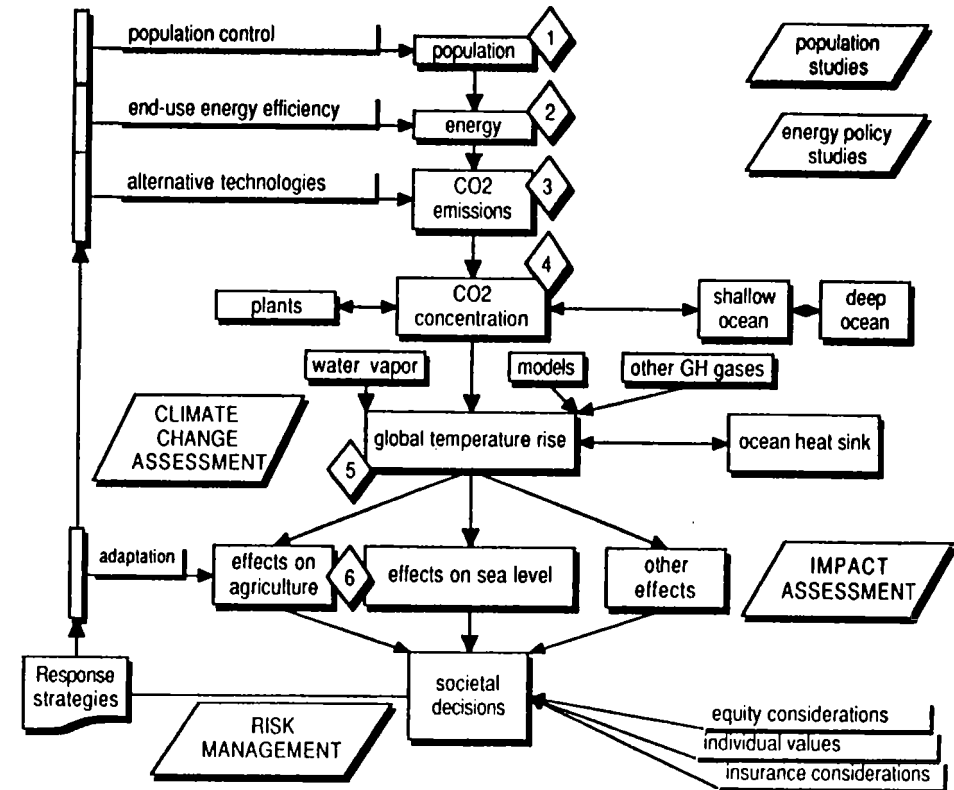
To some extent, the layout and formula bring together ongoing calculations of global warming. Examples are the report from Working Group of the IPCC on Response Strategies (Bernthal, 1990) which discusses various energy scenarios for the world that encompass Factors 1, 2 and 3; the scientific discussion of the fate of CO₂ in the environment designates Factor 4; the output of General Circulation Models—with attached controversy—is represented by Factor 5; report of the IPCC Working Group I (Houghton et al., 1990) describes Factors 4, 5, and 6; the IPCC Working Group II (Tegart et al., 1990) also addressed Factor 6 through the study of the various impacts of global change. Consider Factors 1-6 in equation (1) that goes with Figure 6.6.

The first Factor is the world population (*popul*); the second Factor is energy production (*energy*) per capita (*person*); the third Factor is the total CO₂ emissions (*CO₂_{emi}*) per unit of energy production (*energy*); the fourth factor is the increase of atmospheric concentration of CO₂ per unit emission (*CO₂_{atmos}*); the fifth factor is the temperature rise (ΔT) per unit of CO₂ concentration (*CO₂_{atmos}*); the sixth Factor is an environmental outcome (Δh) (such as sea level rise) per unit temperature rise (ΔT). These factors are discussed in other chapters of this report.

Equation (1) indicates the following: the product of the first two factors is the world energy use; the product of the factors one through three is the total of the world CO₂; the product of factors one through four is CO₂ concentration, and so on. In writing Equation 1, the authors explicitly assumes that each factor were independent of all the others (Shlyakhter et al., 1994).

Units in Equation (1) are balanced automatically. In addition, one must recognise that branchings are possible, for instance before Factor 6, that alternative diagrams may be discussed for different possible outcomes, and that economic activities—but for energy, agriculture, and response strategies—as well as correlations between the different factors are neglected.

Figure 6.6: Layout of the progression of the physical processes involved in global warming. This framework consists of three parts: climate change assessment, impact assessment, and risk management. Population and energy policy studies together with the models of climate system serve as inputs to climate change assessments. Impact assessment is concerned with the effects of climate change. World population, energy consumption and CO₂ emissions appear as endpoints in risk management decisions. Redrawn after Shlyakhter et al. (1994).



Equation (1) and factors 1-6 as referred to on Figure 6.6

$$\Delta h = \text{Popul} \cdot \left(\frac{\text{energy}}{\text{person}} \right) \cdot \left(\frac{\text{CO}_{2\text{emi}}}{\text{energy}} \right) \cdot \left(\frac{\text{CO}_{2\text{atmos}}}{\text{CO}_{2\text{emi}}} \right) \cdot \left(\frac{\Delta T}{\text{CO}_{2\text{atmos}}} \right) \cdot \left(\frac{\Delta h}{\Delta T} \right)$$

6.4.1.2 Combining uncertainties

One cannot deal with uncertainties from climate change like in other fields. To simplify matters, consider two classes of uncertainties (see Section 1) as follows: risk-like uncertainties and "strong" uncertainties. To be practical, we consider here that the first class of uncertainties branches into two types (a) "stochastic uncertainties", and (b) "uncertainties of fact".¹ The second class still is referred to as the class of "strong" uncertainties, otherwise called "unexpected" uncertainties. The uncertainties that are attached to climate change are factual, stochastic, and unexpected in character.

The point is to address all types of uncertainties as they cascade throughout the model. The first class of uncertainties can be dealt with by drawing upon experience from two other fields (the study of safety of nuclear power stations or of chemical manufacturing plants, and calculations of the risks of chemical carcinogens). To illustrate, the absence of information concerning regional impacts would make them randomly distributed; however, based on the hypothesis of a CO₂ doubling, the scatter of predictions for the sensitivity of climate system would be comparable to the uncertainty of the slope of a dose-response curve. The second class of uncertainties will necessitate expanding the uncertainty distribution, hedging against unsuspected uncertainties, and encouraging people to behave in productive ways that are *not* predictable from past behaviour (Shlyakhter et al., 1994).

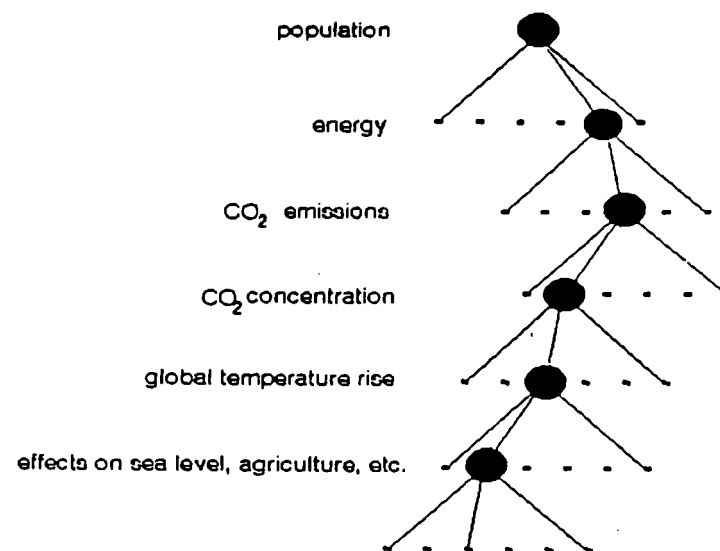
Each Factor in Figure 6.6 and Equation (1) has attached uncertainties of the two classes. According to Shlyakhter et al., "an important issue is what these uncertainties are and how to combine them to give the overall, or total, uncertainty in the final outcome"—in short, the uncertainty signature of climate change induced risks.

Schneider (1983), as mentioned by Shlyakhter et al., "suggests that uncertainties be combined by considering each component of the overall CO₂ problem as part of a cascading pyramid of uncertainties" (Shlyakhter et al., 1994). Figure 6.7 shows how this probability tree might look like.²

¹ "A statement that a cancer risk is 10⁻⁶ (one in a million) per life means that an individual is unlikely to develop cancer from a given exposure to a particular chemical, but one person in a million will. Thus, there is a «stochastic uncertainty» for a given individual." "A different type of uncertainty is the uncertainty of the slope of a dose-response curve, which gives the projected number of cancers per unit exposure. As typically construed, this slope, regardless of its value, is the same for all exposed individuals. This type of uncertainty is sometimes referred to as «uncertainty of fact», to distinguish it from stochastic uncertainty." (Shlyakhter et al., 1994). Both types are risk-like uncertainties with respect to the ways and means used to make predictions.

² Note that the possible correlations between the different factors in Equation (1) are neglected though climate change associated risks have been basically defined as correlative risks; this adds to the complication—see Section 6.1

Figure 6.7: Cascading of uncertainties (Shlyakhter et al., 1994)



There is an infinite number of possible values for each factor. For each elements in Figure 6.7, the authors show three choices: low, medium, and high. This makes 729 possible scenarios (36). It would not be efficient to evaluate each of the 729 scenarios. Instead, the choice of most assessors of global warming "is to evaluate the uncertainties by considering a continuum of choices for each factor, governed by a probability distribution". Shlyakhter et al. (1994) "suggest that the three values chosen for each factor in Figure 6.7 be the median and two extreme points of a distribution, one of each side of the mean." Their position is less conservative than usually done through risk assessments in the US where for instance the EPA's approach to uncertainty propagation sticks to a conservative upper limit for each risk factor, that are then multiplied to arrive at a total risk level for regulation.

The probability tree procedure is more general and delivers more information to the risk manager. Mathematically, assuming independence of each factor, the probability distributions can be combined similarly to the event tree procedure developed by Rasmussen for calculating the probability of a nuclear reactor or other industrial plant accident (Atomic Energy Commission, 1975). This, however, does not preclude the recognition that "strong" uncertainties cannot be treated in a statistical fashion. After the combined uncertainty for the impact of interest is evaluated, one can hedge against the

unaccounted errors. This can be done, according to Shlyakhter *et al.*, by assuming an exponential distribution instead of a normal distribution or errors and deriving an appropriate safety factor. "A clear message from the history of science is that unexpected uncertainties in models and parameters are quite common, and that new results are often far away from old values. In interpreting the predictions of climate change models, scientists recognise this, and often recommend cautious action accordingly" (Ibid.).

Accordingly, one can stipulate that, in principle, mitigation strategies would be concerned by the first class of risks while betting on climate states (insurance and risk trading considerations) would deal with strong/unexpected uncertainties.

Yet, according to such a static model, it is supposed that the decision on what, if anything, to do is made simultaneously with the assessment. Under the climate change problem, decisions on what to do will be made frequently over time. The risk assessment as well as the decision-making process must then constitute a tâtonnement process over time. This is discussed further in Subsection 6.4.2.

6.4.1.3 Evaluation of policy alternatives

Evaluating policy alternatives consists in statuting about policy objectives and research priorities. Under the climate change problem, this might lead to revise some decision rules, either.

Basically, the policy research community is used to think that:

- when a policy objective has been identified, identify the most effective policy strategy for meeting that objective; with respect to the climate change problem, this would mean posing the question of which strategy with the greatest potential for
 - population,
 - energy,
 - CO₂ emissions,
 - CO₂ concentration,
 - each main effect?
- when uncertainties have been identified: identify key areas where better information is needed; this means considering the value of further refining information as well as expert judgements that are needed
 - about poorly understood parts of the problems,

- of returns to policy-motivated research investment (Dowlatabadi and Morgan, 1993).

Yet, identifying a policy objective is subject to the reliability one can put on results from models and calculations. A basic question is then: Is there any unambiguously indicated dominant abatement schedule among choices, say, ranging from no abatement to limiting emissions of CO₂ to 50% of 1990 levels? Answers range from:

- (a) ICAM-1: NO; to
- (b) PAGE: YES; despite uncertainty, Europe should unilaterally adopt stringent abatement and adaptation programs.

Under these circumstances, decision rules are of crucial importance. To illustrate, consider two quite different situations.

- (a) The expected value decision rule. It maximises the expected utility value under some (budgetary and/or environmental) constraint. This rule might identify a per capita emission limit as the appropriate policy objective. Situation : expected welfare effects would be high. An "economist" in the developed world might stick to this rule.

- (b) The precautionary principle, which says: minimise the worst possible outcome.

This principle might identify stringent reduction in greenhouse gas emission as the appropriate policy objective. Situation: expected ecological impacts would be high. An "environmentalist" in the developed world might stick to this principle.

These rules do not apply a priori. The risk assessment of potential climate changes will help at avoiding this bias by giving estimates of the possible outcomes.

Yet, these results must be communicated to whoever makes decision about options for mitigation or other parallel tasks such as insurance considerations. An open question is: *are policy makers better served by best guess scenarios* for each factor (population growth, energy production, temperature increase,...) *than by probability distributions of these estimates?* Shlyakhter *et al.* use the latter approach. "It has been frequently pointed out that different decisions will require different degrees of caution. More formally, acceptable risk levels will be set at different percentiles of the final probability distribution of outcomes. Policy analysts and decision-makers can then draw distinctions between those scenarios that are *probable* and those that are *possible* but extremely unlikely. *Those risks that fall below a particular threshold of probability*—and thereby are ignored by a particular

group or society—are called «*de minimis*» risks. How societies and governments decide what constitutes *de minimis* risk in particular situations or contexts is largely a matter of political judgement" (Shlyakhter et al.).

Shlyakhter, Valverde Jr., and Wilson (1994) have summarised their point as follows: "Again, an analogy can be made with nuclear reactor safety. In its early days, the Atomic Energy Commission defined a set of «maximum credible accidents» and demanded that reactor designers introduce a safety system to prevent these accidents, but there remains a probability of the safety systems failing simultaneously with the accident. An estimation of these individual probabilities and their combinations becomes the core of probabilistic risk assessment (Atomic Energy Commission, 1975). It is therefore crucial to determine the specific questions that the risk analysis is intended to illuminate. [The question is:] «At what probability of a serious effect should society take action?» Is there, in other words, a *de minimis* risk? Although there is no clear definition of a *de minimis* risk, it can generally be seen to be closely akin to a related concept, namely, the probability of «surprise». Although many conceptions and definitions are possible, our use of the word *surprise* is meant to denote those situations where the true values of a particular uncertain parameter, e.g., the slope of a dose-response curve, climate sensitivity to CO₂ doubling, etc., appear at least 2.6 standard deviations away from its current «best guess» value. For a random variable that is assumed to be normally distributed, the probability that the «true» value is more than 2.6 standard deviations from the current «best guess» is just 1 percent. (...) It is interesting to note that public opinion polls suggest that many people are unconcerned about a 5 percent chance of a climate-related catastrophe within their lifetime, although they are concerned about a 1 percent chance of a nuclear accident. We also note that an airliner with a calculated chance of failure far lower than 5 percent in its 70 year life would not be allowed to fly in commercial service."

6.4.2 Decision Making Representations

Policies for limiting climate change due to greenhouse-gas emissions are neither one-shot decisions nor go/not go type of decision making. Questions better are on whether to take action now or later, on how stringent any emissions reductions, should be in the near and long term, on how and how much to revise later reductions policies implemented now as scientific understanding of climate change improves, on how to "sequence" acting and learning processes. Here we consider how a sequential

decision making might look like, then, to which extend anticipatory behaviour already are at work. Last, a portfolio analysis analogy is made with respect to the current debate on policies for limiting potential climate changes.

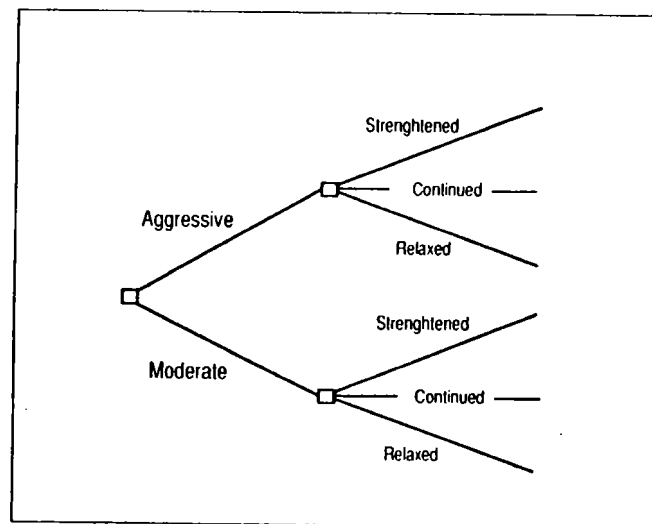
6.4.2.1 Sequential decision making strategies

Our example of sequential decision making strategy draw on Hammitt et al., 1992. According to well publicised works (see also for instance Singer et al., 1991, Manne and Richels, 1991, 1992, IUCC, 1993, Richels, 1994, Peck, 1994), first decisions might be to take those actions where the cost is not high while considering more aggressive-reduction policies.

First, energy conservation represents a set of low-cost, quickly implemented policies. To illustrate, if adopted at t_0 , energy intensity falls 30% over 20 years (Hammitt et al., 1992). This corresponds to some minimal agreement made of two complementary actions : conserve energy by discouraging wasteful use globally, and improve efficiency in energy use (Singer et al., 1991).

Figure 6.7: Decision tree for sequential policy choice.

At the beginning of the first period, (1992) either the moderate reduction or aggressive reduction near-term abatement policy is selected. At the beginning of the second period (2002), uncertainties about climate sensitivity and the damages of climate change are substantially resolved and the chosen policy is amended to limit climate change to the "optimal" level. Hammitt et al., (1992).



Second, fuel switching represents a more aggressive-reduction policy. It is a set of high-cost, slowly implemented emission-reduction technologies. They are produced by long-lived capital equipment using either emitting or non-emitting technologies (fossil fuel vs. nuclear, solar, biomass). Both have construction periods of about 10 years, and an operating period of roughly 30 years (Hammitt et al., 1992). The motto is: use non-fossil fuel energy sources wherever this makes economic sense (Singer et al., 1991). "The policy decisions are whether to begin substituting non-emitting or emitting equipment, and if so, the rate at which to substitute, specified as the transition half-life, or the time until half the capital stock then operating is non-emitting" (Hammitt et al., 1992).

Hammitt *et al.* consider two near-term policies, aggressive and moderate reduction.

Under the aggressive-reduction policy, conservation and fuel-switching are adopted together starting in 1992.

Under the moderate-reduction policy, only the conservation policy is adopted and implemented in 1992. At the beginning of the second period (2002), uncertainties about climate sensitivity and the damages of climate change are thought to be substantially resolved and the chosen policy is amended to limit climate change to some "optimal" level.

Sequential *act-then-learn* strategies for decision making have also been constructed by Manne and Richels (1991, 1992) in the energy sector. Decisions are made at discrete points in time, namely every decade. The value of new information then depends on changes in the probabilities assigned to each scenario before and after the study. "If the probabilities of three scenarios remain equal, then the study's value is zero; if, on the other hand, only one scenario can be selected, a study can be worth as much as 100 billion dollars" (Shlyakhter et al., 1994).

Critics of such strategies stress that they are sensible only if something is done in the time between the discrete assessments (Shlyakhter et al., 1994), and that a 10-yr. delay may have little effect on the ensuing climate profile (Schlesinger and Jiang, 1991)—thus "the rate at which emissions can be reduced may be more important than when reductions begin" (Hammitt et al., 1992).

6.4.2.2 Anticipatory behaviour exploration

Business-as-usual scenarios play a central role in the current greenhouse debate. They constitute "baselines" which are supposed to deliver the accurate description of *how emissions evolve in the absence of carbon constraints*. "By indicating how much carbon will be deposited in the atmosphere

if emissions continue unabated, the baseline provides a point of reference for evaluating the efficacy of strategies to limit emissions" (Manne and Richels, 1993).

Yet, the models used for producing baseline projections all apply deterministic approaches (Energy Modelling Forum, 1993); that is, one acts as if technology choices were made once and for all. In other words, when applying models, one acts as if all uncertainty relative to climate change issues were fully resolved at the time one starts to compute projections.

What is at stake in the debate?

At the time when climate change was a purely scientific issue, business as usual ran unconstrained. Today, business as usual is facing uncertainty about the possibility of a carbon constraint. The opportunity to learn the state of the world before taking action is not at hand. Therefore, "in the absence of assurances that no constraint will be imposed, investors are likely to opt for a less carbon-intensive supply and demand-side mix" (Manne and Richels, 1993).

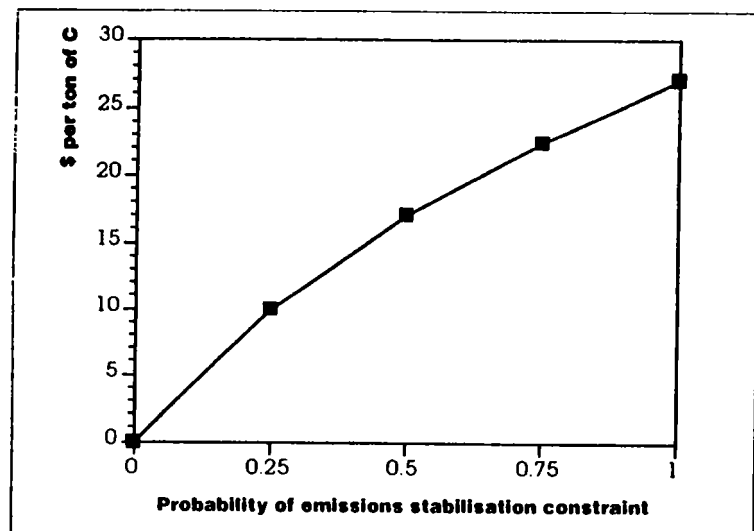
It turns out that *usual* "business-as-usual" scenarios deliver erroneous baselines, and thus references "for evaluating the efficacy of strategies to limit emissions". In particular, they overestimate emissions. Two which extend?

Uncertainty across scenarios has been visited through sensitivity analyses (Nordhaus and Yohe, 1983, Edmonds and Reilly, 1986). It is not at issue here. Specifically, we are interested with uncertainty *within* scenarios. Uncertainty within scenarios means, at least for those periods in which investors might weight the possibility of a carbon constraint, that the threat of emission limits can be an incentive to invest in less carbon-intensive alternatives, that it can impact long-lived technology choices.

In principle, the higher the probability of a carbon constraint, the greater will be the impact. In other words, the higher the likelihood of a constraint on future emissions, and consequently the more the investors proficiently anticipate future limits, the higher will be the "tax" they currently will implicitly account for. Indeed, the purpose of a carbon tax is to raise the price of carbon-intensive fuels in order to induce fuel switching towards less carbon-intensive energy sources. The anticipatory behaviour on the part of energy and, more generally, industry investors, leads to the same result.

It is interesting to stress that the purpose of any true environmental tax is to steer such a behaviour, not to let the tax be paid (as taxpayers do).

Figure 6.8: Implicit Tax on Carbon in the Year 2000
Drawn after Manne and Richels (1993)



Looking ahead, one can easily imagine the relationships between the probability of emissions stabilisation constraint and the implicit tax in dollars per ton of carbon. Such a relationship is plotted on the figure above. The numbers on the y-axis are numbers computed by Manne and Richels (1993) for the United States energy sector in the year 2000. According to the calculations, the key number for the US is a carbon tax of \$17.50 per ton for a 50/50 confidence on future emission constraints. This means that, in the Manne and Richels' example, US energy sector decision makers are "acting as though a carbon tax of \$17.50 per ton were already in place".

A \$17.50/t C tax is analogue to a \$4.73/t CO₂ tax. In contrast to proposed carbon/energy taxes, the US implicit carbon tax is about one fifth of the EU 1990-2000 \$22.4/t CO₂ tax, one fifth of the Swiss 2025 emissions stabilisation \$20/t CO₂ tax, and more than sixty per cent of the OECD (but Japan) 2010/2050 stabilisation objective at 1990 emission level \$13.5/t CO₂ tax—to list a few examples (Pillet, 1993b).

In sum, it turns out that emissions are reduced by 2000 relative to usual baseline scenarios although maybe the true tax (the constraint) will not take effect by this date. This means that

- 1 alternatives to usual "business-as-usual" scenarios must be computed in as far as one needs
- 2 references for evaluating the efficacy of ongoing as well as programmed strategies to limit emissions.

3 6.4.2.3 Portfolio analysis analogy for climate change decision making (after Haites, 1994)

4 Numerous policy measures are available to limit the impacts of climate change. Countries will typi-
 5 cally implement several of these policy measures since no one measure is clearly superior. The deci-
 6 sion then is to choose the portfolio of policy measures best suited to the country's circumstances and
 7 to adjust the portfolio over time in response to new developments.

8 Although governments will be making climate change decisions for most of the next century, this
 9 does not mean that they have unlimited opportunities to adjust the size and mix of their portfolio of
 10 climate change policies. The total resources devoted to measures to limit climate change (the size of
 11 the portfolio) and the mix of measures implemented (the mix of the portfolio) cannot be changed as
 12 often as governments deem appropriate because of lock-in effects as well as other time-, attitude-, and
 13 scientific results-related factors. In many cases, instead of making decisions, options will be taken.

14 In this respect, the key for selecting an optimal portfolio is to understand how the options interact
 15 —e.g., better greenhouse information will influence technology development and emission reduction
 16 decisions (Manne and Richels, 1993).

17 In principle, the policy measures/options available to countries to limit climate change and its im-
 18 pacts include:

- 19 • climate research aimed at better understanding the causes and impacts of climate change;
- 20 • technology research aimed at improving the cost-effectiveness of greenhouse gas mitigation
- 21 technologies such as energy efficiency and non-fossil energy sources;
- 22 • joint implementation, technology transfer and other forms of international cooperation to limit
- 23 climate change;
- 24 • phasing out existing policies, such as subsidies to fossil fuels, that reduce welfare and directly
- 25 of indirectly increase greenhouse gas emissions;
- 26 • measures to reduce emissions, or increase sequestration, of greenhouse gases,
- 27 • measures to adapt to the consequences of climate change; and
- 28 • insurance orchestration to hedge against strong/unexpected uncertainties.

1 The specific policy measures available vary from country to country; research capabilities vary,
 2 the inefficient existing policies vary, the costs and availability of measures to reduce greenhouse gas
 3 emissions vary, the costs and availability of measures to increase sequestration of greenhouse gases
 4 vary, the damages due to climatic change and the measures for adapting to these damages vary.

5 Government decisions concerning the portfolio of climate change policies must consider the
 6 different types of uncertainties associated with climate change and with the policy measures. The
 7 timing, magnitude and characteristics of climate change, particularly as they affect a specific country,
 8 are uncertain. The costs and effectiveness of policies aimed at limiting climate change are also
 9 uncertain. What will be the nature, magnitude and timing of damage due to climate change? What
 10 will we learn about climate change given a particular research budget? Will technology research lead
 11 to more cost-effective mitigation measures? Will other countries abide by their commitments to limit
 12 climate change? Such uncertainties can never be eliminated, but they must be considered in the
 13 selection of climate change policies and policy options.

14 A portfolio manager attempts to get the best return given a level of risk (as derived from a given
 15 level of uncertainty of a given type). The appropriate level of risk can be derived from the investor's
 16 assets using assumptions about maximising expected value behaviour. The investor can also impose
 17 constraints on the portfolio to reflect his or her preferences. Investing some or all of the funds in
 18 "environmentally friendly" assets or prohibiting investments in specified industries, regions, or assets
 19 for ethical reasons are examples of such restrictions.

20 Countries likewise will select a portfolio of climate change policies that reflect, at least implicitly,
 21 a variety of objectives and constraints. A country may look for the economically optimal portfolio of
 22 climate change policies. However, considerations of the impacts of the policy mix on different socio-
 23 economic groups, international equity, and intergenerational equity are likely to come into play.
 24 These objectives will have different weights and will vary from country to country.

25 An operational model to analyse the optimal portfolio of climate change policies for a country is
 26 not feasible given the state of our knowledge. But even the sparse information on the expected costs
 27 and benefits of some to the broad policy options can yield some useful insights.

- 28 • Peck and Teisberg (1993), and Manne and Richels (1993) have estimated the value of spending
 29 on climate research. It is shown that the expected return is several times the current level of
 30 climate research spending. The same analysis could be performed for technology research. To

1 better encounter uncertainty, the main idea is to consider spending on climate research and
 2 climate-related technology improvements as an insurance premium, and not as subsidies to be
 3 randomly allocated. Indeed, the key for selecting an optimal portfolio is to understand how the
 4 options interact, e.g., better greenhouse information will influence technology development as
 5 well as emission reduction decisions. If one believes that there are great risks from global
 6 warming and that the insurance premium is negligible, there is little reason to delay. If, on the
 7 contrary, the insurance premium is expensive, it may be worthwhile to pursue alternatives to
 8 immediate cutbacks on emissions (Manne and Richels, 1993).

- 9 • Several researchers compare the costs of unilateral action and international cooperation to ad-
 10 dress climate change. The analyses consistently show large returns to international coopera-
 11 tion. International cooperation should however contain an instrument by which welfare can be
 12 redistributed among nations. If it is not the case, as shown by Pillet et al. (1993), small coun-
 13 tries with a comparative advantage in the production of clean commodities and a high emis-
 14 sions reduction marginal cost, might have arguments for doing nothing and thus adopting a
 15 free-rider behaviour until a complete international climate agreement is concluded.
- 16 • An OECD analysis of the effects of phasing out existing inefficient policies suggested that
 17 greenhouse gas emissions would be reduced by over 25% with a net economic benefit. In
 18 many cases eliminating existing subsidies is politically very difficult, nevertheless a large net
 19 benefit is possible from this policy.
- 20 • An emissions reduction supply curve or other analysis of the costs and potential emissions re-
 21 ductions that could be achieved through a wide range of specific measures has been conducted
 22 for many countries. Virtually every study shows that some emissions reductions are possible
 23 at very low, possibly negative, cost. Many of the measures also yield other environmental
 24 benefits such as reductions in acid rain, ground-level ozone precursors, and toxic discharges.
- 25 • Adaptation measures that reduce some of the damage due to climate change are available in
 26 some countries; building dikes to protect low lying coastal areas from sea level rise for exam-
 27 ple. Such measures can be implemented where they cost less than the damage that would oth-
 28 erwise occur.
- 29 • Climate change insurance contracts and transfers, and trading of risk positions between
 30 regions and countries can be referred to to face unexpected uncertainties and collective risks.

It turns out that three main forms of policy options dominate current discussions: continued intensive science research to reduce climate and impact uncertainties, development of new supply and conservation technologies to reduce abatement costs, and immediate emissions reductions in order to slow down climate changes. The issue for the "option-taker" is not one of either-or but one of finding the right blend of options. Policy makers must decide how to divide greenhouse spending among competing needs. What portion goes to resolving climate uncertainties? What portion goes to technology development? And what portion goes to immediate abatement of emissions? (Richels, 1994). Using the portfolio analysis analogy, a country must use the available information to decide upon the size of its investment in climate change limitation and on the allocation of that investment across policy measures.

The size of the investment will reflect the country's objectives and its obligations under international agreements (see UN Framework Convention on Climate Change, 1992). Assume that the country has ratified an international agreement that specifies national greenhouse gas emissions limits. Then the size of its climate change investment reflects the most cost-effective means of achieving the country's agreed emissions limit plus expenditures on research and adaptation measures. In the absence of an international agreement a country may have little alternative but to implement necessary adaptation measures. Since almost every country accounts for only a small fraction of global greenhouse gas emissions, unilateral actions will have only a negligible effect on the pace and extent of climate change. No country, acting alone will be able to appreciably reduce the damage it suffers due to climate change except by implementing adaptation measures. This suggests that all countries have an economic incentive to reduce emissions of greenhouse gas emissions.

At a global level, well formulated benefit-cost analyses can help establish an appropriate level of climate change investment. Climate change policy does not involve a one-time choice—or some go/not go type of decision—between distinct, long-term options (do nothing or implement policy "X" for the next century), the types of decisions to which benefit-cost analysis has historically been applied. Since climate change policy can be modified frequently and incrementally, the "option values" of decisions must also be considered (the option value of deferring action on climate change can be interpreted as an insurance premium to cover the cost of damages that may result).

The level of their investment in climate change policy will be influenced by factors beyond the strictly economic considerations mentioned above. Expected damage to ecosystems, expected sea

level rise, potential socio-economic impacts, international equity concerns, intergenerational equity, and economic development strategies based on development of mitigation and adaptation technologies are examples of other considerations that may influence a country's climate change limitation spending.

Incorporating option values into the benefit-cost analyses of the policy measures indicates that some action on climate change is economically justified by every country. No country can be confident that it will not incur damage as a result of climate change. Thus, delaying action to limit climate change is an option that has a cost, at least an insurance premium. Every country has available policy measures that have negative or very low costs after accounting for any associated benefits. Thus every country has some climate change mitigation measures that are economically justified.

Normally, the mix of assets in the portfolio is adjusted so that the risk-return ratio is equal at the margin. As discussed above, only sketchy information is available on the expected costs and benefits of the main policy measures. The variability of the costs and benefits for these broad policy options is not known. Governments can make subjective assessments of the variability of costs and benefits of different policy measures. The risks associated with phasing out existing inefficient programs or implementing energy-efficiency measures are lower than those associated with reforestation to sequester carbon or construction of sea walls. The latter offer only climate change benefits while the former also yield other benefits.

Governments can change their portfolio of climate change policies in response to new information and developments. Indeed, both the investment in climate change limitation and the mix of policies should change over time. For example, once inefficient existing policies have been eliminated they drop out of the portfolio.

6.4.3 (Drafted) Conclusions

Conclusions could be drafted around the following topics:

- exploration of interactions and correlations between the different parts of the problem,
- assessment of the propagation of uncertainties through the analysis,
- systematic evaluation of climate stabilisation benefits,
- systematic evaluation of non-market costs/benefits of climate change,
- development of multiple impact metrics (integrated ecological-economic approach),

- 1 • probability assessment of risk-like uncertainties,
- 2 • integration of subjective expert judgements about poorly understood parts of the problem, as well
- 3 as about strong uncertainties (as linked for instance to possible abrupt changes and catastrophes),
- 4 • cascading of decision rules to go with portfolio analysis and to be used along with the reliability
- 5 assessment with which the various pieces of the climate puzzle are understood,
- 6 • identifying key areas where better information is needed,
- 7 • further exploring climate change related insurance and risk trading policies.
- 8

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Chap 7 RESPONSE OPTIONS

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A Generic Assessment of Response Options

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1. Introduction

In recent years a host of response policies has been proposed in order to cope with possible climate change. 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.

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 policies (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 integrated 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).

In section 8 the overall policy conclusions will be laid down.

Sections 1-3 therefore provide the methodological base; sections 4-5 the survey of the options, and sections 6-8 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.

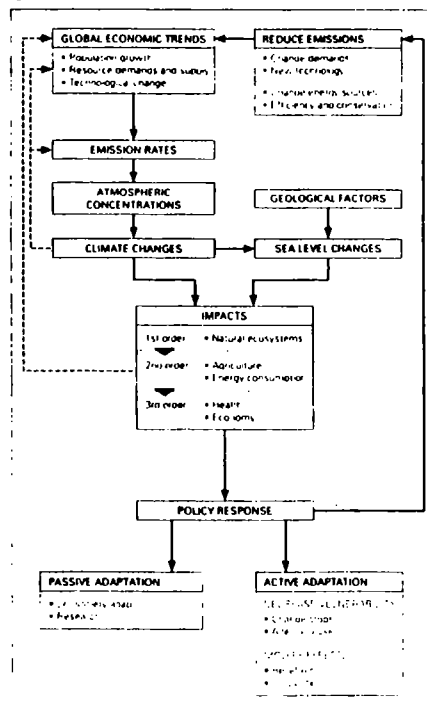


Figure 1. Schematic overview of options available to counter the greenhouse effect and their feedbacks.

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

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

- 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 serious 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. Various types of options may even reinforce each other. A successful population policy as part of a broader policy mix, aimed at reducing birth rates in a populous developing 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 rich industrial country, many technically feasible options for emission reductions may become available and cost-effective. If technological change speeds up in a broad range of economic activities, this may significantly 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. It is commonly acknowledged in this respect that the cost-effectiveness of the various options at the margin 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 insight in 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 viability are therefore highly time and location specific.

In discussing the potential of the various mitigation options a distinction can be made between measures concerning CO₂ and measures concerning other greenhouse gases. A subsequent distinction is between source-reduction and sink-enhancement oriented measures.

The various examples of mitigation options are (except for some 'exotic' 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. fuel switch between fossil fuels
 3. renewable energy
 4. nuclear energy

(1-4 = source-reduction)

 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 is the single largest source of carbon, much of the mitigation effort can be concentrated here. Options 1-4 each address an element 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 character of the energy conversion pro-

cess. 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.¹

A 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.² It may also refer to activities designed to preserve or enhance carbon uptake by soils.

2.2 Adaptation Options

Adaptation is meant to reduce the value of damages from climate change. 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. 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 5 of this report focuses on the former, here 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 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 of changes to be expected. Whereas 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 rapidly, 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 imposed 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 learned 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 industrial situation, and that may pose serious dilemmas to society. Other evolutionary trends and structural adjustment processes, e.g. due to population increase, 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, each of them may be expected also to play an im-

stant role in shaping the economic, political and social system of tomorrow, especially if policy makers' time horizon is only a few decades or even shorter. To illustrate, Western nations may consecutively well face a combination of problems such as urbanization, unemployment, massive international migration, changing patterns of economic competitiveness, and wars and conflicts, to mention only a few of the most important ones, that may easily attract more public and political attention than the climate change issue.

All these problems suggest their own response options, for instance in the sphere of consumption and lifestyle policies, population and migration policies, technology and non-global 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, population policies being one of the clearest examples.

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.

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.

A simple example may serve to illustrate the above point. Suppose a Western donor considers cooperation with a developing country with respect to afforestation in that country. The question may then arise as to what investment/transfer 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 from 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. Moreover, in the assessment attention can 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 measures.

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 significant private no-regrets options as part of the literature suggests.

The practical obstacles for a welfare economic assessment of climate change response options can be particularly large 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 reasons. Three, virtually all 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:

- a) average costs may diminish at a larger scale of application (internal economies of scale);
- b) costs may diminish at a larger scale of application of other options, because of positive external effects (external economies of scale);
- c) costs may diminish as the application time progresses (learning effects);
- d) 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;
- e) costs may diminish, depending on the rate of diffusion of technologies, public education and lifestyle changes, which in themselves 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 emission target, also produce energy and are substituting for traditional fossil energy production. 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).

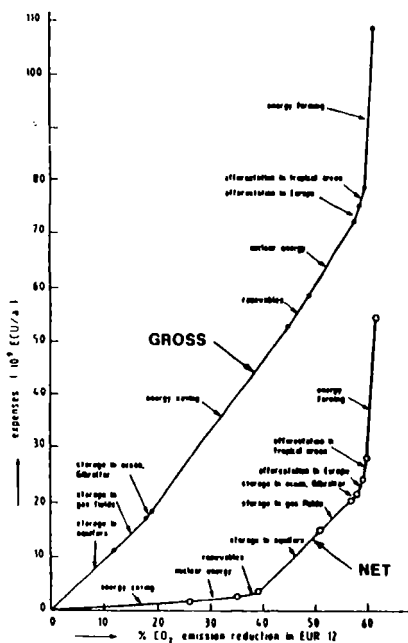


Figure 2. Options for CO₂ emission reduction in the EU, net and gross costs, and effectiveness.

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 one economic and/or (non-global) environmental reason or another, have greenhouse gas emission changes as an (un-)intended 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 (bottom-up) engineering efficiency approach alone may easily create a biased perspective. A more complete (top-down) assessment must recognize different priorities between countries, the impact of externalities, the political acceptability at various levels, and distributional aspects. In this respect there seem to be good reasons to pay attention to the special position of developing countries and 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:

$$CO_2 = (CO_2/E)^x (E/GDP)^x (GDP/P)^x P.$$

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 and/or energy intensity. The need to reduce carbon and energy intensities becomes stronger, the higher the growth rate of population and the more ambitiously targets are set.

with respect to welfare 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 autonomously. Energy intensity per unit 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. 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 electric refrigerators became nearly 67% more efficient; the efficiency of motorcars increased from around 9.4 to about 13 km/litre. 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 Brazil, Pakistan, India and Malaysia (+20%, +26%, +24% and +48% during 1970-1988, according to Imran and Barnes, 1990), and in various others, energy intensity in the past actually increased.

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 fuel switch, substituting fossil fuels by nuclear and renewable energy. However, various projections with respect to developing countries and countries in transition 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 individual production processes and structural changes in the economy (increasing weight of less energy intensive sectors). Only a few studies explicitly incorporate the impact of structural changes (most focus on energy efficiency measures).³ In addition, 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 perspective, 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 into the secondary ones.

Among virtually all (bottom-up) 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 at a negative net cost (no regrets policy). One basic explanation of its potential is that the overall primary (energy as recovered or gathered directly from natural sources) to useful energy (i.e. energy in so far as it provides useful services) efficiency is estimated at 34% only at a global level; lowest with 22% in the developing economies and the highest with 42% in the reforming economies (Nakicenovic and Grübler, 1993). These data reflect primary to final (energy carriers delivered to the point of consumption) energy efficiency (global average efficiency: 74%; highest in the developing economies: about 80%; lowest in the economies in transition: 69%) times final to useful energy efficiency (global average 46%; only 30% in the economies in transition and almost 53% in the market economies). 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 (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 improvements would bring the greatest benefits. Most studies suggest that a large potential exists in many sectors and regions,⁴ while at the same time acknowledging severe institutional, economic, and social barriers that may delay or inhibit the achievement of efficiency potentials in the near future. An illustrative example is IEA/OECD (1991) as shown in table 1.

Other studies focus on the energy efficiency improvement potential by analyzing on the level of single technologies, 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. In addition, an increasing amount of circumstantial evidence about energy efficiency savings potential has become available. To illustrate, recent estimates for the US show energy saving potentials of 45% in buildings and 30% in industries (Rubin et al., 1992). In rural areas of developing countries, to give another example, the 10-20% efficiency of traditional stoves (zero or low capital costs) can be improved to over 60%, but raising capital costs to \$50-70 (Baldwin, 1986), roughly equivalent to 30-50% of the average annual per capita savings in India (Mathur, 1991).

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 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);

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 ¹	(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%
Chemicals	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 E).

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*
Market economies				
Efficiency improvement	15	45	84	144
Structural change/recycling	95	n.a.	25	120
Fuel substitution	6	n.a.	n.a.	>>8
Process technology change	0	2	98	100
Reforming economies				
Efficiency improvement	48	63	n.a.	>101
Structural change/recycling	185	60	n.a.	>215
Fuel substitution	10	n.a.	n.a.	>>10
Process technology change	0	10	46	56
Developing countries				
Efficiency improvement	12	41	n.a.	>53
Structural change/recycling	19	29	n.a.	>48
Fuel substitution	3	n.a.	n.a.	>>3
Process technology change	0	8	56	64
World				
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: GRÜBLER ET AL. (1994)

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 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 socio-economic 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 to allocate 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 to those in industrialized countries at present, notwithstanding adverse factors such as the fast growth in commercial energy use and the increasing role of industrialization (Ewing, 1985; US Congress, 1992).

By contrast, energy conservation may be achieved somewhat easier in the industrialized countries insofar as changes in lifestyle involving less materials and energy consuming patterns of consumption 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.¹

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 Gröbler et al. (1993a) in table 2, arguing that a potential reduction of 920 MtC (over 40% of current emissions) could be achieved, 370 MtC of which at net negative or modest positive costs (greatest opportunities in reforming economies). 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.

Obviously the scope for no regrets options is rather sensitive to the annuity rate adopted. Indeed, in the various studies, rates do vary to a significant degree. Estimates, based on an annual discount rate of 30%, of reduction potentials and costs of CO₂ emissions in the transportation sector achievable at negative or zero specific reduction costs range from 15% (Brazil), 18% (EU), to 21% (USA) (Ledbetter and Ross, 1989).

The issue as to what discount factor should be used is even more crucial as far as options to reduce carbon emissions in the households and services sector are concerned. Studies that have tried to assess the implicit consumer discount rates of household investments in heating, cooling and other home appliances reveal wide ranges varying (depending among others on income classes) between 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.

Sensitivity analysis corroborates the above sensitivity. 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 serious 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 options, there clearly is also considerable scope for conservation options even if their assessment often cannot be but rather qualitative and impressionistic. There seems to be considerable scope for a reduction in energy use in the Western world by imposing stricter standards with respect to energy and materials use, institutional licensing, and most of all alterations and adjustments in lifestyles.

4.2 Fuel Switch Between Fossils

According to most studies the present dominance of

fossils in global energy demand (1990: 77%) will continue to exist in the next decades to come, e.g. varying between 76 and 66% in 2020 according to the WEC scenarios (WEC Commission, 1993, p. 106) (table 3 next).

	1980	1990	In 2020			
			A	B ₁	B ₂	C
Coal	14	23	49	38	30	21
Oil	10	28	46	45	38	29
Natural Gas	04	17	36	36	30	25
Nuclear	—	04	10	10	08	07
Large Hydro	015	05	10	10	09	07
"Traditional"	05	09	13	13	13	11
"New" Renewables	—	02	08	08	06	13
Total	33	88	172	160	124	113

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 most benign within the triarchy of fossils, to increase from the present quarter of fossils 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 fossils is due to the large resource base⁴ and the strongly vested position in the current vintage of technologies. Estimates point out that even total identified reserves will suffice to provide for current (1990) levels of energy consumption for the next 130 years.⁵ Obviously, this time span may become considerably shorter if energy use in the developing countries (relative to the use in the industrialized countries) increases rapidly both in absolute and relative terms.

Of the three fossil fuels, natural gas is least and coal is most carbon-intensive.⁶ Additional environmental advantages of natural gas are for instance the very low emissions of sulphur dioxide. Therefore, a switch from coal and/or oil to natural gas is sometimes seen as a vigorous response policy. 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.⁹

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 even of the costs of switching 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 \$199 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 technically feasible is expected to involve net direct implementation costs of some \$199 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 CO₂.¹⁰ 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).¹¹ 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%¹² for switching from coal to gas and at 4% for switching from oil to gas (adopting a global warming potential of 21). These figures point to the need of severely controlling leakage rates.¹³ An additional question is, 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 leakage rates 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 fuel switching for these countries may be considered large, especially if the environmental costs are not taken into account.

4.3 Renewable Energy Technology

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 in principle require no additional energy input. Moreover, exploitation of renewable energy resources with appropriate technologies has the advantage of releasing no (net) carbon.¹⁴ So, a shift in the energy mix towards renewables will result in reduced greenhouse gas emissions if substituting for fossil fuels.

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, supply of hydro power, and biomass, adverse effects may arise for the local population. Moreover, adverse environmental side-effects may occur, such as on a local scale smog by the use of traditional biomass

(fuelwood, dung, and crop residues), and on a regional scale 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.¹⁵ To understand the main factors underlying costs and potential of renewables as a group, a detailed treatment of their diversity is required.¹⁶ 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*	930	59.6
large hydro	465	29.8
total	1559	100

Table 4. Breakdown of renewable energy technologies in 1990.

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'¹⁷ 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 factor and length of useful life assumed are cases in point. As for 2), costs are strongly influenced by site-specificity and (temporal) variability of supply as mentioned before, and by the form of final energy delivered.¹⁸

Other aspects relevant for cost behaviour are learning effects, economies of scale, notably in the case of wind, and the need for storage and/or transport of the energy just after its generation. 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 distant. Preferably generated electricity should be fed into a linked distribution system of sufficient size that the intermittency does not matter (to give an example, wind power could reach about 25% of total capacity on the UK grid before intermittency becomes a serious problem).

Current prices of hydro, wind and some solar and biomass technologies as enlisted in table 6 are already competitive with conventional resources. Looking ahead, the table suggests substantial cost reductions for virtually all major classes to be forthcoming within the next few decades.¹⁹ However,

a. Source: Johansson et al. (1993), WEC (1993), S&SHER 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

	solar	wind	hydro	geother- mal	ocean	biomass
Current use ^a	54	3.2	2281.2 ^a	36.5	0.6	4713 ^a
Practicable potential estimate						
Johansson et al. (1993) ¹						
		1395	4931	53...	247	8003
Swisher et al. (1993) ²		489-1592	20148	1499	48-240	7031-7269
WEC (1993) ³			8295 ^a	178-405		

Table 6. Estimates of current¹ and future costs of renewable energy technologies (\$c/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 (22.61) ^c 5 (50) ^d (all 1984 £c)	3.5-4.2 ^b (4.48-7.62) (20) ⁱ	-	(3.6-9.2)	5-20 ^m (p/kWh) (11.5-50) 6.7-8 ⁿ	-	7.58-12.80 (11.85-16.68 ^q 12.70-20.85 ^r 15.64-23.70 ^s)
Johansson et al. ²	4.5-11.7 (7.5-32.8) ^e 4.9-9.4 (8.5-28) ^f	3.13-4.46 (4.29-8.4)		3-12 ^g 0.15-2.5 ^h	(5-30) ^m 12-25 ⁿ 22-30 ^o		1.86-2.73 (2.73-3.86)
Swisher et al. ³	5-10 ^d (12) 4-8 ^e (25) 4-8 ^f (30)	3-6 (7)	5-10 (5)	-	8-10 ^m	5	6 ^q (8) 7 ^r (13) 10 ^s (15) 1 ^t
WEC ⁴	no storage 0.4-2.5 (0.5-10) ^e 1-11 (1.2-28) ^f 4-14 (28-45) ^g	3-9 (5-10)		n.a.	(5-12) ^m (5-7) ⁿ (12) ^o (10-14) ^p	n.a.	n.a.

1. current costs in parentheses; 2. 1984; a. passive solar; b. active solar; c. solar thermal; d. solar thermal (line 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 herbage; v. biomass

SOURCES: IEA (1987), JOHANSSON ET AL. (1993), SWISHER ET AL. (1993), WEC (1993)

whether they will actually grow 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. Whereas competition between fossils is straightforward, in general such is not the case for renewables. E.g. solar and geothermal energy can often 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 in the developing countries are its large potential and modest price on the spot relative to availability and prices of conventional resources, determining the renewables' opportunity costs. 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.

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%.³⁰ 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 Energy³¹

Nuclear energy production, now accounting for about 5% of all primary energy production or about 20% of the world's electricity generation, can in

principle be carbon-free.³² Moreover, its technology has long passed the demonstration stage except for the still to be solved problem of the storage of nuclear waste. However, further dissemination could be strongly prohibited by the lack of public acceptance due to 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 limitations in mind, one can argue that 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 of the UK cost-effective potential, see Jackson, 1991). Because of its large investment costs, the nuclear option is somewhat inflexible. According to Mills et al., 1991, p. 540 (see table 7), costs to produce electricity with nuclear energy (\$/kWh) are even less than many of the renewable options considered next, although costs seem to have been rising instead of falling (MacKerron, 1992).

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.

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 coun-

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 (coal): \$0.44/kWh)				
End-use efficiency ^b				
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 ^c (busbar costs)				
Available technologies				
Biomass steam-electric (wood-based)	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. ^b Three lighting examples: The first two measures result in a net benefit because reduced labour costs exceed incremental capital costs³³ (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).³⁴ 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.³⁵ US field data, multi-family space heating: includes measured data from 42 actual projects in the USA.³⁶ ^c STIG (Steam-injected gas turbine) for gasified coal: 2 × 50 MW costs: STIG for natural gas: 4 × \$1 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 ³⁷ O&M costs assumed same as for gas-fired STIG systems. Biomass-steam: \$1 500/kW capital cost, \$0.05/kWh O&M, \$1.5/GJ fuel cost, wind, solar, thermal, and solar photovoltaics.³⁸ 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, \$1 090/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.³⁹ Gasified coal v biomass 111 MW BIG-ISTIG system.⁴⁰

SOURCE: Mills ET AL. (1991), p.540

tries 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. 1).

Plants 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.²³ To date, most research that was spent on power plants. For these, two classes of recovering technologies exist:²⁴ modifications in the energy conversion process in order to enhance the CO₂ content of the flue gases, and separation of the CO₂ from the flue gases (scrubbing) by add-on technology without modifying the energy conversion process. Technologies of the former type, which are now in experiment, are an Integrated Coal Gasifier Combined Cycle (ICGCC), modification of the boiler and modification of the gas turbine.²⁵ Scrubbing encompasses chemical absorption, membrane separation and cold distillation. Of these, chemical absorption is most developed and membrane separation and cold distillation least.²⁶

Depending on the place of disposal, transport will take place onshore or offshore. Onshore, pipelines are most economical. Estimated costs vary between \$10 to \$20 per tonne of 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 1/2 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 atmosphere is prohibited or at least delayed as much as possible (not all applications ensure entire or long-term storage of the carbon)²⁷.

Disposal can occur in two ways: either it is utilized in (long-lived) products or productive activities,²⁸ or it is stored underground, in aquifers (almost unlimited potential to store), or in the ocean.²⁹ Especially in the latter cases environmental risks seem to be involved, however.

4.6 Enhancing Sinks: Forestry Options³⁰

Unlike removal options, in options enhancing sinks carbon is removed *after* dispersion in the atmosphere. 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).³¹ 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 defor-

estation, reforestation, afforestation,³² 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 therein. 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 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 an 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 carbon sinks than trees which are allowed to mature in old-growth forests. This has large implications 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 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; 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/ha³³ for the main forest species.³⁴

ad 1. In the literature there is near consensus that 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 the latter. The potential for slowing deforestation is therefore hard to estimate and require to: 1) apply effective solutions to highly politicised problems such as inequitable land distribution and lack of secure land tenure; 2) 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 for all tropical forests. 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 Grubler 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. The relationship with the former is that according to Sedjo and Solomon (1989) the 2.9 GtC annually 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 Grubler 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 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 (Grubler et al., 1993b, p. 499). This impression is reinforced by the fact, that experience with the closest alternative, afforestation, has so far produced mixed results. On the one hand some success-stories can be told about afforestation 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 reforesta-

tion 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 to a large extent 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 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 point 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.

Source	Tropical Agroforestry - Plantation	Temperate Plantation	Boreal Plantation - Protection
Andrasko (1993)	3-5	3-6	0-2
Dixon et al. (1993)	4-16	6-60	2-50
Kranke and Dixon (1993)		1-7	1-8
Houghton et al. (1991)	3-12	4-37	

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 (106-338)
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 practices.
Source: Drawn from Turner et al. (1993).

that the estimates generally assume 'cemetery' forest. The tables suggest 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).

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 are likely to rise with the scale of the effort. Four forces underlie this cost pattern:

- diminishing growth rates as less suitable 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;
- rising establishment costs due to higher opportunity costs as plantation establishment moves from fallow land to land suitable for alternative uses;³³
- 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 area 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.³⁴ 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.

Study	Total Carbon Sequestered (million tons per year)			
	140	280	420	7181
	\$/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.

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 apparent that only for low levels of sequestering effort do figures correspond roughly. For larger areas, 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 presumably 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.

4.7 Methane

After CO₂, emissions of methane (CH₄) most likely accounts for the largest share (about 18%) in greenhouse warming, although there is still considerable uncertainty about methane emissions.³⁵ 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 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 inadequate flaring operations and exploration and drilling activities.

Data available for 1984 on the fraction of vented and 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 (I) (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 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.

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 costs of eliminating US paddy rice production at about \$0.5/tCO₂, and costs 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.³⁶

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 items will be considered. The question of when to adapt is one of balancing a mix of mitigation options against one of adaptation options. In the literature hardly any attention has been paid to any possible trade-off between both sets of options. The section concludes with some remarks on modelling adaptation.

5.1 Adaptation to what?

Climate change may cause accelerated sealevel rise, possibly attended with floods or hurricanes, changes in regional temperature, an increase in storminess and changes in the run off of river water

Table 11.

Agricultural Yield Changes 2xCO₂ (percent of Gross Agricultural Product)*

region/scenario ^b	UKMO			GISS			GFDL			avg. 2+3 ^d	avg. 1 ^e	diff. avg. ^f
	1	2	3	1	2	3	1	2	3			
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
CEE&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
SA&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:

* After Rosenzweig et al. (1993) and 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 the no adaptation scenario 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 d.

Source: Tol (1994), p.5

due to changing precipitation (in terms of mean value and variability). Research on the likely impacts of climate change differs considerably as to the assumptions of scenario building: IPCC (1994) works with one meter sea level rise in 100 years, whereas others work with a scenario of 50 cm. In addition, the appropriate or adequate response options to be called for differ significantly for all these impacts.

Global research on sealevel rise (Tol, 1994; Nordhaus, 1993; Cline, 1992a; Frankhauser, 1992, 1993, 1994a and 1994b; and IPCC, 1994), has pointed to the need for integrated coastal zone management on the World Coast Conference in the Netherlands, 1993 (IPCC, 1994). On the impacts of changes in river discharges, only some scattered information is available. As an example, the discharge of the river Rhine in the Netherlands is predicted to fall by 10 to 15 percent due to an assumed temperature increase of 4°C in the Alpine part of the basin (Kwadijk, 1991 as cited in Penning-Rowell and Fordham, 1994, p.26). However, no research is available yet to combine the effects of changes in precipitation with the effects of temperature rise.

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

Finally, effects on agriculture may be caused by regional changes in temperature and by sea level rise. A sea level rise of one meter would affect the supply of rice of more than 200 million people in Asia (IPCC, 1994). Changes in temperature have mixed regional effects (Tol, 1994 based on Rosenzweig 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) protection, or c) accommodation.

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, forestry, loss of species and 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 prevented on economic grounds by coastal infrastructure 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
SA&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 <50%

Table 12. Annual costs of sea level rise.

Source: Tol (1993), p.50

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) Protection cost estimates against sea level rise differ somewhat: Tol (1994), assuming a 0.5 meter rise, estimates global coastal defence on an annual

to be \$1994 9.5 billion; IPCC (1994), assuming a one meter rise, computes costs to be \$1994 10.0 billion per year; whereas Ayres and Walter (1991, as cited in Winpenny, 1994) derive a figure of \$1991 50-100 billion.

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

c) Accommodation to sea level rise means a combination of retreat and protection. In the state of transition it may involve that countries have to deal with inundation, flooding and erosion, causing loss of lives, damage to assets, to agriculture and to the environment (Penning-Rowsell and Fordham, 1994).

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

ii) 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;

iii) 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;

iv) 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 Conversion (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 the risks of damages due to climate change for an individual household will become larger for the marginal groups 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 approaches of adaptation to climate change are only available 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-Rowsell and Fordham (1994) present a general methodology for adaptation. Models for flood hazard assessment and management can be found in Klaus et al. (19-

94). Specific for river zone management, including the institutional setting, Correia et al. (1994) present a framework for analysis.

Today two important problems can be mentioned in modeling adaptation. First, the general greenhouse assessment problematique, i.e. the handling of time, uncertainty and discount rate. Second, and rather typical for the adaptation option, the valuation of intangibles like wetlands and species is a major problem: a valuation in \$ per person per threatened species is clearly incomparable with the investment costs in \$/km coast for coastal protection.

6. An Integrated 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 integrated framework that allows a simultaneous evaluation of the various technologies. If emission reduction targets are to be achieved in an optimal way, a full picture of all the alternatives should be available. The need for such an integrated 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 will be outpaced by another one after a certain scale of application has been reached, etc.

The need for an integrated 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 if applied in developing countries or countries in transition are often considerably more cost-effective than if applied elsewhere (McKinsey&Company, 1989).

A number of studies have been carried out in the tradition of the integrated 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' tradition, commonly pursuing a greater level of detail (Jackson, 1991; Rubin, 1992; Mills et al., 1991; Kram, 1994b).²⁹

The 'top-down' studies show, that the differences between the various' options cost functions for the various regions indeed 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 and burden of 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 are incorporated into the cost functions employed. As was explained in section 3, cost functions may differ depending on whether they have been designed in the tradition of the engineering efficiency approach or of the welfare economic approach. This will obviously have a strong impact

on integrated assessment. Welfare economic considerations may cause the various options' cost curves to become steeper or less steep or to shift up- or downwards relative to what would otherwise be the case. In so far as one may assume that welfare considerations all in all will cause various options' cost functions of developing countries and countries in transition 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 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 saving, efficiency improvement and fuel switch options.

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 fuel switch (especially in Eastern Europe, that is if methane leakages can be limited).

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, 1988; 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 com-

pared to the data base, respectively. Obviously, various other sensitivity tests, e.g. on the impact of changing lifestyles, could be carried out.)

A detailed integrated 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 first, considerable diversity among these countries in their optimal paths 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.

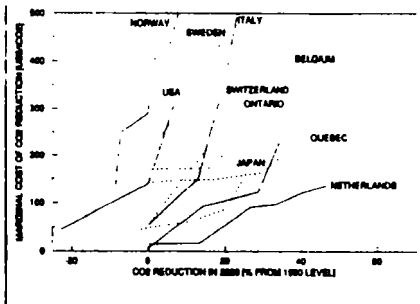


Figure 3. Marginal costs of CO₂ emission reduction for a number of OECD countries.

Source: Kram, 1994a, p. XIV.

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

Table 13. Base case simulation - Version 2

Option	Level of emission reduction (MtC)			
	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: Jepma and Lee (1994)

... that the most efficient allocation of emission reductions would be at the point of equal marginal abatement. This provides another argument why options should be implemented jointly, irrespective of the issue how the actual burden is shared among the countries.

7. International Policy Cooperation

Though the industrialized countries constitute only 13% of the world's population, they account for 55% 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, Art. 4.2.a, and in Principle 7 of the Rio Declaration on Environment and Development. In addition, much of the technological capabilities rests with the industrialized countries and they do not face the financial constraints to the degree of those of the developing countries.

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 and the countries in transition in the greenhouse discussion 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 the North and South Africa together (1:5).

- The relative use of traditional energy (woodfuel, 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 37% of total energy use for Africa to 98% for the Middle East; within Africa, 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 West and Latin America oil.

- In terms of energy use per capita (toe), the regions vary from 0.53 for Asia to 5.06 for the West or by 1:10. Between Western subregions it still varies from 3.39 for Western Europe to 8.3 for Northern America.

- The energy intensities (toe/\$1000 GDP) varies from 0.29 for the West to 1.19 for Asia (1:4). Between Western subregions it varies from 0.17 for Japan/Australasia to 0.4 for Northern America. However, energy intensity in toe/US\$100 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/US\$PPP100 (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 or its exports. If these two factors are taken into account, Southern energy intensity would be higher than that in toe/US100PPPS but probably lower than that in nominal terms (Van Ettinger, 1994, p. 118, note 9).

Most scenarios suggest that during the next few decades most of the growth in carbon emissions will take place in the developing countries. According to the data summarized in chapter 10 of this report,

TABLE 14.

Comparison of the 1990 development and energy situations in the main (sub-)regions.

Region	Tr (%)	Fossil Fuels %					SEner (Mtoe)	Popul (million)	GNP (billion US\$)	GNP (\$ per capita)	Toe per capita	Toe per thousand US\$
		Co	Oi	NG	EF	Al (%)						
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	20 819	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	1	46	25	19	90	9	352	125	388	3 101	2.81	0.91
ex-USSR	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	5	na	na	na	92	3	154	150	227	1 507	1.02	0.68
sub-Sahara	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; EF = total fossils; Al = alternatives (nuclear, hydro, wind, geothermal, etc.) (all % of total energy); SEner = 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. 42

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 reforming economies 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 emitter 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 and countries in transition seems to be significant, 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 will have to be sufficient stimulus to induce any change. Some improvement can be affected comparatively easily through good house-keeping like better insulation. Others like investment in new equipments and appliances will not be so easy as these not only require new funds, but may also call for major managerial efforts and retraining, slowing down the speed of adoption of even highly profitable technologies.

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 psycho-sociological factors may also be important. A review of recent research of diffusion of energy technologies in developing countries shows that there are many other factors, economic and financial, institutional and others, which influence the successful adoption of these technologies (Barnett, 1990). 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. Moreover, one necessary ingredient for adaptation of technology, namely a local pool of skill to draw upon, may be lacking or be inadequate in many cases with the result that even proven technologies may spread rather slowly in these countries.

8. Conclusions

◆ measures difficult to compare consistently: enhancing carbon sinks (forestry) only means to gain time, so intermediate response option, removal also due to constraint on utilization and storage capacity, option to gain time

whereas renewables are truly sustainable, long-term response policies

◆ efficiency and conservation no regrets policy in any case to be strived for

◆ gas could bridge the gap between the fossil and the renewable era

◆ favourable conditions for application of ret's: remoteness from conventional energy supplies, small size, ...

◆ diversity of fuel mix

Notes

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

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

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

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

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

4. For a recent survey of bottom-up engineering studies on energy efficiency potential, see Geller, (1994)

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

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

7. Total global energy consumption amounted 10 TWyr in 1990, whereas identified fossil energy reserves are estimated at 1,280 TWyr (Rogner et al. 1993, p. 463).

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

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

10. Adopting a 100-year time horizon.

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

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

13. See e.g. Jackson (1991) for an analysis of cost-effectiveness in the UK, explicitly incorporating CH_4 -leakage.
14. In this respect, electricity and hydrogen appear as rather ideal intermittent energy carriers from a technological point of view.
15. See e.g. IPCC (1991), Johansson et al. (1993), WEC Commission (1993) or WEC (1994).
16. Solar can broadly be subdivided in solar thermal, solar architecture, solar thermal-electric, photovoltaic systems and thermochemical and photochemical systems. Wind and hydro are relatively homogeneous energy technologies, the largest differences stemming from scale of operation. Here, distinction is made between small/medium scale and large scale conversion systems. In contrast, biomass appears to be the most complex of all technologies. A wide range of conversion technologies exist, depending on the type of feedstock used and the form of energy output required. Geothermal consists of hydrothermal, hot dry rock, geopressured and magma resources technologies. Current ocean technologies encompass tidal, wave, biomass and salt and thermal gradient technologies.
17. Different approaches exist to get hold of the concept of 'practicable', i.e. realizable, potential. Most common dimensions of distinction are physical, technical and economical, the ensuing potentials each being a subset of the earlier mentioned one. The physical potential would denote the maximum potential that is constrained by geological and meteorological factors only. Technical potential would refer to that part of physical potential that can be exploited given the state of technology at hand. Finally, the remainder of technical potential after excluding what is not deemed feasible due to prevailing economical constraints (such as a prohibitive level of costs, institutional constraints in the energy markets, etc.) would pass for economical potential. Notice that, for the present purpose, the former of the three can be considered constant in time, whereas the others prevail only at a certain moment.
Practicable potential now would be defined as somewhere between technical and economical potential. This is, because the two do not hold independently, but are interlinked in time: e.g. technical potential is enlarged by investments that stimulate technological progress. Conversely, the impact of improvements of, say, silicon films in photovoltaic systems on the price of solar energy is obvious.
18. 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).
19. 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.
20. Estimates are 21.3 to 29.6% in 2020 by WEC (1993b), 15% (6% of which hydro) in 2020 by Grubler et al. (1993) and close to 43% in 2025 by Johansson et al. (1993). According to Grubler 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 (!) (Grubler et al. 1993, p. 580). In the past the mean duration for replacing most technological systems was about 30 to 40 years.
21. For an extensive discussion on the nuclear option, see WG IIa, Second Assessment Report.
Only relatively minor fossil fuel inputs are used that support the overall functioning of the breed reactor.
22. Recovery of carbon at power plants has the advantage of removing carbon from energy before it is distributed to highly dispersed end-users.
23. As the use of coal and natural gas is predominant in power plants, virtually no technologies are based on oil.
24. In an ICGCC coal is converted prior to combustion. After some intermediate steps, CO_2 and H_2 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 IGCC or a STEG can be modified by changing the combustion medium into a O_2/CO_2 medium.
25. 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.

27. In enhanced oil recovery, part of the injected CO_2 reenters the atmosphere, and in food packaging CO_2 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.
28. 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.
29. 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) CO_2 (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.
30. 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.
31. Grubler et al., 1993, p. 499; see also Houghton, 1990.
32. 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.
33. Besides carbon stored in the forest wood itself, soil carbon and carbon in other biomass growing in the forest are included.
34. 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).
35. Opportunity costs for land would in theory largely be reflected in land market rents.
36. See e.g. Moulton and Richards (1990), Adams et al. (1992) and Parks and Hardie (1992).
37. 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).
38. For an overview of the costs of greenhouse damages, see also chapter 3 of this report.
39. 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.

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**Chap 8
POLICY INSTR.**

Divider Title: _____

updated
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We have not
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Geneva trip.

US note to WGIII
on 1st version of
scenarios chapter

August 8, 1994

Mr. James Bruce
Dr. Hoesung Lee
IPCC WGIII Technical Support Unit
145 King Street West, Suite 1002
Toronto, Ontario M5H 3X6 CANADA

Dear Sirs,

Attached please find the United States' comments on the IPCC Working Group III report on Emission Scenarios to be included in the 1994 Interim Assessment Report as Chapter 6.

The United States has important concerns regarding the draft. In our view, the chapter does not adequately follow the outline approved by the IPCC Working Group III plenary. In light of this outline, we believe the chapter should focus on identifying and addressing the key input assumptions which drive the scenarios. At present, it is unclear whether the range in model estimates is the result of different input assumptions or of different fundamental approaches models use to derive the scenarios (i.e. parameterizations, solution algorithms). In this respect the draft should focus on identifying the differences in input assumptions and model structures that produce a varying range of scenario outputs. It is also important that the chapter address sulfur emissions, given the role of aerosols in the climate system, and given the content of chapters 1-5 of the Assessment.

We suggest that the report go forward with careful wording noting that this evaluation has been limited and has given *no reason to indicate that these scenarios are not appropriate* for input into climate models and for evaluating the climatic and environmental consequences of current greenhouse gas policies. We urge that the chapter delete the proposed framework for evaluating scenarios since laying out criteria in this way leads to the presumption that scenarios should be developed to satisfy the four proposed purposes. Also, the authors' proposal that IPCC act as an umbrella organization to develop comparable, comprehensive emissions scenarios should be deleted. The decision on what needs to be done for and after 1995 should be made by the IPCC plenary.

We also suggest that the Summary for Policymakers and the Executive Summary be substantially revised. As written, these parts of the text do not include many of the important points and necessary caveats stated in the underlying document. In particular,

they do not clearly state the purposes of and guidelines for this report or adequately describe the inherent uncertainty of emissions scenarios.

The United States appreciates the time and effort that has gone into the preparation of this report. Through our comments we hope to assure that the final product is not only accurate, but of value to the policy community. In order to provide the most constructive possible suggestions, we begin by providing introductory comments, reflecting general concerns, then proceed to detailed, line-by-line comments. We look forward to receipt of the completed final text, and wish IPCC Working Group III and its lead authors every success in their continued efforts to prepare this important document for publication.

Sincerely,

Rafe Pomerance
Deputy Assistant Secretary
Environment and Development

Attachments:
As stated

GENERAL COMMENTS

Recognizing the importance of this chapter as part of the 1994 IPCC Interim Assessment Report, the United States has conducted an extensive review. As a prelude to the line-by-line comments on the Summary for Policymakers, the Executive Summary and the main body of the report, we have compiled general comments on the report and the process which produced it. In our view, the most crucial of these comments include the following:

1. Identification of Key Input Assumptions and their Importance

While the chapter provides some overall sense of the validity of the IS92 scenarios through comparison with the results of other emission scenarios, a complete substantive evaluation of the validity of individual scenarios or sets of scenarios would require evaluation of the plausibility of scenario input assumptions with respect to both socio-economic and technical matters. This socio-economic and technical evaluation is necessary, for example, in order to clarify whether the range in model estimates is the result of different input assumptions or of fundamentally different approaches that various models use to estimate the emissions scenarios (i.e. use of different parameterizations and solution algorithms).

Key assumptions undoubtedly vary considerably across scenarios to give rise to the wide range of emission projections. Assumptions regarding technology used for energy production and consumption, treatment of reserves, lifestyle and land use and management (amongst others) should be described and analyzed. Some of the differences in input assumptions may reflect a reasonable degree of uncertainty regarding key driving forces of future emissions. In other instances, input assumptions may represent very extreme and unlikely cases. It is important to evaluate the effect of different assumptions and their interactions with different modeling approaches on the plausibility of the resulting emission profiles. For sets of scenarios, such as the IS92 scenarios, it is important to evaluate whether the range of assumptions adequately reflects the probability distribution of uncertain inputs.

The type of world underlying scenario assumptions should also be described. Scenario assumptions, such as population and per capita income growth rates, energy supply costs, land use changes, and rates and character of technological change should be supplemented with their implications for living standards and other social conditions. For example, some scenarios may be based upon very low population growth rates that could only be achieved by draconian population controls not contemplated by even the most repressive of governments, severe famine, wars, or unprecedented income growth in poor countries. In other scenarios, per capita income growth is very low by historical standards and may indicate nearly stagnant living standards in many parts of the world. Scenarios with high rates of deforestation may imply severe degradation of natural resources. Policy

makers will likely find characterizations of the type of world implied by scenario assumptions more informative than documentation of rates of change of key variables. This will enable policy makers to make their own judgments about the plausibility of scenarios. The type of world implied by scenario assumptions could also have implications for the vulnerability of societies and the environment to climate change and is important to describe for this reason too.

The chapter also fails to identify the key assumptions to which emissions are most sensitive. The Kaya identity, the decomposition of CO₂ emissions growth into four components (population, per capita income, energy intensity, and carbon intensity), is very useful for understanding how the scenarios vary in the sources of projected emissions growth. However, the decomposition does not explain why growth of each of the components vary across scenarios, nor why emissions in aggregate vary across the scenarios. It is our suggestion that the Stanford University Energy Modelling Forum (EMF) could be useful as regards additional sensitivity testing of input assumptions.

The text of the chapter also does not make clear whether the scenarios contain any feedback mechanisms. The text should clarify whether the scenarios dynamically feed back on themselves and respond to energy/economic interactions. It should also be made clear that climatic feedback is not modelled.

If the tasks of identifying and evaluating the key assumptions to which emissions are most sensitive, and documentation of the different assumptions made, cannot be performed in time for inclusion in the 1994 Interim Assessment Report, then we urge that the chapter, policy makers' summary, and executive summary be revised to: state that these tasks are part of the original charge; state that the tasks have not been performed; identify the constraints that prevented performance of the tasks; and highlight the importance of the tasks for future assessment of emissions scenarios. Making these additions to the chapter will help demonstrate the responsiveness of the IPCC to the INC.

2. Purposes/Criteria for Evaluation of Scenarios

The recommendation in the Summary for Policymakers and the Executive Summary that the IS92 scenarios be used for evaluating the climatic and environmental consequences of current greenhouse gas policies is generally sound and should be stated clearly and at the outset of the Summary for Policymakers, the Executive Summary and the main body of the chapter. The tone of the main body of text at present does not adequately support the conclusion and should be appropriately revised.

In addition, whether or not it is the authors' intent, laying out criteria for evaluation in the framework used in this chapter leads to the presumption that scenarios should be developed to satisfy the four proposed purposes. The IPCC has not been tasked to develop scenarios that would satisfy these purposes, and this report should not imply such. Furthermore, there is substantial divergence of opinion regarding mandatory vs. recommended requirements for various purposes, as well as the appropriate delineation of purposes. Since we consider the introduction of this framework to be inappropriate for the

purpose of this assessment, we strongly urge that the framework be dropped and that conclusions regarding appropriate applications of scenarios and limitations be included in the text, as appropriate. Our line-by-line comments make changes to the text to retain appropriate commentary, while eliminating introduction of this framework.

3. Range of Emission Scenarios

An explicit assessment should be made of whether or not scenarios that lie outside of the IS92 range are of sufficiently low probability that attention can prudently be focused on the IS92 scenarios. The authors will need to go beyond a mere cataloguing of whether or not the range of emissions in the IS92 scenarios is wider or narrower than ranges found in other scenarios. Is the probability high enough that a wider range of scenarios should be used? If the range needs to be expanded, how? Should higher emission scenarios be considered? Lower? Both?

We believe the recommendation that no individual IS92 scenario be used for evaluating the climatic and environmental consequences of current policies is sound, but the reasoning is flawed. Whether or not a scenario is accepted as a "medium case" is irrelevant to this question. The use of any single scenario to evaluate possible changes in climate and the environment, whether it is a central case scenario or not, is inadequate because of the high degree of uncertainty about future emissions. Actual emissions in the year 2030 could plausibly deviate by almost a factor of two from a central estimate. For this reason, evaluating the possible effects of greenhouse gas emissions based upon a single emission scenario is not advisable. It has nothing to do with whether or not we have a reliable estimate of the mean or median of the distribution.

5. What is a scenario?

At present, the draft defines the term "non-intervention scenario" as "an emission scenario that does not make any assumptions about climate policies to reduce greenhouse gases." We believe a more helpful and policy-relevant distinction would be policies in place (non-intervention) vs. additional policy (intervention) scenarios. Under this schema, the question whether or not a policy is in place principally for climate reasons is moot. It should be noted that non-intervention scenarios will need to change over time as policies change. This issue should be clarified in the text of the chapter as well as in the Summary for Policymakers and the Executive Summary.

The basis for scenarios of greenhouse gas emissions and our confidence in them over different time horizons needs to be more fully described. The chapter correctly observes that we are more certain of emission levels in the near term than in the distant future. More discussion is needed, however, to explain why this is true. In the relatively near term, the year 2020, for example, emissions will be determined largely by currently known technologies; current population, incomes, energy consumption, and land use patterns; and recently observed trends for these variables. Consequently, we have relatively high confidence in projections of near term emissions. In the more distant future, year 2100, the

current state of the world and recent historical trends will prove less reliable as guides to what may happen. Emissions for the very distant future are therefore more speculative. These points should be brought out and expanded upon in the chapter. This report might draw upon the explanation of the nature of emission scenarios set forth in the IPCC 1992 report for this purpose.

5. Sulfur emissions

It is especially important that this chapter address sulfur emissions, given the role of aerosols in the climate system and the implications of the difference in timing of the climate effects between aerosol and CO₂ mitigation impacts. Sulfur emissions are alluded to several times, but nowhere are their trends quantitatively specified in this chapter. This needs to be done with some degree of spatial resolution, preferably at a sub-continental scale for the major emitting regions, if the climate effects of aerosols are to be analyzed. Short-lived trace gases, such as NO_x and VOCs should also be adequately considered.

6. Coordination with other IPCC Working Groups

Attention should be paid to ensuring that the 1990 emission rates for CH₄ and N₂O used in this chapter are consistent with those developed by WG I authors in Chapter 2 of this report and by relevant mitigation chapter authors in WG II for the SAR. Moreover, it is important to harmonize with the WG II authors the underlying assumptions regarding land-moderated GHG emissions, e.g. vegetation carbon densities, effects of management practices on CH₄ and N₂O emissions, etc.



INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE



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MEMORANDUM

TO: Recipients of the Emissions Scenarios Chapter

FROM: Erik Haites, Head, Technical Support Unit, Working Group III

RE: August 29 Draft of "An Evaluation of the IPCC IS92 Emissions Scenarios"

DATE: August 31, 1994

Over 1,000 comments on the May 16 draft were received from peer and government reviewers. The Writing Team had only two weeks to prepare a revised draft. Not all of the comments could be addressed in the August 29 draft.

The following items will be included in a draft that will be brought to the IPCC Plenary on September 27:

- Revised discussion of cumulative CO₂ emissions due to deforestation (revised lower bound).
- Revised discussion of Current Commitments.
- Inclusion of a discussion of the IS92 global SO₂ emissions scenarios.

On behalf of the Writing Team I apologize for any inconvenience this may cause.

P938005.7/memo.429

An Evaluation of the IPCC IS92 Emission Scenarios

Draft: 29 August 1994

IPCC Working Group III, Writing Team 10

J. Alcamo (Convener), A. Bouwman, J. Edmonds,
A. Grübler, T. Morita, A. Sugandhy

Chapter 6 An Evaluation of the IPCC IS92 Emission Scenarios

CONTENTS

Polymakers Summary

Executive Summary

6.1 Background and Scope

- 6.1.1 Terms of Reference
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Summary for Policy Makers

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An Evaluation of the IPCC IS92 Emission Scenarios

IPCC Working Group III, Writing Team 10

What are the IPCC IS92 Emission Scenarios?

This chapter presents an evaluation of the emission scenarios published by the IPCC in 1992, and especially a discussion of their input assumptions and results. Other scenarios are included by way of comparison to the IPCC scenarios. Also covered is the appropriate uses of these emission scenarios in scientific assessment and policy making.

Emission scenarios in this evaluation are projections of anthropogenic emissions of gases that have the potential to affect climate, based on assumptions about future trends of key determinants such as population, economic growth, technological change, land use and emission control policies. In 1992 the IPCC sponsored development of emission scenarios as inputs to global climate models because of the scarcity of comprehensive emission scenarios available in the literature at the time. These scenarios, called the *IS92 scenarios*, are *not* forecasts, nor are they attempted predictions of the most likely level of future emissions. Rather, they project possible emissions levels given possible future values for the key determinants.

The IS92 scenarios are among the most comprehensive available, providing estimates of direct and indirect greenhouse gases by source for four regions over the period 1990 through 2100.¹ The six scenarios cover a wide range of values for the key input assumptions. Only one out of six scenarios makes any assumptions about climate policies to reduce emissions of greenhouse gases.

How Were the IS92 Emission Scenarios Evaluated?

There are no accepted criteria for evaluating scenarios. Moreover, since scenarios deal with the future, they cannot be compared to observations. As an alternative, the "reasonableness" of their input assumptions and methodology can be examined, but this is best done by comparing several models in an organized intercomparison exercise. This intercomparison was outside the scope of this evaluation. We have chosen instead to evaluate the IS92 emission scenarios by comparing the range of their emission projections and their major input assumptions with those of other published non-intervention scenarios. While this comparison does not answer all questions about the scenarios, it does provide information about the position of the scenarios relative to other work in the scientific community, and it was feasible in the short time available for this evaluation.

¹ The IS92 scenarios are presented in the IPCC Supplementary Report to the First Assessment. The scenarios include estimated emissions of carbon dioxide (CO₂), methane (CH₄), nitrous oxide (NO₂) and halocarbons (e.g. CFCs and HCFCs) which affect radiative forcing directly and carbon monoxide (CO), nitrogen oxides (NO_x), volatile organic compounds (VOCs), and sulfur (S) which affect radiative forcing indirectly. The activities for which emissions are estimated include energy production and use, deforestation, cement, enteric fermentation, rice, animal wastes, landfills, biomass burning, domestic sewage, fertilized soils, land clearing, adipic acid, nitric acid, and halocarbon use. The four regions are OECD, Eastern Europe and former USSR, China and Centrally Planned Asia, and Other.

Since few other scenarios are as comprehensive as the IS92 scenarios, the evaluation concentrates on a limited number of important greenhouse gases and source categories. The most important category of emissions is energy related carbon dioxide (CO₂), and much of the evaluation centers on this type of emissions. Also covered are emissions of methane (CH₄), nitrous oxide (N₂O) and sulfur (S) emissions from the energy sector; as well as CO₂ from deforestation, and CH₄ and N₂O from selected land use sources. Both global and regional emission scenarios are evaluated.

What Was Not Covered by the Evaluation?

We did not evaluate the types of models used for scenario development, nor the sensitivity of input variables to government actions. Both of these topics can best be addressed by comparing the different models used to compute emission scenarios. This intercomparison requires the full cooperation of different modeling groups and extensive analysis, and there was neither the time nor funds available in the evaluation for this task. We also did not compare the scenarios to the emission inventories of countries because there were too few country estimates available to make substantial improvements in regional and global emission scenarios. It should be noted, that although the scope of the evaluation was somewhat limited, it is believed that a wider scope would not have led to significantly different conclusions.

What Are the Findings About Scenarios In General?

Almost all published reference scenarios (including the IS92 scenarios) show an increase in greenhouse gas emissions over the next century. Only one of the six IS92 scenarios, IS92c, shows a decline in total CO₂ emissions between 1990 and 2100 and even it projects increases in emissions of almost all of the other direct and indirect greenhouse gases except the halocarbons controlled by the Montreal Protocol.

The set of published scenarios show a very wide range of projected emissions in annual CO₂ emissions. For energy related CO₂ emissions, the extremes in the literature span a huge range, from 1.2 to 60 Pg C per year² in 2100, and diverge greatly from 1990 to 2100. The IS92 scenarios bracket a large part of this range, spanning from 4.6 to 34.9 Pg C per year. Energy related emissions currently dominate other types of emissions, and are expected to do so for the next century.

Projected emissions of CO₂ related to deforestation also differ widely. Unlike energy emissions which diverge with time, land use emissions have their widest range (0.8 to 4.8 Pg C per year) in the middle of the 21st century. Most scenarios of this type then converge on zero by the end of the century because they project that driving forces of deforestation

² The symbols "Pg C" stand for petagrams of carbon dioxide emissions in units of carbon (C). A petagram is 10¹⁵ grams, and it is the same as a gigaton of emissions. Units of gigatons were used earlier to describe CO₂ emissions, but petagrams conform more closely to standard international scientific units, and are therefore entering into common usage.

1 equilibrate or forests are depleted.

2
3 **The wide range of projected emissions of the IS92 and other scenarios stems mostly from**
4 **differences in scenario input assumptions.** Some of the uncertainty of future emission
5 projections can be attributed to the different methods and models used to compute emissions.
6 However, there is evidence from model intercomparisons that differences in models only a
7 explain a small part of the wide range of emission estimates. Most of this range arises from
8 differences in input assumptions of the scenarios. For energy CO₂ emissions, population and
9 economic growth assumptions usually play a key role, as well as assumptions that influence
10 the amount of carbon-based fuels used in the economy. For land use CO₂ emissions, the
11 deforestation rate and the carbon content of vegetation are particularly important input
12 assumptions.

13
14 **What input assumptions are important to the IS92 Scenarios in particular?** In addition
15 to the factors mentioned above, other assumptions are important in influencing the estimates
16 of energy related CO₂ emissions in the IS92 scenarios. These include labor productivity, the
17 growth of demand for energy in developing countries as incomes rise, and the rate of
18 technological improvement of energy efficiency.

19
20 **Cumulative emissions have a smaller range than annual emissions.** If the annual energy
21 CO₂ emissions of the IS92 scenarios are summed up over the period 1990 to 2100, they
22 amount to 700 Pg C for the lowest scenario and 2078 Pg C for the highest. The cumulative
23 emissions of non-IPCC scenarios range from 492 to 3447 Pg C. These ranges are smaller than
24 the range of annual CO₂ emissions in year 2100. Cumulative emissions are important from
25 the climate analysis standpoint because CO₂ and other direct greenhouse gases can affect
26 climate over decades to centuries after they are emitted. This stems from the integrative
27 nature of the atmosphere-ocean system.

28
29 **Even the lowest reference scenario may lead to increased atmospheric concentrations of**
30 **CO₂.** The cumulative CO₂ emissions (1990-2100) of the lowest IPCC scenario (700 Pg C) far
31 exceeds the cumulative emissions between 1860 and 1990 (approximately 215 Pg C). Whether
32 or not future emissions will accumulate in the atmosphere depends on many biogeochemical
33 factors, some of which are taken into account by carbon cycle models. Model calculations of
34 this sort from Working Group I indicate that the emissions of the lowest IPCC scenario could
35 raise atmospheric concentrations of CO₂ to approximately 480 ppmv by 2100. Hence, the
36 lowest IPCC scenario (which leads to lower CO₂ emissions in 2100 than at present) will add
37 more carbon to the atmosphere over 110 years than was added in the last 130 years, and this
38 could result in an increase in atmospheric CO₂.

39
40
41 **How Can Policymakers Take Into Account the Large Uncertainties of Future Emission**
42 **Estimates?**

43
44 Policymakers have a range of options for factoring in the large uncertainties of future
45 emissions in their studies of policies.

1 **One option is to focus policy studies on a time horizon shorter than 2100, say year 2050**
2 **or earlier.** The uncertainty of estimates is much lower for energy emissions in 2050 than in
3 2100. This does not mean that climate impact studies should be limited to this time horizon,
4 because as noted above, CO₂ and other greenhouse gases can affect climate over a period of
5 decades to centuries after they are emitted.

6
7 **A second option would be test the robustness of policies to a wide range of reference**
8 **emission estimates.** Put another way, will the policy intervention be effective in achieving
9 its emission objectives even for a wide range of reference scenarios?

10
11 **Yet another option would be to focus policy studies on cumulative emissions over a**
12 **period of time, rather than annual emissions of a particular year.** As noted above,
13 cumulative emissions have a lower range of uncertainty than annual emissions, and take into
14 account the integrative nature of the atmosphere and ocean.

15
16
17 **Current commitments have a relatively small impact on the IS92 emission scenarios.**
18 Since the IS92 emission scenarios were prepared, the United Nations Framework Convention
19 on Climate Change has come into force. Under Article 4 of the Convention Annex 1 countries
20 undertake to alter long term trends and reduce anthropogenic emissions to earlier levels by
21 the end of the present decade. Incorporating these commitments into the IS92 scenarios could
22 result in significant reductions in the emissions of certain regions, but on a *global* basis
23 reductions of only 10% or less in CO₂ emissions should be expected (relative to an
24 intermediate IPCC reference scenario). This percentage reduction can be somewhat greater
25 or smaller, depending on the year and reference scenario it is compared to.

26 27 28 **What Are the Uses and Limitations of the IPCC IS92 Scenarios?**

29
30 **The IS92 emission scenarios are among the most comprehensive available in terms of**
31 **the sources and direct and indirect greenhouse gases covered.** In particular they include
32 sulfur emissions which very few other scenarios include. This comprehensiveness is important
33 from the climate modeling standpoint because omitting any significant greenhouse gases in
34 a climate model adds a low bias to climate change calculations.

35
36 **Is one IS92 scenario more likely than another?** In some ways, the IS92a scenario is an
37 intermediate scenario. For example, its population projections are close to the medium
38 projections of three different international organizations, and its global CO₂ estimates are near
39 the center of the range of published scenarios, at least up to year 2050. In other ways it is not
40 representative of the literature, as in the case of some of its regional input assumptions. In any
41 event, being an intermediate scenario is not the same as being the most likely scenario, and
42 our evaluation did not reveal one IS92 scenario to be more likely than any another.

43
44 **The full range of scenarios should be used for climate analysis.** Considering the degree
45 of uncertainty, wide range of views about future emissions, and the absence of a most likely
46 scenario, it is unwise to use only one scenario for climate analysis. Rather, it is recommended

1 to use the full range of IS92 scenarios for this purpose.

2
3 Users of the IPCC scenarios are cautioned, however, that the lowest scenario (IS92c) has
4 emission levels and some input assumptions that are more characteristic of a policy rather
5 than a reference scenario.

6
7 **The IS92 emission scenarios are suitable for use as input to atmosphere/climate models**
8 **to assess possible consequences of no further action to limit anthropogenic greenhouse**
9 **gas emissions.** This was the intended purpose of the scenarios, and we confirm that they are
10 suitable for this purpose. The input assumptions and global emissions of the IS92 scenarios
11 span much of the range of other scenarios, and in this way can be said to reflect the current
12 range of views about future emission estimates. Moreover, they are among the most
13 comprehensive available, and their results are sufficiently documented to allow comparisons
14 with other scenarios, and use in models.

15
16 **The IS92 emission scenarios are not suitable for other purposes.** The IS92 scenarios were
17 not designed for other purposes, and indeed they are not suitable for assessing consequences
18 of intervention to reduce greenhouse gas emissions, to examine the feasibility and costs of
19 mitigating greenhouse gases, nor as input to negotiating possible emission reductions. New
20 scenarios will be needed for these purposes.

21 22 23 24 **What About New Scenarios?**

25
26 **What scenarios are needed?** New reference scenarios are needed to explore a variety of
27 economic development pathways, for example a closing of the income gap between
28 industrialized and developing regions. Also needed are scenarios that take into account the
29 latest developments in economic restructuring in many regions, as well as the emissions
30 commitments contained in the Framework Convention. This is only a partial list.

31
32 **The estimation of non-CO₂ emissions is weak in current scenarios and needs to be**
33 **improved.** There is a lack of knowledge or agreement on how to represent the processes of
34 non-CO₂ emissions in emission models. Work is needed to improve estimation of these gases,
35 especially from the land use and other non-energy sectors.

36
37 **Emissions inventory data should be used to improve baseline data of scenarios.** One of
38 the largest sources of uncertainty in non-CO₂ emission scenarios is the uncertainty of baseline
39 emission estimates. Countries are beginning to compile inventories of their anthropogenic
40 emissions of greenhouse gases, and these data should be used to improve baseline estimates
41 in new scenarios.

How Should New Scenarios Be Developed?

It is recommended that the IPCC or other suitable organization provide an "umbrella" under which different groups can develop comparable, comprehensive emission scenarios. The process for developing scenarios should emphasize *openness, pluralism, comparability, and harmonization*. This includes opening up the process to the wide participation of the research community, particularly from developing countries. A central archive should be established to make available the results of models and other information to any group. In addition, new scenarios should be widely disseminated to countries, international organizations, non-governmental organizations, and the scientific community.

The IPCC can play a role in the preparation of emission scenarios. The IPCC sponsored development of the IS92 emission scenarios because of the scarcity of comprehensive emission scenarios available in the literature at the time. Several research groups are now able to develop comprehensive emission scenarios but they have not yet organized themselves for this purpose. An important question to be answered is whether the IPCC should take on the "umbrella" role described above or encourage another organization to fulfill that capacity and limit its role to assessing the scenarios literature.

Capacity-building is crucial. Special effort is needed to improve the capabilities of researchers to analyze and develop scenarios, especially in developing countries and in countries with economies in transition. With this in mind, it is especially important to build up their capabilities to (i) estimate baseline emissions, (ii) prepare data on the driving forces of emissions, and (iii) run computer models of emissions.

EXECUTIVE SUMMARY

Scenarios of greenhouse gas emissions play an important role in the analysis of potential climate change. From a scientific standpoint, they provide a departure point for analysing the potential occurrence and impacts of climate change; from the policy perspective they can provide information about the consequences of action or inaction to reduce greenhouse gas emissions. Recognizing this pivotal function, the IPCC undertook the development of a comprehensive and international set of emission scenarios as part of their First Assessment (1990). Shortly thereafter (1992) their original reference scenario, SA90, was updated with new information and six new reference scenarios were developed -- IS92 a through f (reported in the Supplement Report to the IPCC First Assessment in 1992).

This report presents an evaluation of the IS92 scenarios. Other published scenarios are also taken into account, but only by way of comparison with the IS92 scenarios. It is emphasized that this evaluation deals mostly with non-intervention scenarios, that is, scenarios that *do not assume any climate policies to reduce greenhouse gas emissions* (although they may assume emission controls for other environmental reasons). This applies to five out of the six IS92 scenarios, and to all other scenarios that we call non-intervention scenarios. Policy scenarios are only briefly discussed in the evaluation.

Because of the very limited time available for this evaluation, it focuses exclusively on CO₂, CH₄ and N₂O and S emission scenarios from energy and land use activities. Other sources of greenhouse gases and sinks are not included.

Time constraints also made it impossible to evaluate scenario results for all regions. Therefore, the evaluation was limited to a few case study regions from the industrialized and developing world.

It is also important to note that no other scenarios were evaluated other than the IS92 scenarios. Therefore the reader should be aware that any shortcomings of the IS92 scenarios identified in this evaluation may or may not apply to other scenarios.

We note here, that despite the somewhat limited

focus of the evaluation, it is believed that a wider scope *would not have led to significantly different conclusions.*

Approach to Evaluation

Since there are no generally accepted procedures for evaluating these or other kinds of scenarios, a new approach is proposed which consists of a set of purposes of scenarios, together with criteria to satisfy these purposes. The following purposes of scenarios are suggested:

Purpose 1. As input to evaluating the environmental/climatic consequences of "non intervention", i.e. no action to reduce greenhouse gas emissions.

Purpose 2. As input to evaluating the environmental/climatic consequences of intervention to reduce greenhouse gas emissions.

Purpose 3. As input to examining the feasibility and costs of mitigating greenhouse gases from different regions and economic sectors, and over time. This can include setting emission reduction targets, and developing scenarios to reach these targets. It can also include examining driving forces of emissions and sinks in order to identify which driving forces can be influenced by policies.

Purpose 4. As input for negotiating possible emission reductions for different countries and geographic regions.

Since the IS92 scenarios were only designed for Purpose 1, the evaluation centers around the suitability of the scenarios for this purpose.

It should also be noted that the mixed scientific/policy nature of scenarios makes it difficult to separate out scientific from policy objectives. Indeed, both Purposes 1 and 2 have scientific and policy goals. From the scientific side, they are used to explore future states of the global climate system, and from the policy side, to assess the consequences on climate and society of different emission levels.

There are no accepted methods for evaluating whether the IS92 scenarios comply with Purpose 1 above, or any other purposes of scenarios. Since scenarios deal with the future, they cannot be compared with observations. The "reasonableness" of their input assumptions and methodology could

be examined, but this is best done by comparing several models in an organized intercomparison exercise. This was outside the scope of this evaluation. We have chosen instead to evaluate the IS92 emissions scenarios by comparing the range of their emission projections and their major input assumptions with those of other non-intervention scenarios. While this comparison does not answer all questions about the scenarios, it does provide information about the position of the scenarios relative to other work in the scientific community, and it was feasible in the short time available for this evaluation.

Energy Related Scenarios - How Different Are Their Results?

Global Results

There are many more scenarios related to energy than to land use because the models and methods used to estimate energy related emissions are more detailed and advanced than those used to compute land use related emissions, and because existing energy models could easily be adapted to generate CO₂ emissions. Consequently much of the comparison of scenarios focuses on this type of scenario. The following can be said of their results:

- Energy related emissions currently dominate other types of CO₂ emissions, and will continue to do so in the future according to all scenarios.

- Almost all published reference scenarios (including the IS92 scenarios) show an increase in energy related CO₂ emissions over the next century. Only one of six IS92 scenarios, IS92c, shows a decline in total CO₂ emissions between 1990 and 2100.

- For energy related CO₂ emissions, the extremes in the literature span a very wide range, from 1.2 to 60 Pg C a⁻¹ in 2100. (The symbols Pg C a⁻¹ stand for petagrams of carbon dioxide emissions in units of carbon (C) per annum. A petagram is 10¹⁵ grams, and is equivalent to a gigaton of emissions.) The IS92 scenarios bracket a large part of this range, spanning from 4.6 to 34.9 Pg C a⁻¹.

- The estimates of emissions diverge greatly with time. The difference between the high and low IS92 scenarios is less than a factor of 2 in 2025, and by 2100 it is nearly a factor of 8. The highest and lowest non-IPCC scenarios evaluated here vary by a factor of 3 in 2025, and a factor of 50 in 2100.

- This very wide range can be explained mostly by differences in the input assumptions of the scenarios, particularly economic and population growth, and assumptions that influence the amount of carbon-based fuels in the economy. Another

factor is the uncertainty of the models used to compute the scenarios.

- The cumulative energy related emissions of the scenarios over the period 1990 to 2100, range from 492 to 3447 Pg C (a factor of 7), which is considerably smaller than the range of annual emissions in 2100. The cumulative emissions of the IS92 scenarios fall within this range (700 to 2078 Pg C).

- The cumulative emissions of energy related carbon dioxide in the period 1860 to 1990 was about 215 Pg C. This is exceeded by even the IS92 scenario (the lowest IPCC scenario) which will emit 700 Pg C in the period 1990 and 2100.

- Cumulative emissions are important from the climate analysis standpoint because CO₂ and other direct greenhouse gases can affect climate over decades to centuries after they are emitted. This is because of the integrative nature of the atmosphere-ocean system.

- Whether or not CO₂ emissions will accumulate in the atmosphere depends on many factors which are partly taken into account by carbon cycle models. Model calculations of this sort from Working Group I indicate that the emissions of the IS92c scenario could raise atmospheric concentrations of CO₂ to approximately 480 ppmv by 2100. Hence, the lowest IPCC scenario (which leads to lower CO₂ emissions in 2100 than at present) could lead to a build-up of CO₂ in the atmosphere.

As compared to CO₂, there are far fewer scenarios of non-CO₂ emissions. For these scenarios an additional source of uncertainty is important, namely, the uncertainty of *baseline* emission estimates. This means that non-CO₂ scenarios have an overall lower reliability than CO₂ scenarios. IS92 estimates of energy related CH₄ and N₂O emissions have a range of a factor of 6 to 7 in the year 2100. The range of IS92 scenarios of non-CO₂ emissions overlap with the few other published scenarios of this type.

Regional Results

There are many regional and country estimates of CO₂ emissions, but these are not identical to the IS92 regions, so comparison was not possible. The following can be said of the few scenarios available for comparison:

- The range of results is about the same as that of global scenarios.

- For the region Eastern Europe and Former Soviet Union, the IS92 scenarios have a higher trend than more recent scenarios that take into account the

change in economic activity in these regions.

- The range of IS92 scenarios is in the lower half of the range of reference estimates for the USA.

Energy Related Scenarios - How Do Their Components Compare ?

Both the IS92 scenarios and other scenarios examined here rely on large numbers of input assumptions. It was outside the scope of this evaluation to assess the differences between all of these assumptions. Therefore in this evaluation the projections of energy CO₂ emissions were broken down into four components, and these components were compared between the scenarios. These were: population growth, economic growth, energy intensity (the amount of primary energy used per unit GDP), and carbon intensity (the amount of carbon emitted per unit primary energy consumed). Some of these are specified as model inputs, and some are derived from model calculations.

- Nearly all scenarios show a downward trend of energy intensity. The energy intensities of the IS92 scenarios have a narrower range than other scenarios.
- The carbon intensity of the IS92 scenarios all show a downward trend, whereas some non-IPCC scenarios decreased while others increased.
- Assumed changes in energy and carbon intensity have an important influence on estimates of emissions, especially in the second half of next century.
- The range of economic growth assumptions of the IS92 scenarios is representative of the range of other global scenarios (this applies to scenarios of both energy and land use emissions). Economic growth rates of the IS92 scenarios are generally lower than historical rates but they would lead nevertheless to large increases in per capita GDP in all regions.
- Other recent population estimates support the plausibility of the medium population growth rate assumed in the IS92 scenarios.
- The IS92 scenarios have the lowest and highest global growth rates of population of all scenarios reviewed. The low projection (IS92c) results in declining global population in the 21st century. These figures are taken from UN projections, and are not inconsistent with other recent high and low estimates.
- It is outside the scope of this report to evaluate the various critical issues related to population projections such as population aging, earth's carrying capacity, and the relationship between economic development and demographic trends.

More research is needed to improve our understanding of these issues so that we can better judge the consistency and likelihood of population projections, and in turn improve our estimates of future emissions.

- In general, the components of the IS92 scenarios are fairly representative of other *global* scenarios, but not of *regional* scenarios. For example, the IS92 scenarios span a much smaller range of assumptions of future energy intensity for China and the USA than the set of non-IPCC scenarios. Hence the IS92 scenarios only represent part of the range of regional perspectives contained in the scenarios examined here.

Energy Related Scenarios -- To What Factors Are Emission Estimates Most Sensitive?

Some of the uncertainty of future emission projections can be attributed to the different methods and models used to compute emissions. However, there is evidence from model intercomparisons that model differences can only explain only a small part of the wide range of emission estimates found in the literature. Most of this range arises from differences in input assumptions of the scenarios. Out of all input assumptions, population and economic growth usually play a key role, as well as assumptions that influence the amount of carbon-based fuels used in the economy.

In addition to the factors mentioned above, the IS92 scenarios are particularly sensitive to assumptions about labor productivity, the growth of demand for energy in developing countries as incomes rise, and the rate of improvement of end-use energy efficiency not related to fuel prices.

Land Use Related Scenarios - How Different Are Their Results?

Global Results

Scenarios related to global land use emissions are much fewer in number than those of the energy system. As with energy related emissions, global estimates are more common in the literature than regional estimates. The following can be said about global CO₂ scenarios related to land use:

- Net deforestation contributes about 20% to current total CO₂ emissions, and most scenarios estimate that this percentage will decline in the future.
- Projected emissions of CO₂ related to deforestation differ widely. Unlike energy emissions which diverge with time, land use emissions have

their widest range (0.8 to 4.8 Pg C per year) in the middle of the 21st century. Most scenarios then converge to zero by the end of the century because they project that driving forces of deforestation equilibrate or forests are depleted.

- The IS92 scenarios fall within the lower half of the range of other global CO₂ scenarios.

- As with energy related emissions, the range of cumulative emissions over the period 1990 to 2100 (80 to 320 Pg C) is considerably smaller than the range of annual emission estimates for year 2100. Above it was noted that this is significant from the point of view of climate impact analysis. Cumulative emissions have an upper bound set by the maximum available amount of terrestrial biomass that could be oxidized (about 600 Pg C neglecting forestation). No similar upper limit is foreseen for energy related emissions in the next century.

Regional Results

With regards to the few published *regional* land use scenarios of CO₂ and other greenhouse gases, there are very considerable differences between the scenarios; the IS92 scenarios sometimes fall within the range of other scenarios and sometimes outside. The range of emission estimates is about the same for regional scenarios as it is for global scenarios, and the scenarios converge in a similar way by the year 2100.

Land Use Related Scenarios - How Do Their Inputs Compare and What Are Their Emission Estimates Sensitive To?

- The assumed rate of deforestation is the most important factor influencing emissions of CO₂ related to deforestation. Most scenarios make very simple assumptions about the driving forces of deforestation, although some scenarios are based on models that simulate land conversion. The different ways of representing deforestation lead to different estimates of deforestation rates, although the set of scenarios examined here agree that forest clearing will diminish by 2100 for the reasons cited above.

- Assumptions about carbon content of vegetation also strongly influence estimates of CO₂ emissions.

- The scenarios examined take a wide variety of different approaches in estimating future emissions. This reflects the lack of knowledge or agreement on how to represent emission-generating processes.

- Not only are processes poorly understood, but even baseline estimates differ between scenarios, which leads to even greater differences in future emission estimates. Results from current emission

inventories are needed to improve these baseline estimates.

- The IS92 scenarios do not take into account the feedback of climate to land use emissions, and this is one reason why their results differ from other scenarios. However, climate feedbacks are quite uncertain, and including them in estimates of land use emission scenarios may or may not improve these estimates.

- In general, the IS92 scenarios do not cover the range of input assumptions found in other scenarios related to land use.

What Are the Uses and Limitations of the IS92 Scenarios?

In evaluating the IS92 scenarios it is important to recall that they were developed only to accomplish Purpose 1. The IS92 scenarios fulfill the most important criteria for this purpose. Specifically, their global results span the range of results of other scenarios, and in this way can be said to reflect the current range of views about future emission estimates. Moreover, the IS92 scenarios are among the most comprehensive scenarios available in their coverage of all important greenhouse gases and precursors of ozone and sulfate aerosol. Also the scenarios are sufficiently documented in reports and in digital form to allow their comparison with other scenarios, and to be used as input files for climate models. As a consequence, they are useful for Purpose 1, namely as input to atmosphere/climate models for examining the environmental/climatic consequences of not acting to reduce greenhouse emissions.

Although the IS92 scenarios were designed with Purpose 1 in mind, it is still interesting to question whether they are useful for the other purposes of scenarios. With regards to Purpose 2 (evaluating the consequences of intervention to reduce emissions), it was found that the IS92 scenarios have emission estimates that are substantially higher than policy scenarios published in the literature. Hence, they should not be used as intervention scenarios.

The IS92 scenarios are inadequate for Purpose 3 (estimation of feasibility and costs of policies) primarily because 5 out of 6 scenarios do not include mitigation measures specifically targeted towards climate change (they were also not intended for this purpose). In addition, they have limited use as reference scenarios for mitigation studies because their input assumptions and results

do not have sufficient detail for geographic regions and sectors. Another reason is that regional results and regional input assumptions of the IS92 scenarios do not cover the full range of views found in other scenarios.

The IS92 scenarios are not appropriate for Purpose 4 (input to negotiating possible emission reductions) because of the high uncertainty of current greenhouse gas estimates from many sectors and countries. However, they do help set the context for such negotiations by indicating the possible range of emissions if no mitigation takes place. It is again noted that the scenarios were not intended for purpose 4.

The Question of New Scenarios

For the reasons noted above, at this time it is recommended that researchers use the IS92 scenarios as input to atmosphere/climate models for examining the consequences of not acting to reduce greenhouse gas emissions (Purpose 1).

As to the use of one IS92 scenario over another -- In some ways the IS92a scenario is intermediate among the scenarios. Its global CO₂ emissions fall near the middle of other scenarios at least up to year 2050, and some of its input assumptions are intermediate. For example, its population assumptions are equal or close to the medium projections recently published by three different international organizations. In other ways, it is not intermediate, particularly in some of its input assumptions.

In any event, being an intermediate scenario is not the same as being the most likely scenario. Indeed, at this time there is no objective basis for assigning a likelihood to one scenario or another. Furthermore, considering the degree of uncertainty about future emissions, it is recommended to use the full range of IS92 scenarios as input to atmosphere/climate models rather than any single scenario.

Users of the IS92 scenarios are cautioned, however, that the lowest scenario (IS92c) has the emission levels and some input assumptions more characteristic of an intervention rather than a non-intervention scenario.

In general, because the IS92 scenarios were not designed and are not suitable for Purposes 2, 3, and 4, new scenarios may be needed to fulfill these

purposes. It is worth repeating that the evaluation did not judge the suitability of non-IS92 scenarios to satisfy these purposes.

New scenarios, if developed, should especially include improvements in the estimation of baseline and future non-CO₂ emissions, particularly from the land use sector.

Although we did not judge the adequacy of all currently available scenarios, it is still likely that new reference scenarios will be needed for the following:

- to take into account the latest information on economic restructuring, especially in the CIS, Eastern Europe, Asia, and Latin America, (we note that restructuring in Eastern Europe and the CIS was partly taken into account in the IS92 scenarios, but it would be worthwhile to include more recent information about this restructuring)
- to evaluate the possible consequences of the Uruguay Round amendments to the General Agreement on Tariffs and Trade
- to explore a variety of economic development pathways, for example, a closing of the income gap between industrialized and developing regions.
- to examine different trends of technological change.
- to take into account the latest information about current emission commitments in connection with the Climate Convention.

The current commitments to stabilize emissions under the Climate Convention could result in large reductions of emissions in certain regions, but on a global basis a reduction of 10% or less is expected in CO₂ emissions (in annual emissions relative to the IS92a scenario). Current commitments will have no effect on the lowest IPCC scenario (IS92c) because emissions in this scenario are lower than would be expected by current commitments.

New scenarios are also needed that are consistent with limits on atmospheric concentrations of greenhouse gases by a specified date. These should be related to the carbon stabilization modeling exercises being performed by IPCC Working Group I.

The Process of Developing Scenarios

If new or updated scenarios are developed it is recommended that the following approach be taken to develop these scenarios. The IPCC or other suitable organization should act as an "umbrella"

under which different groups can develop comparable, comprehensive emission scenarios. The process for developing scenarios should draw on current experience in harmonizing scenarios and model calculations, by emphasizing the following:

-- *Openness*. Scenario development should be open to the wide participation of the research community, particularly from developing countries. This requires extensive documentation of modeling assumptions and inputs;

-- *Pluralism*. A diversity of groups, approaches and methodologies should be encouraged, although they should be harmonized as noted below;

-- *Comparability*. Reporting conventions of input and output should be standardized.

-- *Harmonization*. Input assumptions and methodologies of the scenarios should be harmonized in order provide a common benchmark for scenarios from different groups.

To accomplish Purpose 3 of emission scenarios (estimation of feasibility and costs of mitigation measures) it is not only important to analyze the costs of emission reductions, but also to assess the costs and benefits of the impacts of emissions on the natural environment and society. Therefore scenarios developed for this purpose should be coupled with their impact on the environment and society in the form of consistent, comprehensive *integrated* scenarios of global change.

Current and new scenarios should be widely disseminated to countries, international organizations, non-governmental organizations and the scientific community. As part of this effort, a central archive should be established to make available the results of new scenarios to any group. The archive should also make available some aspects of the models and input assumptions used to derive scenarios. In addition, special effort is needed to improve the capabilities of researchers to analyze and develop scenarios, especially in developing regions. The IPCC can play a role in these activities.

6.1 Background and Scope

6.1.1 Terms of Reference

This chapter presents an evaluation of the IPCC IS92 emission scenarios. The evaluation is a response to a request from the Chairman of the Intergovernmental Negotiating Committee for the Framework Convention on Climate Change that IPCC prepare "an evaluation of current scenarios of greenhouse gas emissions ..." before the March, 1995 meeting of the Conference of Parties (UNGA document A/AC.237/30). According to the approved work plan, the key question of the evaluation is "Which issues and uncertainties about key variables may critically affect future net greenhouse gas emissions and aerosol concentrations?" Among the issues to be explored:

- Types of models available for scenario development;
- Assumptions made in developing the IS92 scenarios;
- Relative importance and sensitivity of different variables in determining future emissions;
- Relationship of the scenarios to emission inventories of countries;
- Appropriate uses, capabilities and limitations of emission scenarios;
- Need for future work on scenarios.

The Bureau of Working Group III further recommended that this evaluation "build heavily" on the scenarios published in the IPCC 1992 Supplement (First Session of Working Group III, Montreal, 3 May, 1993, WGIII/1st/Doc.1, Rev.2).

An appropriate question at the outset is, "Who is the audience for this evaluation?". The Work Plan of Working Group III implies both a scientific and policy audience by asking for recommendations on new scenarios that would "... serve the needs of climate modeling, planning of response measures, and provision of information to the Conference of Parties ...". Indeed, scenarios by nature have both scientific and policy aspects; from a scientific standpoint, they provide a reference point for computing the potential occurrence and impacts of climate change; from the policy perspective they provide information about the consequences of intervention or inaction to reduce greenhouse gas emissions. But in practice it is difficult to separate out scientific from policy aspects of scenarios, and in this chapter we do not try.

In this chapter we first present the scope and approach of the evaluation, and then a brief overview of IS92 scenario assumptions and results. This is followed by a comparison of the IS92 and other scenarios during which we examine much more closely the assumptions and results of the IS92 scenarios. Finally, the uses and limitations of scenarios are presented, together with recommendations.

6.1.2 Scope of Evaluation

Only six months were available to meet the INC deadline for this evaluation. This time constraint, together with the lack of a budget for further analysis led to narrowing the focus of the evaluation:

- Only the most recent IPCC scenarios are evaluated since these are the most recent scenarios developed under the IPCC process. These scenarios are reported in the IPCC 1992 Supplement (Leggett, *et al.*, 1992; Pepper, *et al.*, 1992), and are hereafter referred to as the "IS92 scenarios".
- The IS92 scenarios are only compared with other published "non-intervention" scenarios because the IS92 scenarios are intended to be "non-intervention" scenarios (that is, they do

not make assumptions about climate policies that would reduce greenhouse gases). Some intervention (or "policy") scenarios are reviewed, but only for comparing them with the lowest IS92 scenarios.¹

- The evaluation focuses on emissions related to energy and land use activity because they are the primary sources of greenhouse gases. Non-anthropogenic, "natural" emissions are not considered.
- Principal attention is given to scenarios of CO₂ emissions because of the critical contribution of CO₂ to radiative forcing, and lesser attention to scenarios of CH₄ and N₂O emissions.
- Scenarios of sulfur emissions are investigated, but not scenarios of ozone's major precursors.
- Sinks of gases are omitted, such as carbon sequestration in forest plantations. An exception is made when scenarios of CO₂ from deforestation are discussed; part of the discussion of deforestation concerns carbon uptake by vegetation.

Certain tasks are not part of the evaluation:

First, this evaluation focuses almost exclusively on scenario results and input assumptions rather than on the methodology behind them. This is because much more time would be needed to properly assess the methodology of the scenarios and because the IS92 emission scenarios appear to be more sensitive to the input assumptions than the methodology.

Second, we did not perform a sensitivity analysis of the model used to generate the IS92 emission scenarios. The funds needed for such work were not available. In any case such an analysis would be best performed as part of a more extensive comparison involving several emission models. This comparison would require the cooperation of various modelling groups and would take longer than the time available.

Third, we did not compare 1990 baseline emissions for the IS92 scenarios with emissions inventories of different countries. There were too few inventories available to be compared. However, as more inventories become available, we recommend that they be used to examine and update the baseline emissions of scenarios.

Fourth, we did not attempt to identify the likelihood of any scenarios. It is our view that there is no objective method of assessing the likelihood of all key assumptions that will influence future emission estimates, especially over the 110 year time horizon of the IS92 scenarios. The poor track record of economic and energy forecasts indicates our inability to predict even the near term future. Thus, we do not attempt to identify a most likely emissions scenario.

6.1.3 Approach to Evaluation

A scenario, in the most general sense, is "a sequence of events", or "an account of a projected course of action or events" (Webster's Ninth Collegiate Dictionary, 1989). An emissions scenario is a projection of future emissions based on specific assumptions about key determinants such as population, economic growth, energy intensity, land use, or emission control policies. Sometimes scenarios are confused with emission profiles, targets, and other

¹ We note in Section 6.2 that the IS92b scenario makes certain assumptions about climate policies.

Box 1. Terminology Related to Emission Scenarios

<i>Emissions Scenario</i>	Projections of future emissions based on specific assumptions about key determinants such as population, economic growth, technological change, land use trends, or emission control policies.
<i>Non-Intervention or Reference Scenario</i>	An emissions scenario that does not make any assumptions about climate policies to reduce greenhouse gases. It is sometimes difficult to distinguish non-intervention and intervention scenarios. For example, assumed high prices of fossil fuels could stem from either resource scarcity or carbon taxes aimed at reducing greenhouse gas emissions.
<i>Intervention or Policy Scenario</i>	An emissions scenario that makes assumptions about <i>climate</i> policies to reduce greenhouse gases. Policies must be intended to mitigate climate change.
<i>Emissions Profile</i>	Level of future emissions derived directly or indirectly from a specific objective.
<i>Emissions Target</i>	A target emissions level for a particular date.
<i>Emissions Trend</i>	A projection of future emissions that is not based on specific determinants or objectives.

concepts (see Box 1). Emission scenarios are also sometimes mixed up with the methodology used to generate them. In most cases emission scenarios are generated with a mathematical model(s) or other computational tools, although in some cases they are developed in an ad hoc manner. As noted above, this chapter focuses almost exclusively on scenario results and input assumptions rather than on the methodology behind them.

Because emission scenarios fall in the grey area between science and policy, it is difficult to select an appropriate benchmark to judge them. Box 2 makes a first attempt at specifying the major purposes of emission scenarios. We recognize that there may be other valid purposes.

Criteria for achieving these purposes are ranked according to "very important", "important", and "desirable" in Table 6.14, presented later in the chapter.

We note here that the IS92 scenarios were only developed with Purpose 1 in mind. Therefore, the scenarios are evaluated in this chapter mainly in the light of how they comply with this purpose. The other purposes are discussed in Section 6.5 when the need for new scenarios is discussed.

Box 2. Proposed Purposes of Emission Scenarios

- | | |
|------------|--|
| Purpose 1. | To evaluate the environmental/climatic consequences of "no intervention" to reduce greenhouse gas emissions. For this purpose a non-intervention scenario is devised and then input to a climate or similar model to evaluate the scenario's environmental/climatic consequences. |
| Purpose 2. | To evaluate the environmental/climatic consequences of intervention to reduce greenhouse gas emissions. For this purpose an intervention scenario is devised, and then input to a climate or similar model to evaluate the scenario's environmental/climatic consequences. |
| Purpose 3. | To examine the feasibility and costs of mitigating greenhouse gases from different regions and economic sectors, and over time. This can include setting emission reduction targets, and developing scenarios to reach these targets. It can also include examining different driving forces of emissions and sinks in order to identify the driving forces which can be influenced by policies. |
| Purpose 4. | As input for negotiating possible emission reductions for different countries and geographic regions. |

Purpose 1 is the most straightforward use of emission scenarios. In this case, a non-intervention emissions scenario is developed, and is then input to a climate model which computes the effect of the emissions pathway on the build-up of greenhouse gases, changes in temperature, precipitation, and other climate variables. Results from the climate model are then sometimes used to evaluate impacts of climate change on sea level rise, agricultural productivity, and other indicators. This type of emissions scenario also serves as a reference point for the intervention scenarios developed for Purpose 2, and for assessing the benefits of reducing greenhouse gas emissions.

In our view a scenario or set of scenarios must comply with three very important criteria to fulfill Purpose 1. The first two are related to the use of the emissions scenario as input to atmosphere/climate models, and the last one has to do with the credibility of the scenarios.

Comprehensive. The scenarios must take into account all important greenhouse gases including precursors of ozone and sulfate aerosol. This is important so that radiative forcing is not incorrectly calculated by the climate model.

Documentation of Output. Sufficient detail is provided for emissions by type, region (if available) and sector, in order to allow comparisons with other scenarios and to prepare inputs for atmosphere/climate models.

Emission Estimates and Input Assumptions of the Scenario Reflect a Range of Views. A single reference scenario is inadequate for this purpose. Instead, a range of scenario results are presented that take into account the uncertainties of basic driving forces of the scenarios. Data on driving forces, as well as parameters in the case that a model is used, reflect the current range of views. In addition, derived variables, for example, carbon intensity of the economy, also reflect current understanding.

We examine the comprehensiveness of the IS92 scenarios in Section 6.2, while the documentation of output is briefly discussed in Sections 6.2 and 6.5. The third criterion, examining if the IS92 scenarios represent a range of views, makes up the core of the evaluation. This is covered in Sections 6.2, 6.3, 6.4 by comparing the emission projections and major input assumptions of the IS92 scenarios with those of other published non-intervention scenarios. It is recognized that published scenarios give only the views of a limited number of experts, principally from industrialized countries. Nevertheless, this comparison does provide information about the position of the scenarios relative to other work in the scientific community, and it can be performed in the short time available for this evaluation.

All published scenarios used for our comparisons are treated equally. We recognize that one may have been prepared by a single researcher using a very simple model while another may have been developed using a very elaborate methodology and been subjected to extensive review. However, we do not believe that any methodology nor any approach to selecting values for the input assumptions is inherently better.

While we consider the above three criteria as the most important benchmarks for Purpose 1, there are three others that are important:

- Reproducibility
- Sensitivity Analysis
- Internal Consistency

These criteria are elaborated in Table 6.14, later in this chapter.

6.2 The IPCC IS92 Scenarios

This evaluation covers the six IPCC emission scenarios, known as the "IS92 scenarios". They are described in the Supplementary Report to the First Assessment (Leggett, et al., 1992), and in more detail in Pepper, et al., 1992. The reader is referred to these publications for details about the scenarios; only a brief overview is presented here.

The basic purpose of the scenarios is to explore possible pathways of greenhouse gas emissions in the absence of new policies to reduce them. The scenarios are among the most comprehensive ever developed in their coverage of all important greenhouse gases -- carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), halocarbons, sulfur oxides (SO_x), and precursors of tropospheric ozone: nitrogen dioxides (NO_x), volatile organic compounds (VOC), and carbon monoxide (CO). The scenarios take into account control of stratospheric ozone depletion and local air pollution problems, and this leads to reductions in emissions of some greenhouse gases. Moreover, the IS92b scenario includes commitments of some OECD countries to stabilize or reduce CO₂ emissions, as they were known up to 1992. Nevertheless, since these emission control commitments in IS92b do not have a large effect on global emissions, we will refer to the entire set of IS92 scenarios as "non-intervention" scenarios.

6.2.1 The ASF Model

A model of the US Environmental Protection Agency called the "Atmospheric Stabilization Framework" (ASF) was used to develop the IS92 scenarios (EPA 1990). The model performs calculations for nine regions. Results for the nine regions are available in electronic form, but in IPCC reports have been aggregated into four regions: OECD, Eastern Europe and former USSR, China and Centrally Planned Asia, and "Other".

The ASF combines modules for computing emissions from energy, industry, agriculture, forests, and land conversion using common assumptions for population, economic growth and structural change.

Findings of the Energy Modeling Forum indicate that fossil fuel carbon emissions are highly sensitive to alternative input assumptions of such key variables as the rate of exogenous end use energy intensity improvement, but relatively insensitive to the form of the model used to generate the scenario. There are thousands of input assumptions that define a case in the ASF.¹ Fortunately, not all assumptions are equally important. The uncertainty analysis conducted by Edmonds et al. (1985) on the energy component of the ASF ranked the three most important factors influencing the variation in reference case fossil fuel CO₂ emissions to be: labor productivity (the prime determinant of GDP), the income elasticity of demand for energy in the developing world (reflecting structural change rates), and the rate of exogenous end-use energy intensity improvement. In addition, fossil fuel CO₂ emissions in the energy component of the ASF model have been shown to be highly sensitive to assumed costs for and resources of renewable energy sources (Edmonds *et al.*, 1994) as well as the environmental costs of extracting fossil fuels.

The energy component of the ASF model is insensitive to population growth

¹ A distinction is sometimes made between model parameters and input assumptions. Model parameters are assumptions that remain constant from case to case, while input assumptions are the set of assumptions whose variation defines cases. There are no formal rules for determining which variables are model parameters and which are input assumptions, and the boundary partitioning assumptions into these two sets can change.

assumptions in the short-term, but sensitive to this assumption in the long-term.² In the long term fossil fuel CO₂ emissions are roughly proportional to population.

The model is relatively insensitive to changes in assumed fossil fuel resources, elasticity of interfuel substitution, the price elasticity of demand for energy and emissions coefficients for fossil fuel carbon. The fossil fuel resource base provides no meaningful constraint on carbon emissions for the next century. Fuel price variation is constrained by energy transformation technologies and the variety of alternative energy forms available so the model is insensitive to the elasticity of interfuel substitution. Although fossil fuel CO₂ emissions are insensitive to the assumed price elasticity of demand for energy, this parameter strongly influences the cost of achieving emissions reduction targets (Edmonds and Barns, 1993). Sensitivity analysis of emission estimates is again taken up in Section 6.3.

The land use component of the ASF is also strongly influenced by assumptions about GDP and population.

6.2.2 Overview of the IS92 Scenarios

To explore a variety of possible pathways of future emissions, the IS92 scenarios cover a wide range of assumptions for population, GDP, agriculture, energy and other determining factors. Specific assumptions are made for each of nine regions. An overview of key assumptions is given in Table 6.1.

Among other recent developments, the IS92 scenarios take into account the London Amendments to the Montreal Protocol; revised population forecasts of the World Bank and United Nations; the report of the Energy-Industry Subgroup of IPCC (ESG, 1990); political and economic changes in the former Soviet Union, Eastern Europe, and the Middle East; and new data on tropical deforestation, and sources and sinks of greenhouse gases.

Scenario IS92a adopts intermediate assumptions (as compared to the other IS92 scenarios) about population and economic growth. The major difference between the IS92b and IS92a scenarios is, as noted above, that IS92b takes into account information available up to 1992 on the commitments of some OECD countries to stabilize their CO₂ emissions. The IS92a and b scenarios give emission estimates that are intermediate to the other IS92 scenarios (Table 6.2).

The IS92c scenario assumes the lowest rates of population and economic growth (as compared to other IS92 scenarios) and severe constraints on fossil fuel supplies. As a result, this is the lowest emissions scenario, and the only one showing a decreasing emissions trend (Table 6.2). Scenario IS92d assumes the low population growth rate of IS92c but a higher economic growth rate. The net result is that it has the second lowest future emission estimates. At the other extreme, the IS92e scenario assumes intermediate population growth and high economic growth rates with plentiful fossil fuels. Consequently, this scenario has the highest estimates of future emissions (Table 6.2). Scenario IS92f uses the highest population estimates of the IS92 scenarios, but lower economic growth assumptions. It is the second highest emissions scenario (Table 6.2).

Much more is said about the assumptions and results of the IS92 scenarios in the remainder of the report.

² Increases in population do not affect GDP for 15 years (the time required for an infant to reach labor force age). Therefore increases in energy demand due to increases in population are countered by decreases in energy demand due to lower per capita income levels.

Table 6.1: Summary of assumptions in the six IPCC 1992 alternative IS92 scenarios.

Scenario	Population	Economic Growth		Energy Supplies	Other	CFCs
IS92a	World Bank 1991 11.3 B by 2100	1990-2025:	2.9%	12,000 EJ Conventional Oil 13,000 EJ Natural Gas Solar costs fall to \$0.075/kWh. 191 EJ/year of biofuels available at \$70/barrel†	Legally enacted and internationally agreed controls on SO _x , NO _x and NMVOC emissions. Efforts to reduce emissions of SO _x , NO _x and CO in developing countries by middle of next century	Partial compliance with Montreal Protocol. Technological transfer results in gradual phase out of CFC's in non-signatory countries by 2075.
IS92b	World Bank 1991 11.3 B by 2100	1990-2025:	2.9%	Same as "a"	Same as "a" plus commitments by many OECD countries to stabilize or reduce CO ₂ emissions.	Global compliance with scheduled phase out of Montreal Protocol.
IS92c	UN Medium-Low Case 6.4 B by 2100	1990-2025:	2.0%	8,000 EJ Conventional Oil 7,300 EJ Natural Gas Nuclear costs decline by 0.4% annually.	Same as "a"	Same as "a"
IS92d	UN Medium-Low Case 6.4 B by 2100	1990-2025:	2.7%	Oil and gas same as "c" Solar costs fall to \$0.065/kWh 272 EJ/year of biofuels available at \$50/barrel	Emission controls extended worldwide for CO, NO _x , NMVOC and SO _x . Halt deforestation. Capture and use of emis- sions from coal mining and gas produc- tion and use.	CFC production phase out by 1997 for industrialized countries. Phase out of HCFCs.
IS92e	World Bank 1991 11.3 B by 2100	1990-2025:	3.5%	18,400 EJ conventional oil Gas same as "a" Phase out nuclear by 2075	Emission controls which increase fossil energy costs by 30%.	Same as "a"
IS92f	UN Medium-High Case 17.6 B by 2100	1990-2025:	2.9%	Oil and gas same as "e" Solar costs fall to \$0.083/kWh Nuclear costs increase to \$0.09/kWh	Same as "a"	Same as "a"

† - Approximate conversion factor: 1 barrel = 6 GJ

Source of Table: Leggett, *et al.* (1992)

Table 6.2: Selected results of the six IS92 scenarios

Scenario	Scenario year	Emissions per year			
		CO ₂ (PgC)	CH ₄ (Tg)	N ₂ O (TgN)	S (TgS)
IS92a	1990	7.4	506	12.9	98
	2025	12.2	659	15.8	141
	2100	20.3	917	17.0	169
IS92b	2025	11.8	659	15.7	140
	2100	19.1	917	16.9	164
IS92c	2025	8.8	589	15.0	115
	2100	4.6	546	13.7	77
IS92d	2025	9.3	584	15.1	104
	2100	10.3	567	14.5	87
IS92e	2025	15.1	692	16.3	163
	2100	35.8	1072	19.1	254
IS92f	2025	14.4	697	16.2	151
	2100	26.6	1168	19.0	204

6.2.3 GDP Assumptions

Both the energy and land use related emission estimates are strongly influenced by the assumptions of GDP and population growth. Although a detailed analysis of these assumptions is outside the scope of this report, the following paragraphs highlight some tentative conclusions and important issues concerning the economic and population assumptions. We begin by briefly reviewing the total GDP growth assumptions of the IS92 scenarios.

The assumptions of the *intermediate* IS92 scenarios (IS92a and b) are partly based on the reference scenario of the Energy and Industry Sub-Group of the First IPCC Assessment (ESG, 1990) for the period up to 2025. Near-term growth rates in the ESG scenario were adjusted downwards in Eastern Europe, CIS, and Persian Gulf, to reflect the consequences of events occurring at the beginning of the 1990s. As noted by the developers of the IS92 scenarios (Leggett, et al., 1992), the medium assumptions for near-term economic growth are generally below or at the low end of the range given by World Bank for 1990-2000 (Table 6.3). In addition, the medium assumptions for economic growth in the period 1990-2025 are

Table 6.3 Growth Assumptions of total GDP (average annual rate)

	World bank†.....								
		Low††	High††	IS92c		IS92a		IS92e	
	1965 1989	1990 2000	1990 2000	1990 2025	1990 2100	1990 2025	1990 2100	1990 2025	1990 2100
OECD	3.2%	2.4%	3.1%	1.8%	0.6%	2.5%	1.7%	3.0%	2.2%
USSR/E.Europe- †††	1.3%	3.2%	3.6%	1.5%	0.5%	2.4%	1.6%	3.2%	2.4%
China & CP* Asia	7.6%	5.6%	6.7%	4.2%	2.5%	5.3%	3.9%	6.1%	4.7%
Other	4.7%	3.8%	4.5%	3.0%	2.1%	4.1%	3.3%	4.8%	4.1%
Global	-	-	-	2.0%	1.2%	2.9%	2.3%	3.5%	3.0%

Source of Table: Leggett, *et al.* (1992)

† Source: World Bank (1991).

†† Estimated using projections of regional growth in GDP/capita and country estimates of GDP, population and population growth from 1990 to 2000.

††† World bank data do not include all countries in Eastern Europe.

* CP= Centrally planned economies.

lower than most regions experienced from 1965 to 1989 with the exception of Africa, Eastern Europe and the CIS (Table 6.3). For these regions it was assumed that structural adjustments will lead to higher than historical growth in the *medium-term*. For the period 2050-2100, all of the IS92 scenarios assume that economic growth will slow because of saturation of consumption and expected slower growth of population (Table 6.3).

As to the high and low assumptions of the IS92 scenarios, because of the uncertainty of future trends of economic growth, the low (IS92c) and high (IS92e) estimates span a wide range of possibilities.

The following additional points can be made about the GDP growth assumptions of the IS92 scenarios:

- As noted in Section 6.3, the high and low rates of growth of *global average* GDP in the IS92 scenarios are quite representative of the wide range of views of other published scenarios. However, somewhat higher and lower global growth rates can be found in the literature about energy scenarios.
- With regards to *regional* results, there are many cases in which the IS92 scenarios are higher or lower than any other scenario. In the case of Eastern Europe and the CIS, the IS92 scenarios take into account economic restructuring in these regions, but they assume higher economic growth rates in the near term than more recent scenarios.

- Although the medium assumptions of the IS92 scenarios are lower than historical growth rates, they nevertheless imply a substantial increase in per capita GDP. For example, in the second half of the next century, per capita GDP in East Asia and Latin America will exceed current levels in OECD Europe. Nevertheless, a large gap will remain between incomes of developed and developing regions, and there is the need to develop emission scenarios which assume a closing of this income gap.
- Emission estimates can be improved by GDP projections that take into account economic restructuring underway in many regions.

Summing up the discussion of GDP assumptions -- The range of total economic growth assumptions of the IS92 scenarios is representative of the range of other global scenarios. However, they are not always representative on the regional level. Economic growth rates of the IS92 scenarios are generally lower than historical rates but they would lead nevertheless to large increases in per capita GDP in all regions.

6.2.4 Population Assumptions

The influence of population assumptions on future emission estimates is significant. The following can be said about the population assumptions of the intermediate IS92 scenarios:

- The medium global assumption of the IS92 scenarios (11.3 billion in year 2100) is based on the latest medium projection of World Bank (1991) (Table 6.4).
- For year 2025, the IS92 medium population projection is very close to the latest medium projections of both the UN (1992) and IASA (1994) (Table 6.4).
- For year 2100 the three medium projections are still somewhat close (Table 6.4).
- Projections from World Bank, UN, and IASA were all made using the cohort-component approach to demographic projections, but they employed very different assumptions about changes in demographic variables. Hence it is significant that the medium projections are close. With regards to the low and high population assumptions of the IS92 scenarios:
- The low and high global assumptions of IS92 (6.4 to 17.6 billion in year 2100) are the latest medium-low and medium-high projections of the UN (1992) (Table 6.4). (The World Bank did not provide high or low projections with its most recent medium projections.)
- The low and high projections of IS92 are the highest and lowest projections of all published scenarios reviewed in this report. Hence, from the emission scenarios point of view, they cover, and expand, the full range of views about future population.
- Recent IASA high projections are close to the high projections of the IS92 scenarios (Table 6.4). The low IASA projection, however, is somewhat above the IS92 low projections (Table 6.4)).

Despite the importance of long-term population assumptions in estimating future emissions, there have been few reviews of these assumptions. In one such review, Morita, *et al.* (1993) reviewed assumptions of global models and concluded that a not implausible range of global population projections for year 2100 was between 5.66 to 19.16 billion people. This is somewhat lower and higher than the range of IS92 assumptions (Table 6.4). The lower bound is from Nordhaus and Yohe (1983), while the upper bound is the high projection from UN (1992), which assumes reproductive rates which actually occurred in Japan during the periods 1947-1950 and 1975-1985. From this perspective Morita, *et al.* judged that the UN

high projection is not impossible. (They made no direct comments about the plausibility of the lower bound).

Because population growth assumptions strongly influence future emission projections, it would be helpful to assess their relative likelihood. Unfortunately, this is not possible at this time because of the many unresolved critical issues related to population projections. As one example, the feasibility of *low* projections is related to the issue of a rapidly aging population. Lutz, et al. (1994) pointed out that IIASA's low population projection for 2100 (the IS92 low projection is even lower, Table 6.4) is based on assumptions about low fertility and mortality rates, and these low rates would lead to an unprecedented aging of the population. For their low population projection, the percentage of the population over age 60 increases in industrialized countries from 17.4% to 44.9% between 1990 and 2100, and in developing countries from 6.9% to 40.2%. In order to judge the likelihood of the low population projections of IS92 or any other scenario, it is important to assess the response of society to the increasing burden of an aging population on its social welfare system. (see, e.g. Lutz, et al. 1994).

Another critical issue is the relationship between high population projections and the earth's carrying capacity, i.e. the ability of society to provide food and resources for its population. The U.N. projections do not take this into account, since mortality rates are never assumed to increase even for the highest population increases. There is very wide disagreement over the size of the earth's carrying capacity; estimates made since the 1980s mostly range from 2 to over 33 billion people, depending on a large variety of assumptions (see review in Heilig, 1994). This range can be compared to the IS92 high population assumption of 17.6 billion people in 2100. If the low figure for carrying capacity is correct then even current population cannot be sustained, whereas the high figure implies that IS92 projections are theoretically possible from the carrying capacity point of view. In order to judge the feasibility of the high population assumptions of the IS92 or any scenario, it would be beneficial to try and narrow the range of estimates about global carrying capacity.

These are only two of the many issues related to demographic studies that require further research and understanding before progress can be made in assessing the likelihood of different population assumptions. Another key issue, the relationship between population and GDP/cap is taken up in the next subsection.

Summing up the discussion of population assumptions, the plausibility of the medium population growth assumption of the IS92 scenarios is supported by other recent population projections. The low and high projections of the IS92 scenarios cover and expand the range of assumptions found in other published scenarios. The IS92 projections are taken from authoritative projections of world population growth, and are not inconsistent with other recent population projections. However, in order to assess the likelihood of the low and high population assumptions, more research is needed to improve our understanding of critical issues related to population projections such as carrying capacity and population aging.

Table 6.4 Population assumptions (in millions)

Region	World Bank(1991)			UN Med-Low		UN-Med		UN-Med-High		IIASA Low		IIASA Central		IIASA High	
	IS92a, b & e			IS92c & d				IS92f							
	1990	2025	2100	2025	2100	2025	2100	2025	2100	2025	2100	2025	2100	2025	2100
OECD	838	939	903	865	503			1,039	1,359						
USSR & E.-Europe	428	496	513	475	337			540	856						
China & CP Asia ¹	1,218	1,721	1,924	1,526	935			1,881	2,385						
Middle East	128	327	603	272	223			349	693						
Africa	648	1,587	2,962	1,375	1,668			1,807	4,651						
Latin America	440	708	896	682	770			832	1,662						
South & East Asia	1,553	2,636	3,538	2,395	1,979			2,999	5,987						
Total	5,252	8,414	11,312	7,591	6,415	8,472	11,186	9,445	17,592	8,093	9,126	8,955	12,562	9,872	16,090

¹ CP=Centrally planned economics

Source: Leggett, *et al.* (1992), except IIASA projections from Lutz *et al.* (1994).

6.2.5 The Relationship Between GDP/capita and Population

This section reviews the issue of the consistency between population and GDP/capita assumptions in the IS92 scenarios. This topic was briefly raised by the developers of the scenarios themselves (Leggett, et al., 1994). The IS92 scenarios combine high population with high GDP/capita assumptions, and low population with low GDP/capita assumptions. While this is logical for performing a sensitivity analysis of key input assumptions, it also implies that high population growth can accompany high economic growth, and conversely low population growth with low economic growth. It should be noted, however, that the developers of the scenarios offer the opinion that GDP/capita and population in reality would most likely be negatively correlated (Leggett, et al., 1992).

Actually, there are many opinions about the connection between population and GDP/capita. Three of these are:

(i) *High population growth is compatible with high economic growth (or low population growth with low economic growth).* As noted, this is implied, if not intended, by the IS92 scenarios. In support of this point of view, Boserup (1981) argued that a larger population density allows for investments in infrastructure, and stimulates technological progress and the growth of financial institutions.

(ii) *Population growth is negatively correlated to economic growth.* The reasoning behind this argument is that improved economic status leads to lower birth rates and eventually lower population growth. This belief is embedded in conventional thinking about the "demographic transition" of societies, which says that fertility in a society goes down as its standard of living goes up. A related point of view is that population growth will lead to resource and capital constraints that in turn, will reduce GDP/capita growth.

In support of a negative correlation between population and GDP/capita Morita, et al. (1994) derived a relationship between total fertility rate and per capita income from cross country Japanese data in the period 1950 to 1985. Applying this relationship globally, they back-calculated the annual per capita GDP growth rate that corresponds to the population growth rates of the IS92a scenario. In this way they estimated that the IS92a scenario should have an effective annual per capita GDP growth rate of 3%, rather than the 1.7% actually used. Hence Morita, et al. (1994) suggest that the population and economic assumptions of this scenario may be inconsistent.

(iii) *Population growth and economic growth are independent.* Based on recent extensive field surveys in developing countries, demographers have begun to argue that there is no empirical evidence to support either of the above points of view, and that the fertility rate in many countries is much more clearly related to the educational level of women and the existence of family planning programs than any economic indicators (see, for example, UN, 1987; Westhoff, 1994; and Lutz, 1994).

As a final comment on this issue, we note that it is possible that the relationship between population and income can vary between cultures, and that the three different relationships may actually correspond to different stages in a society's development.

Summing up the discussion of the relationship between population and GDP/capita, there are at least three points of view about this relationship, and it is beyond the scope of this evaluation to pass judgement on their validity. It is important to note, however, that the issue of population and GDP/capita is relevant to judging the consistency and likelihood of population and economic assumptions which in turn is needed for improving future emission projections. Hence, it would be beneficial to improve the understanding of the population-GDP/capita relationship.

6.3 Comparison of Scenarios Related to Energy

In this section we compare the IS92 energy related emission scenarios to other published non-intervention scenarios. The goal of this comparison is to determine the degree to which the IS92 scenarios reflect the range of emissions and major input assumptions found in other scenarios at both the global and regional level.

First global and then regional emissions are analysed. Scenarios of CO₂, CH₄ and N₂O are examined, although the IS92 scenarios consider the full spectrum of greenhouse gases. Because of the limited scope of this evaluation, the regional analysis was limited to four representative regions: China and Centrally Planned Asia, Eastern Europe and the former Soviet Union, Africa, and the United States. These regions were selected because they are in different stages of economic development.

For global and regional emissions we first assess the accuracy of the base year (1990) emission data in comparison to the latest emission inventory based on UN energy statistics (Marland *et al.*, 1989 and 1993). Next, we compare future emissions paths of IS92 to the range of emissions of other published non-intervention scenarios with similar methodology, and the range spanned by the 16th and 84th percentile (median plus/minus one standard deviation) of the poll of energy scenarios assembled by the International Energy Workshop (Manne and Schrattenholzer, 1991, 1993, 1994). Finally, we compare the main input assumptions and scenario components of the IS92 and other published scenarios.

6.3.1 Global Energy Scenarios

6.3.1.1 Results from Global CO₂ Emission Scenarios

Of all the greenhouse gas emissions carbon dioxide (CO₂) is the most studied. Of all the CO₂ sources, fossil fuel combustion is the most studied. This interest arises from the fact that fossil fuel CO₂ emissions contribute more to current and potential future climate change than any other single gas released by any other single human activity. It dominates the IS92 scenarios (IPCC, 1992). There is also a large literature on scenarios of global fossil fuel carbon emissions as compared to land use emissions. This is because the models and methods used to estimate energy related emissions are more detailed and advanced than those used to compute land use related emissions, and because existing energy models could easily be adapted to generate CO₂ emissions.

It is interesting that scenarios developed in the past decade (beginning in 1983) have a narrower range of future emission estimates than those developed in the previous decade. Scenarios no longer anticipate emissions of greater than 90 Pg C a⁻¹ in the year 2050, as considered, for example by Jason (1979), Bacastow and Keeling (1981), and Siegenthaler and Oeschger (1978). The highest estimate of the post 1983 period projects emissions of 35 Pg C a⁻¹ in the year 2050, (Lashof and Tirpak, 1990).

The IS92 scenario estimate of base year (1990) emissions, 6 Pg C a⁻¹, is close to the estimate of 5.9 Pg C a⁻¹ by Boden *et al.* (1992) and Marland *et al.* (1993). Estimates for 1990 from other published scenarios range from 5.4 to 6.8 Pg C a⁻¹.

Future estimates of emissions diverge substantially with time (Figure 6.1), and resemble each other only in that they almost all increase with time. A notable exception is the IS92c scenario which declines from 1990 to 2100. For the year 2025, the spread of non-IS92 scenario emissions ranges from 6.7 Pg C a⁻¹ in Ausubel *et al.* (1988), to 19.8 Pg C a⁻¹ for Lashof and Tirpak (1990). The IS92 scenarios range between 7.4 (IS92c) to 13.5 Pg C a⁻¹ (IS92e). As another indication of the range of views of the energy community, the 16th and 84th percentile range from the International Energy Workshop (IEW) scenario poll, is between 6.9 and 10.9 Pg C a⁻¹ for the year 2020.

By the year 2100 the range of non-intervention scenarios expands significantly, with the IS92 scenarios extending from 4.6 to 35 Pg C a⁻¹, a factor of more than seven. The lowest non-IS92 scenario examined is given by Ausubel *et al.* (1988), 1.2 Pg C a⁻¹, while the highest is given by Ogawa (1990) at 60 Pg C a⁻¹, a range of 50. This range also encompasses the range of 12 reference scenarios compared by the Energy Modeling Forum (the "EMF-12" study) (Weyant, 1993). These scenarios span from 20 (Global-Macro) to 43 Pg C a⁻¹ (CETA). The EMF-12 results are particularly interesting because they were obtained from models with harmonized input assumptions about population and economic activity. Consequently, they highlight how future emission estimates can vary because of differences in models as well as differences in input assumptions.

Histograms of projected emissions (Figure 6.2) show that emission estimates are relatively closely clustered in the year 2020, but also their divergence afterwards. The frequency of the mode also becomes smaller and smaller with time indicating that the scenarios agree less and less about the central estimate of emissions. The interval that contains each of the IS92 cases is also indicated, and shows that the IS92 scenarios bracket a majority of other scenarios, but never capture their full range. This is particularly clear for the year 2100. Throughout the period, there are always scenarios with substantially more or less fossil fuel carbon emissions than the IS92 scenario set.

Additional information about the range of future emissions can be obtained by examining results from detailed uncertainty analyses. These were conducted by Nordhaus and Yohe (1983), Edmonds *et al.* (1986), Manne and Richels (1993), and de Vries, *et al.* (1994).

It is noteworthy that despite the enormous range of results produced by the uncertainty analyses (Figure 6.3), emissions almost always increase with time, with the exception of the extremes of results. The uncertainty analysis of Edmonds *et al.* (1986) shows a range of 2 and 87 Pg C a⁻¹ for the 5th and 95th percentile cases respectively in the year 2075, and a range of 4 to 27 Pg C a⁻¹ between the 25th and 75th percentiles. The uncertainty analysis of Nordhaus and Yohe (1983) span the range 12 to 27 Pg C a⁻¹ for the year 2100 between their 25th and 75th percentiles, and 7 to 55 Pg C a⁻¹ between their 5th and 95th percentile cases.

It should be emphasized that these results stem from differences among models *as well as uncertainties of input assumptions such as population and economic activity*. By comparison, when input assumptions are fixed between scenarios, a much lower range of emission estimates is found. For example, it was noted above that when key model inputs were harmonized in the EMF-12 scenarios, emission estimates in year 2100 varied by only a factor of two rather than over a factor of 40, as found in the uncertainty studies. This is consistent with the recent results of de Vries *et al.* (1994), who only assigned uncertainty to model input parameters, while fixing other input assumptions such as population and economic growth relative to a base case. As a consequence, they computed emission estimates for the year 2050 ranging by only a factor of about two, from 11.3 to 24.4 Pg C a⁻¹ (5th and 95th percentiles).

While published energy related emission estimates for 2100 vary by a factor 50 between the highest and lowest reference scenarios and by a factor more than 7 in the IS92 scenarios, cumulative emissions have a much smaller variation. The cumulative emissions of the published scenarios over the period 1990 to 2100 (Figure 6.4) vary by a factor 7 (from 492 Pg C in Ausubel *et al.*, 1988, to 3447 Pg in Lashof and Tirpak, 1990). The cumulative emissions of the IS92 scenarios vary by a factor of 3 between IS92c (700 Pg) and IS92e (2078 Pg). Cumulative emissions of policy scenarios are obviously lower, ranging from 290 Pg (Lazarus *et al.*, 1993) to 600 Pg (Lashof and Tirpak, 1990) in the scenarios reviewed.

The above cumulative emission figures can also be compared to the cumulative energy related carbon emissions between 1860 to 1990 of about 215 Pg C a⁻¹ (IS92, 1990, Marland *et al.*, 1989, Nakićenović *et al.*, 1993). Thus, even the lowest reference and policy scenarios indicate that more energy related carbon will be emitted from 1990 to 2100, than in the last 130 years.

It is important to note that cumulative emissions are not equivalent to the amount of atmospheric accumulation of carbon. The relationship between emissions and atmospheric accumulation is described by carbon cycle models, discussed in the IPCC Working Group I report. Carbon cycle models can be used to translate any time profile of carbon emissions into a corresponding time profile of atmospheric concentrations of CO₂. In a modeling exercise of this type, Working Group I of the IPCC estimated that the IS92c scenario could raise atmospheric CO₂ levels to 480 ppm by 2100.

We also note that a few scenarios, for example Cline (1991) and Manne and Richels (1994), have explored emissions over yet longer time periods. These cases extend beyond the time frame of the IS92 scenarios, and therefore we have not examined the implications of these scenarios in the period beyond the year 2100. We note that cumulative emissions in such scenarios may be significantly greater than the cases examined here. Such scenarios consider depletion of all available oil, gas, and coal. The magnitude and distribution of these fuels is discussed in the Energy Supply Mitigation Chapter of the IPCC Working Group II report.

Summing up the discussion of results of global energy related CO₂ scenarios, the scenarios diverge with time and almost all have an upward trend. Their range is much narrower in year 2020 and 2050 than in year 2100. The IS92 scenarios follow the same pattern, and fall within the range of the majority of published scenarios.

The lowest and highest published scenarios reviewed in this report vary by a factor

of 50 in the year 2100. Much of this large range, however, can be attributed to the wide range of input assumptions, such as economic activity, end-use energy intensity, and the energy supply mix. The range of estimates for cumulative emissions between 1990 and 2100 is much narrower than for annual emissions (a factor of 7 versus a factor of 50).

6.3.1.2 Components of Global CO₂ Emissions Scenarios

The limited scope of this report makes it impossible to carefully examine and compare all input assumptions of published scenarios. Instead, selected energy related scenarios are compared by breaking down the calculated emissions into different components:

$$\text{CO}_2 \text{ Emissions} = \text{Population} * (\text{GDP/Population}) * (\text{Energy/GDP}) * (\text{CO}_2/\text{Energy})$$

In this equation, the ratio "Energy/GDP" represents the *energy intensity* (primary energy consumed per unit GDP). Energy intensity data are indexed to 1990 data because of the incomparability of GNP/GDP data in different studies. The ratio "CO₂/Energy" is the *carbon intensity* (carbon emissions per unit primary energy consumed) which reflects the amount of carbon-based fuels used in the energy economy. Carbon intensity is given as kg C per GJ.

Such an approach for analyzing the components of future CO₂ emissions has been proposed by Kaya (1989) and applied by Edmonds and Barns (1992), Ogawa (1991) and Grubler *et al.* (1993) among others.

The decomposition of CO₂ emissions growth into the four components provides an accounting of the sources of future emissions. The decomposition is useful because it provides an indication of where to look for differences in scenario assumptions that may account for differences in projected emissions. It does not, however, identify the key assumptions nor provide an explanation of the fundamental causes of differences in emissions projections. The decomposition is also useful because it coincides with four broad areas of public policy concern that can potentially influence future emissions: demographics, economic growth and development, energy conservation, and energy supply.

Population is an input assumptions in most models, whereas energy intensity is partly specified and partly computed by the model. Carbon intensity is usually determined by the interaction of a variety of assumptions including those concerning availability and cost of fossil energy resources, relative fuel prices, availability and cost of renewable energies.

There are additional caveats that should be noted. First, for the purposes of this comparison, not only population and income, but all of the components are treated as independent from one another. This assumption may be inconsistent with some models that assume that components, such as per capita income and energy intensity, are related to one another. Second, the influence of some components on emissions may depend on the aggregation level of the analysis (global versus regional or national). Hence, an analysis of components of emissions on the global level may mask decisive differences between regions. For this reason, the component analysis should only be used to compare the input assumptions and results of different scenarios and not, for example, for projecting emissions on the basis of population growth in different regions.

Table 6.5 shows the growth rates of components of selected scenarios including the

IS92 scenarios up to the year 2020¹. The IS92 scenarios are in most instances within the range of alternative scenarios, although not always representative of the range. They span a representative range of global economic growth rates, but the population growth assumptions of IS92c, d and IS92f are lower and higher, respectively, than any of the published scenarios. Population and GDP was discussed earlier in Section 6.2, and will not be discussed further here.

Figures 6.5 and 6.6 depicts the ranges of energy intensity and carbon intensity for published global scenarios. It is noteworthy that all scenarios reviewed showed decreasing energy intensities, with a median value of about 1 percent per year. The IS92 scenarios fall within a majority of published scenarios, although they cover a narrower range, especially up to 2020. There is also a significant overlap particularly before 2020, between the ranges of reference and policy scenarios, although the policy scenarios are generally lower.

Most scenarios assume that carbon intensity decreases at a lower rate than energy intensity (Figure 6.6); in some cases the carbon intensity increases, indicating increased use of carbon-rich fuels such as synthetic fossil fuels or coal (Table 6.5). However, on the average, carbon intensity in the non-intervention scenarios decrease at a rate of about 0.2 percent per year (1990-2020 average). This is somewhat lower than the long-term historical average of 0.3 percent per year (Nakićenović *et al.*, 1993). Up to the year 2020, the rate of carbon intensities assumed in the IS92 scenarios agrees with the IEW poll and other reference scenarios. However, all the IS92 scenarios have declining carbon intensities. Beyond the year 2020, the range of published reference scenarios shows a much wider variation than the IS92 cases. In some non-IS92 scenarios, carbon intensities increase with time due to a rapid expansion of coal production and use, a case not considered in IS92. Carbon intensities assumed in policy scenarios are generally lower than those of the IS92 and other non-intervention scenarios, although some reference scenarios have quite low carbon intensities as in the case of the "methane economy" of Ausubel *et al.* (1988).

The decomposition of global emissions of the IS92 and non-IS92 emissions tell a generally consistent story about the sources of emissions growth and the uncertainty of future emissions. In all scenarios, population growth and per capita income growth contribute to rising global CO₂ emissions over time. Growing world population and incomes increase the consumption of energy, giving rise to greater emissions. The relative contribution of per capita income growth to global CO₂ emissions is slightly greater than the contribution of population growth in most but not all scenarios.

Decreases in energy intensity is an offsetting influence that mitigates emission growth in all scenarios, consistent with historical observations. With a decrease in energy intensity, energy consumption for a given population and per capita income declines. Consequently, carbon emissions also decline. Declining energy intensity offsets roughly one-fifth to one-half of the effects of population and per capita income growth depending upon the scenario. The IS92 scenarios reflect a much narrower range of changes in future energy intensity in comparison to other scenarios. This is the most important source of the narrower range of carbon emissions displayed by the IS92 scenarios relative to the range of emissions in other

¹. For an analysis of the period beyond 2020, see Grubler (1994).

published scenarios.

Global carbon intensity is projected to decline in all IS92 scenarios and the vast majority of other scenarios, providing an additional offsetting effect to mitigate the effects of growing population and per capita incomes. This reflects a shift toward greater reliance on energy resources that emit less carbon per unit of energy. The offset from declining carbon intensity is typically much less than the offset from declining energy intensity. As in the case of energy intensity, the IS92 scenarios display a narrower range of changes in carbon intensity relative to other scenarios. A small number of non-IS92 scenarios even allow for the possibility of increases in carbon intensity over time, adding another source of positive emission growth. This possibility is not allowed for in any of the IS92 scenarios.

The decomposition of CO₂ emissions growth into the components of population growth, per capita income growth, energy intensity, and carbon intensity identify the general sources of emission growth from energy use. But the decomposition does not explain why the contributions of the four components differ across scenarios. To understand the fundamental causes of differences in emissions from one scenario to the next, it is necessary to explore and evaluate differences in assumptions regarding the factors that determine growth in population, per capita income, energy intensity, and carbon intensity.

In most emission scenarios, population and per capita income growth, or their composite effect on total income, are input assumptions. These are the input assumptions that are important sources of differences in projected emissions. The determinants of population and per capita income growth, and feedbacks between them, however, are not explicitly incorporated into emission scenarios (see section 6.2). Identifying the factors influencing population and per capita income growth, and exploration of the uncertainties regarding their evolution through time, are therefore important remaining tasks.

Input assumptions that drive differences in energy and carbon intensity across scenarios include different estimates of reserves and supply costs of carbon and non-carbon emitting energy resources; income and price elasticities of households' demands for energy, production of energy intensive goods and services, and many others. A particularly important component is technological change at both levels of energy production and energy end use. Because of time limitations, differences in assumptions regarding factors that influence energy and carbon intensity have not been compared across scenarios. Consequently, another important task that still remains is the exploration of the causes of differences in energy intensity and carbon intensity trends and their role in shaping future emissions.

Summing up the discussion of the components of global CO₂ emissions, especially for energy and carbon intensity -- The energy intensity assumptions of the IS92 scenarios have a narrower range than other published scenarios. The carbon intensity assumptions of the IS92 scenarios all show a downward trend in contrast to the set of published scenarios, some of which increase and some of which decrease with time. An important task for new scenario work is to explore the future trends of energy and carbon intensity.

6.3.1.3 Global Scenarios of Sulfur Emissions from Energy

To Be Included

Table 6.5 1990-2020 World average annual growth rates¹ (percent per year) for selected non-intervention (reference) scenarios and range from intervention (policy) scenarios

Non-intervention Scenarios ³	POP	GDP Capita	GDP	Energy GDP	Carbon Energy	Carbon Emissions
1-1 IS92a	1.40	1.53	2.92	-0.97	-0.24	1.68
1-2 IS92b	1.40	1.53	2.92	-1.08	-0.26	1.54
1-3 IS92c	1.10	0.92	2.00	-0.86	-0.55	0.56
1-4 IS92d	1.10	1.75	2.83	-1.10	-0.68	1.00
1-5 IS92e	1.40	2.29	3.71	-1.16	-0.11	2.39
1-6 IS92f	1.75	1.36	3.10	-0.85	-0.03	2.19
8-4 IPCC-EIS	1.24	1.74	3.00	-0.80	0.05	2.23
20-3 IEW-84% ²			3.36	-0.75	0.05	1.95
20-2 IEW-50% ²			2.78	-1.16	-0.18	1.44
20-4 IEW-16% ²			2.46	-1.71	-0.67	0.63
18 ECS '92	1.42	0.78	2.21	-0.75	-0.16	1.28
6-1 CH ₄ -Efficiency	1.29	0.83	2.13	-0.78	-0.85	0.47
16-1 CHALLENGE			2.55	-0.94	-0.18	1.41
31-2 WEC A	1.43	2.36	3.82	-1.50	-0.01	2.25
31-1 WEC B	1.43	1.85	3.30	-1.84	-0.22	1.17
3-1 E&R B	1.13	1.68	2.85	-1.03	-0.23	1.54
7-1 EPA-SCW	1.43	0.35	1.79	-0.72	-0.07	0.98
7-2 EPA-RCW	1.29	1.35	2.65	-0.70	0.04	1.98
12-2 GREEN			2.71	-0.53	0.14	2.31
30-1 12RT			2.50	-0.99	0.00	1.49
27-2 IMAGE 2.0-CW	1.40	1.61	3.00	-0.56	-0.25	2.20
Minimum ²	1.10	0.35	1.79	-1.84	-0.85	0.47
Median ²	1.40	1.53	2.83	-0.94	-0.18	1.54
Mean ²	1.35	1.46	2.79	-0.99	-0.21	1.56
Maximum ²	1.75	2.36	3.82	-0.53	0.14	2.39
<i>Policy Scenarios</i>						
Minimum ²	1.17	0.35	1.79	-2.40	-1.94	-1.31
Median ²	1.29	1.35	2.65	-1.78	-1.19	-0.32
Mean ²	1.32	1.37	2.66	-1.74	-1.16	-0.29
Maximum ²	1.43	2.19	3.50	-1.08	-0.52	0.24

1) Component growth rates do not add exactly to (sub)totals due to independent rounding errors.

2) Component growth rates do not add as calculated from original frequency distributions.

3) Reference for scenarios given in Appendix 6.1.

BOLD denotes IPCC scenarios

Table 6.6 1990-2020 China and centrally planned Asia average annual growth rates¹ (percent per year) for selected non-intervention (reference) scenarios and range from intervention (policy) scenarios

Non-intervention Scenarios ³	POP	GDP Capita	GDP	Energy GDP	Carbon Energy	Carbon Emissions
1-1 IS92a	1.03	3.91	4.98	-1.73	-0.32	2.84
1-2 IS92b	1.03	3.91	4.98	-1.73	-0.32	2.84
1-3 IS92c	0.69	2.98	3.70	-1.61	-0.51	1.51
1-4 IS92d	0.69	4.09	4.81	-1.88	-0.57	2.25
1-5 IS92e	1.03	4.83	5.91	-2.00	-0.21	3.57
1-6 IS92f	1.31	3.75	5.12	-1.57	-0.22	3.24
8-4 IPCC-EIS	0.78	4.49	5.30	-2.44	0.30	3.04
20-3 IEW-84% ²			5.74	-0.96	-0.29	3.15
20-2 IEW-50% ²			4.79	-1.61	-0.38	2.77
20-4 IEW-16% ²			3.88	-2.49	-0.38	2.33
18 ECS '92	0.97	2.01	3.00	-1.02	-0.18	1.76
33-2 ESCAPE S1			5.50	-1.42	-0.20	3.78
37 He <i>et al.</i> (c)	0.68	3.96	4.67	-1.60	-0.34	2.75
31-2 WEC A	0.94	5.07	6.06	-2.85	-0.24	2.79
31-1 WEC B	0.94	4.08	5.06	-2.40	-0.03	2.51
3-1 E&R B	0.91	2.34	3.28	-0.22	-0.52	2.52
7-1 EPA-SCW	0.90	2.25	3.17	-0.81	-0.58	1.74
7-2 EPA-RCW	1.02	4.11	5.17	-1.21	-0.47	3.41
12-2 GREEN			4.40	-0.27	0.25	4.38
30-1 12RT			4.03	-1.36	-0.38	2.22
27-2 IMAGE 2.0-CW	1.02	4.15	5.21	-0.82	-0.21	4.13
Minimum ²	0.67	2.01	3.00	-2.85	-0.58	1.51
Median ²	0.94	3.91	4.90	-1.59	-0.30	2.85
Mean ²	0.93	3.73	4.66	-1.52	-0.28	2.83
Maximum ²	1.31	5.07	6.06	-0.22	0.30	4.38
<i>Policy Scenarios</i>						
Minimum ²	0.81	2.25	2.34	-4.32	-1.72	-0.82
Median ²	0.94	4.08	4.48	-1.89	-1.06	1.24
Mean ²	0.94	3.70	4.24	-2.24	-1.03	0.86
Maximum ²	1.02	4.11	5.17	-0.53	-0.52	2.29

1) Component growth rates do not add exactly to (sub)totals due to independent rounding errors.

2) Component growth rates do not add as calculated from original frequency distributions.

3) Reference for scenarios given Appendix 6.1.

BOLD denotes IPCC scenarios

Table 6.7 1990-2020 Eastern Europe and ex-USSR average annual growth rates¹ (percent per year) for selected non-intervention (reference) scenarios and range from intervention (policy) scenarios

Non-intervention Scenarios ³	POP	GDP Capita	GDP	Energy GDP	Carbon Energy	Carbon Emissions
1-1 IS92a	0.43	1.49	1.93	-0.66	-0.24	1.01
1-2 IS92b	0.43	1.49	1.93	-0.66	-0.24	1.01
1-3 IS92c	0.31	0.95	1.26	-0.69	-0.50	0.06
1-4 IS92d	0.31	1.88	2.21	-1.03	-0.67	0.48
1-5 IS92e	0.43	2.83	3.27	-1.37	-0.19	1.67
1-6 IS92f	0.67	1.73	2.31	-0.88	-0.13	1.28
8-4 IPCC-EIS	0.70	2.49	3.20	-1.14	-0.17	1.84
20-3 IEW-84% ²			2.98	-1.06	-0.34	0.46
20-2 IEW-50% ²			2.16	-1.42	-0.36	0.07
20-4 IEW-16% ²			1.51	-2.01	-0.41	-0.25
18 ECS '92	0.49	2.18	2.68	-1.52	-0.24	0.88
34-1 Bashmakov Base	0.58	0.77	1.36	-0.93	-0.05	0.37
35-1 Sinyak <i>et al.</i> DAU	0.56	1.44	2.00	-1.09	-0.41	0.49
31-2 WEC A	0.52	1.85	2.38	-1.81	-0.62	-0.10
31-1 WEC B	0.52	1.85	2.38	-2.13	-0.38	-0.18
3-1 E&R B	0.48	1.62	2.11	-1.07	-0.40	0.61
7-1 EPA-SCW	0.52	1.73	2.27	-1.29	-0.17	0.78
7-2 EPA-SCW	0.45	3.80	4.27	-2.97	-0.16	1.01
12-2 GREEN			2.51	-0.63	0.32	2.19
30-1 12RT			2.29	-2.00	-0.29	-0.05
27-2 IMAGE 2.0-CW	0.43	1.48	1.91	0.72	-1.62	0.99
Minimum ²	0.31	0.77	1.26	-2.97	-1.62	-0.25
Median ²	0.48	1.73	2.29	-1.12	-0.23	0.61
Mean ²	0.49	1.85	2.63	-1.17	-0.29	0.76
Maximum ²	0.70	3.80	4.25	0.72	0.32	2.42
<i>Policy Scenarios</i>						
Minimum ²	0.37	0.77	1.36	-4.01	-1.96	-1.79
Median ²	0.52	1.85	2.38	-2.41	-1.24	-1.34
Mean ²	0.50	2.26	2.68	-2.59	-1.15	-1.13
Maximum ²	0.58	3.80	4.27	-1.45	-0.21	-0.25

1) Component growth rates do not add exactly to (sub)totals due to independent rounding errors.

2) Component growth rates do not add as calculated from original frequency distributions.

3) References for scenarios given in Appendix 6.1.

BOLD denotes IPCC scenarios

Table 6.8 1990-2020 Africa average annual growth rates¹ (percent per year) for selected non-intervention (reference) scenarios and range from intervention (policy) scenarios

Non-intervention Scenarios ²	POP	GDP Capita	GDP	Energy GDP	Carbon Energy	Carbon Emissions
1-1 IS92a	2.63	1.25	3.92	0.26	-0.21	3.98
1-2 IS92b	2.63	1.25	3.92	0.26	-0.21	3.98
1-3 IS92c	2.20	0.40	2.60	0.40	-0.39	2.61
1-4 IS92d	2.20	1.46	3.69	0.09	-0.44	3.32
1-5 IS92e	2.63	2.11	4.80	0.17	-0.19	4.78
1-6 IS92f	3.03	1.06	4.12	0.51	-0.12	4.53
8-4 IPCC-EIS	2.42	1.55	4.00	-0.48	0.46	3.99
20-3 IEW-84% ³			3.82	-0.52	0.10	3.33
20-2 IEW-50% ²			3.64	-0.28	-0.17	3.28
20-4 IEW-16% ²			3.45	-0.63	-0.09	3.06
38-1 UNEP base	1.86	2.53	4.44	-1.40	0.47	3.46
31-2 WEC A	2.94	2.98	6.00	-0.58	1.17	6.61
31-1 WEC B	2.94	2.00	5.00	-1.67	0.26	3.51
3-1 E&R B	1.56	2.29	3.89	-1.46	0.07	2.44
7-1 EPA-SCW	2.72	0.01	2.73	-0.17	0.86	3.45
7-2 EPA-RCW	2.42	1.71	4.17	-0.10	0.72	4.81
27-2 IMAGE 2.0-CW	2.63	1.25	3.92	0.53	-0.16	4.30
Minimum ³	1.56	0.01	2.60	-1.67	-0.44	2.44
Median ³	2.63	1.50	3.92	-0.17	-0.09	3.51
Average ³	2.49	1.56	4.00	-0.30	0.13	3.85
Maximum ³	3.03	2.98	6.00	0.53	1.17	6.61
<i>Policy Scenarios</i>						
Minimum ³	1.86	0.01	2.73	-2.19	-4.01	-0.31
Median ³	2.57	1.71	4.15	-1.46	-1.13	1.25
Mean ³	2.51	1.53	4.08	-1.31	-1.47	1.21
Maximum ³	2.94	2.53	5.00	-0.30	-0.11	2.43

1) Component growth rates do not add exactly to (sub)totals due to independent rounding errors.

2) Refers to non-OPEC developing countries. Component growth rates do not add as calculated from original frequency distributions.

3) Component growth rates do not add as calculated from original frequency distributions.

4) References for scenarios given in Appendix 6.1.

BOLD denotes IPCC scenarios

Table 6.9 1990-2020 USA average annual growth rates¹ (percent per year) for selected non-intervention (reference) scenarios and range from intervention (policy) scenarios

Non-intervention Scenarios ³	POP	GDP Capita	GDP	Energy GDP	Carbon Energy	Carbon Emissions
1-1 IS92a	0.57	2.33	2.91	-1.81	-0.26	0.78
1-2 IS92b	0.57	2.33	2.91	-1.81	-0.26	0.78
1-3 IS92c	0.22	1.72	1.94	-1.59	-0.63	-0.31
1-4 IS92d	0.22	2.45	2.67	-1.94	-0.88	-0.21
1-5 IS92e	0.57	2.91	3.49	-1.98	-0.11	1.34
1-6 IS92f	0.90	2.09	3.00	-1.62	0.00	1.34
8-4 IPCC-EIS	0.56	0.90	1.46	-0.20	0.16	1.42
20-3 IEW-84% ²			2.36	-0.88	0.29	1.37
20-2 IEW-50% ²			2.20	-0.96	0.24	1.24
20-4 IEW-16% ²			2.03	-1.18	-0.22	0.80
18 ECS '92	0.54	1.09	1.63	-1.21	-0.25	0.15
16-1 CHALLENGE			1.28	-0.66	0.03	0.80
36-1 EMF 12 (lowest)			2.20	-1.38	-0.24	0.49
36-2 EMF 12 (highest)			2.20	-1.04	0.13	1.24
31-2 WEC A	0.56	1.83	2.40	-1.94	-0.44	-0.02
31-1 WEC B	0.56	1.83	2.40	-2.08	-0.40	-0.13
3-1 E&R B	0.51	1.63	2.15	-1.09	0.22	1.26
7-1 EPA-SCW	0.53	1.13	1.67	-1.29	0.00	0.35
7-2 EPA-RCW	0.43	2.23	2.64	-1.83	0.02	0.81
32 NES			2.08	-0.32	-0.12	1.63
12-2 GREEN			2.27	-0.97	-0.05	1.23
30-1 12RT			2.20	-1.06	0.16	1.28
27-2 IMAGE 2.0-CW	0.56	2.33	2.91	-2.17	-0.22	0.46
Minimum ²	0.22	0.90	1.28	-2.17	-0.88	-0.31
Median ²	0.56	1.96	2.20	-1.29	-0.11	0.80
Mean ²	0.52	1.91	2.31	-1.35	-0.12	0.79
Maximum ²	0.90	2.91	3.49	-0.20	0.29	1.63
<i>Policy Scenarios</i>						
Minimum ²	0.43	1.04	1.19	-2.88	-2.98	-2.30
Median ²	0.53	1.83	2.14	-1.91	-1.13	-0.97
Mean ²	0.51	1.69	2.08	-1.87	-1.18	-1.08
Maximum ²	0.56	2.23	2.67	-0.66	-0.53	0.73

1) Component growth rates do not add exactly to (sub)totals due to independent rounding errors.

2) Component growth rates do not add as calculated from original frequency distributions.

3) Reference for scenarios given in Appendix 6.1.

BOLD denotes IPCC scenarios

6.3.1.4 Global Scenarios of CH₄ and N₂O Emissions from Energy

Although fossil fuel CO₂ is not the only radiatively important gas associated with human activities, far less attention has been paid to non-CO₂ greenhouse gases. Here we compare the IS92 scenarios with the few others available for energy related CH₄ and N₂O emissions (Alcamo *et al.*, 1994; Edmonds, 1993; Lashof and Tirpak, 1990; Matsuoka *et al.*, 1993; Messner and Strubegger, 1991; and Nakicenovic *et al.*, 1993). The IS92 scenarios provide a broad range of possible future trajectories for both CH₄ and N₂O (Figure 6.7). By the year 2100 the difference between the high and low cases for CH₄ and N₂O is similar to that for CO₂ (that is, a factor of about seven or eight). Of particular importance to CH₄ and N₂O scenarios is the significant uncertainty of base year (1990) emissions, which reflects the gaps in data collection and knowledge about the processes which lead to these emissions.

6.3.2 Regional Energy Scenarios

The background report for the IS92 scenarios gives results for four regions: OECD, Eastern Europe and the Former Soviet Union, China and Centrally Planned Asia, and Rest of the World (Pepper *et al.*, 1992). The original IS92 analysis, however, was conducted for nine regions. For our analysis we use the following regions: China and Centrally Planned Asia, Central and Eastern Europe and the former Soviet Union (EEFSU), Africa, and the United States of America (USA). These were selected because they are in different stages of economic and demographic development. The USA was selected in particular because there are a large number of published scenarios for this region.

Only CO₂ emissions are analyzed because of the scarcity of non-CO₂ regional scenarios in the literature. The main components of the different scenarios for the period 1990-2020 are given in Tables 6.5 to 6.8 and Figures 6.8 to 6.10.

6.3.2.1 China and Centrally Planned Asia²

The carbon emissions of the IS92 scenarios are within the range of other reference scenarios. However, their underlying driving forces are not representative of other published scenarios.

The IS92 scenarios assume GDP increases that are on the high side of other scenarios, while their range of assumptions about energy intensity and carbon intensity for China is both narrower and lower than the range of other scenarios.

Figure 6.8 shows the range of carbon emission scenarios up to the year 2100. The IS92a, IS92b, IS92d and IS92f scenarios are well within the 16th to 84th percentile range of the IEW poll for 2020. The IS92a is close to the IEW poll median and consequently can be considered as a "middle of the road" scenario. Conversely both IS92e and IS92c expand the range of all other long-term (2100) emission scenarios reviewed. IS92e is the highest, and IS92c is the lowest of all reference scenarios analyzed.

²In the ASF model used for the IS92 scenarios these include Cambodia, Laos, Mongolia, North Korea and Vietnam.

Analysis of the components in the growth of carbon emissions (Table 6.6) indicates the importance of economic and population growth assumptions followed by decreases in energy intensity. By 2100 IS92e assumes the highest and IS92c the lowest GDP growth rates of all scenarios reviewed. In all scenarios the intensity of energy use decreases typically about 1.5 percent per year in reference cases and well above 2 percent in policy cases (Figure 6.9). The resulting improvements in energy efficiency across all scenarios are large, but within the range of both historical experience and calculations of the theoretical minimum requirements derived from exergy analysis (cf. Nakićenović *et al.*, 1993). The IS92 scenarios have a narrower range of assumed energy intensities than other scenarios. Most scenarios also anticipate further decarbonization of the energy system, i.e. a decrease in carbon intensity of 0.2 to 0.5 percent per year (Figure 6.10). The IS92 range is lower than other reference scenarios (cf. the IEW poll). Indeed, the low carbon intensities assumed in IS92c, IS92d and IS92e for China in the years after 2050 are more characteristic of policy scenarios than non-intervention scenarios.

6.3.2.2 Eastern Europe and former USSR (EEFSU)

The IS92 scenarios do not fully capture current perceptions about the trends of energy related emissions in EEFSU in the medium term (up to 2020). First, the IS92 base year (1990) emission estimate (1.7 Pg C a^{-1}) exceeds by 30 percent the most recent estimate based on UN energy statistics ($1.304 \text{ Pg C a}^{-1}$) (Marland *et al.*, 1993). Second, assumptions in the IS92 scenarios about high growth rates (particularly for GDP) are probably unrealistic considering the current economic crisis. This leads to medium term estimates of CO_2 emissions in the IS92 scenarios that are rather higher and narrower in range than other published scenarios (Figure 6.8). The range of IS92 scenarios in 2025 span from 1.8 to 3.0 Pg C a^{-1} , whereas the more recent IEW poll spans a range of 1 to 1.6 Pg C a^{-1} by 2020. Because of the uncertainty of economic trends, the range of medium-term emission estimates from the literature (Figure 6.8) is perhaps the largest for any region.

Most long term scenarios (including IS92) represent more or less a pre-1990 "business as usual" point of view, and do not fully take into account the economic crisis in EEFSU. By year 2100 the published scenarios have a range of over a factor of eight. One reason for such a wide spread is that both IS92c and IS92d are beyond the emission range of other published scenarios, and are more characteristic of policy scenarios.

As expected, the rate of economic growth has the largest range of any input variable (Table 6.7). Recent scenarios (e.g. Bashmakov, 1992 and Sinyak *et al.*, 1992) assume much lower values (nearly a factor of two) than scenarios developed before 1991.

Almost all scenarios agree that both energy and carbon intensities will decline. The projected decline in energy intensity ranges between 1 to 2 percent per year (Figure 6.9), although there are significant differences in assumed short term (up to 2000) and longer term (2020 and beyond) trends. As indicated by results from the IEW poll, short term energy intensities in the region could increase. In fact, between 1990 and 1992 the energy intensity of the former USSR increased by 23 percent (ECE, 1993) as economic output fell more rapidly than energy consumption. Over the longer term, significant improvements in energy intensities could occur following economic restructuring and replacement of inefficient capital stock and the removal of price distortions. Current estimates of energy conservation in the former USSR for instance indicate a potential of more than 50 percent of actual consumption

(Bashmakov, 1992 and Sinyak, 1993). The significant uncertainty in future emissions due to economic restructuring are also confirmed by recent studies of other economies in transition like Hungary (HCS, 1994).

The extent and timing of these efficiency improvements is of course uncertain, and is reflected in the scenario ranges of the IEW poll. This range is wider than the range of assumptions used in the IS92 scenarios (Figure 6.9). Most scenarios also project declining carbon intensities of around 0.3 percent per year (Figure 6.10), although statistical data and base year calibration problems in some models/scenarios remain significant (illustrated by the wide range in 1990 carbon intensities). By 2020, the range spanned by the IS92 scenarios is narrow, but continues to be representative of "middle of the road" scenarios available in the literature. Over the long term (2100) the range of IS92 scenarios is much wider and at the low end of published scenarios. Carbon intensities of the IS92c and d scenarios are close to the values of published policy scenarios (Figure 6.10).

6.3.2.3 Africa

The IS92 scenarios account for half of all the available scenarios of long term energy related emissions for Africa.

The range of emissions scenarios is among the widest both in absolute and relative terms of all regions covered in this review (Figure 6.8). By 2020 regional emissions range between 0.3 to 0.8 Pg C a⁻¹, and increases to 0.5 to 5.2 Pg C a⁻¹ (i.e. a factor of 10). However even for the highest scenario, per capita carbon emissions by 2100 would still remain significantly below current OECD averages. Overall, the range of absolute emission projections trajectories spanned by the IS92 scenarios is in good agreement with the limited number of published scenarios.

The above cumulative emission figures can also be compared to the cumulative energy related carbon emissions between 1860 to 1990 of about 215 Pg C a⁻¹ (IS92, 1990, Marland *et al.*, 1989, Nakićenović *et al.*, 1993). Thus, even the lowest reference and policy scenarios indicate that more energy related carbon will be emitted from 1990 to 2100, than from the onset of the Industrial Revolution to the present. Conversely, the IS92 scenarios do not well represent the range of driving forces of other scenarios³, particularly for energy and carbon intensities (See Tables 6.9 and 6.10).

Up to year 2020, population growth rates dominate over per capita GDP growth (Table 6.8), but afterwards becomes less important than other driving forces (cf. Grübler, 1994). Up to 2020, assumed per capita economic growth rates show a large range (0 to 3 percent per year), with GDP growth rates ranging from 2.6 to 6 percent annually. IS92c assumes the lowest GDP growth rate of all reference scenarios reviewed.

Scenarios differ substantially in their assumptions about energy and carbon intensities up to 2020. Whereas the IS92 scenarios all assume increasing energy intensities (Figure 6.9), all but one of the other scenarios project decreasing energy intensities. Conversely, the IS92 scenarios all project declining carbon intensities (Figure 6.10), whereas all but one of the other scenarios anticipate increasing carbon intensities. The IS92 scenarios also assume a

³ In particular the IS92 scenarios show different trends from recent scenarios developed for African countries by UNEP, for example Christensen *et al.* (1994).

much smaller range of energy intensities than is found in other scenarios (Figure 6.9). The overlap between reference and policy scenarios is another indication of the lack of a common view on trends in Africa (Figures 6.8, 6.9, and 6.10).

6.3.2.4 USA

This region has the largest number of published scenarios available, with over 50 covered in this review. The IS92 scenarios only partly reflect the range of views captured by the published scenarios.

The range spanned by scenarios of future USA emissions is large (Figure 6.8). For 2020, scenario results range between 1.2 (IS92c) to 2.3 Pg C a⁻¹ (e.g. IPCC-EIS, or NES). The IS92 scenarios are skewed to the low side (Figure 6.8). By 2100, the range of published scenarios widens from 0.6 (IS92c) to 4.5 Pg C a⁻¹ (highest scenario from the EMF-12 model runs). The IS92 scenarios range by a factor of five by 2100, and continue to cover the low side of the range of published scenarios.

The upper range of the published scenarios imply a large increase in USA emissions by 2100 (up to 3.2 Pg C a⁻¹). However, such increases may be unlikely in a developed, service-oriented economy such as the USA, which already has one of the highest per capita emission levels in the world. The lower emission estimates of the majority of other published scenarios supports this view.

Assumptions about the trend of energy intensity vary significantly between scenarios, although all scenarios assume a decline in intensity (Table 6.9 and Figure 6.9). The range of energy intensities spanned by the IS92 scenarios (and the IEW poll) appears narrow, especially up to 2020. Over the long term (2050 and beyond) there is also a significant overlap between reference and policy scenarios. One interpretation of this overlap is that distinction between climate policies targeted towards improving energy efficiency, and efficiency improvements due to other reasons, becomes increasingly blurred in the long term.

Although all non-intervention scenarios assume that energy intensity declines, they do not make the same assumption for carbon intensity. Some show a decrease because of increased reliance on low or no-carbon fuels, while others increase in carbon intensity due to assumptions about greater use of coal, for example. Both IS92c and IS92d assume much lower carbon intensities than other reference scenarios (Table 6.9).

Over longer time horizons, changes in energy intensity and carbon intensity become as important determinants of uncertainties of future emissions as changes in population and economic growth (cf. Grubler, 1994). This implies that over the long run, differences in models and parameter assumptions may become more important than uncertainties of future population and economic growth. This conclusion is also supported by results of the EMF-12 exercise (Gaskins and Weyant, 1993, and Weyant 1993). It also suggests that more scenarios are needed to represent a wider range of views on changes in energy and carbon intensity of the future economy.

Summing up the discussion of regional energy scenarios, there are several instances in which emission estimates of the IS92 scenarios are not representative of the range of other published scenarios. In the case of Eastern Europe and the former Soviet Union, IS92 estimates are considerably higher than other recently published scenarios that take into account the current economic situation in this region. For the USA, the IS92 scenarios span

a lower range of emission estimates than the range of other published scenarios. The input assumptions of the IS92 scenarios (e.g. economic growth and carbon intensity) are in many cases not representative of other published regional scenarios.

6.3.3 Relative Importance and Sensitivity of Emissions to Different Variables

A sensitivity analysis investigated the relative influence of three factors, GDP, energy intensity, and carbon intensity on energy related CO₂ emissions. Population was not included as a factor because information about population assumptions are not available for all scenarios reviewed. In addition, the sensitivity of emission estimates to varying assumptions about population growth is clearly illustrated by the IS92 scenarios which have higher and lower population assumptions than any other scenario reviewed here. Sensitivity is expressed as the change in emissions relative to IS92a emissions, to changes in GDP, energy intensity, and carbon intensity derived from the extremes of non-intervention scenarios of the sample presented in Tables 6.4 to 6.8.⁴

With regards to non-intervention scenarios over the medium term (up to 2020), assumptions about GDP growth are the most important, followed by energy intensity or carbon intensity (Figure 6.11). Over the longer term (2050 and 2100) energy and carbon intensity become increasingly important globally and in some regions, although GDP growth continues to be the most important factor. If policy scenarios are included in the analysis, then assumptions about carbon intensity become as important as GDP growth assumptions (Figure 6.11).

Comparison of reference and policy scenarios suggests that uncertainties in driving forces of emissions within reference cases are at least as large as the uncertainties between reference and policy cases. This implies that over a time horizon of 50 to 100 years it is difficult to distinguish between the effect of climate policies and the effect of societal/technological changes irrespective of climate policies.

The sensitivity analysis suggests large impacts on emissions in varying critical input assumptions and model parameters for future emission scenarios. These sensitivities are so large over the time horizon up to 2100 that the writing team recommends against the use of a single scenario as input to climate models. An informed assessment of possible consequences of uncertain future emission paths necessitates the use of a range of scenarios. Moreover the distribution of sensitivities for different emission components of non-IS92 scenarios around IS92a is highly skewed and is particularly divergent at the regional level. Therefore, the IS92a scenario may not be suitable as a "central" or "middle of the road" scenario, especially for regional emission estimates (see also Figure 6.2 above). Even if a

⁴ E.g. the emission impact of a difference in energy intensity between IS92a and the min/max values of all non-intervention scenarios taken together is:

$$C_{IS92a} - (GNP_{IS92a} \times (PE/GNP)_{min/max} \times (C/PE)_{IS92a}).$$

In case intervention (policy) scenarios result in an expanded sensitivity range these are plotted separately in Figure 6.11. For reasons of data consistency, min/max values are calculated using IS92a 1990 base year values and applying respective min/max growth rates from the total scenario sample to them. Note that for the purposes of this sensitivity analysis the driving variables are treated as independent.

scenario clearly represented a consensus view of the evolution of most critical input assumptions and driving forces of future emissions, this would not imply that such a scenario has a higher likelihood than an alternative case. This is an additional reason to refrain from using a single emission scenario as input to assess the climate consequences of no action to reduce greenhouse gas emissions. Even if policies do not change, the future will be different from the present and is thus inherently uncertain.

Published uncertainty analyses also provide information about the relative importance of different input assumptions. We have already discussed the emission results of four published uncertainty analyses (section 6.3.1.2). Here we discuss their findings regarding the importance of input assumptions. Nordhaus and Yohe (1983) identified ten key input parameters to which they assigned probability distributions. Their analysis singled out the elasticity of substitution between fossil and non-fossil energy use as the most important parameter in explaining the uncertainty in carbon emissions. In addition, they found the rate of growth of total factor productivity, a measure which affects both labor and energy productivity, to be next most important. Interestingly, population assumptions were low on the list of factors affecting baseline emissions. Edmonds *et al.* (1986) obtained a similar result. However, the range of population growth assumptions used in both uncertainty studies did not encompass the current range of population projections which limits their conclusions.

Edmonds *et al.* (1986) performed a uncertainty analysis similar to Nordhaus and Yohe (1983), but their model contained much more detail about energy producing and consuming sectors. The carbon emissions forecasts from this study formed a biased distribution with median values significantly below the mean values. Edmonds *et al.* identified the four most important factors in explaining carbon emissions uncertainty as labor productivity in developing countries, labor productivity in developed countries, end-use energy efficiency improvements, and the world income elasticity of energy demand.

EPA (1990) also performed a sensitivity analysis of the ASF model which was used to generate the IS92 scenarios. The most important factors were: higher prices for coal and cost reductions for non-fossil energy technologies, both leading to emission reductions. Conversely, the impact of increasing the resource base for oil or gas was found to have comparatively small impact.

Manne and Richels (1993) performed an uncertainty analysis in which a poll of experts was used to set uncertainty distributions of key input parameters such as GDP growth rates, elasticity of substitution between energy and labor and capital, rate of autonomous energy efficiency improvements (AEEI), commercial year for economically-competitive carbon-free electricity, and the cost of the non-electric backstop technology. They found that the most important parameter was above all the potential GDP growth rates, followed by the AEEI and (to a smaller extent) the two supply side technology parameters. At the same time, the elasticity of substitution between energy and capital and labor only had only a minor influence in reference scenarios (assuming comparatively modest energy price increases), a situation that changes however drastically in policy intervention cases.

As noted earlier, de Vries *et al.* (1994) did not evaluate the uncertainty of model driving forces, but concentrated instead on the influence of uncertain model parameters on scenario results. They found that the most important parameters were the elasticities of energy demand, and the parameters which are used to describe consumer responses to fuel price increases.

Summing up the discussion of sensitivity analysis -- Variations in the rate of GDP growth across regions, which reflect the combined population and per capita income growth are the most important sources of variation in CO₂ emissions in the near to medium term. Over time, however, variations in the rates of change in energy and carbon intensity are equally important to GDP growth globally and in some regions. Results of the sensitivity analysis did not suggest that the IS92a or any of the IS92 scenarios is a "central" or "medium" case or has higher likelihood than alternative scenarios. In addition, results of uncertainty analysis point out that emission estimates are sensitive to the structure and processes used in models to represent the real world. Consequently, in order to obtain a full range of views about future emissions, it is also important to use a wide range of models and methodologies.

6.3.4 Discussion

The global CO₂ estimates of the IS92 scenarios bracket a majority of other published non-intervention scenarios, and therefore, can be considered to reflect a reasonable range of fossil fuel scenarios. While some plausible scenarios fall above or below the range spanned by the IS92 scenarios, the number of such scenarios is comparatively small.

In comparison to CO₂ emissions, the literature on non-CO₂ greenhouse related gases is limited. Few other studies considered the variety of gaseous emissions reported by the IS92 scenarios. An important reason for the divergence of emission estimates for non-CO₂ gases is the lack of agreement on base year emissions. This reflects a lack of knowledge or agreement on how to represent emission-causing processes.

While the IS92 scenarios were designed as non-intervention reference cases, emission estimates of the lowest scenario (IS92c) falls within the range of published policy scenarios. Nevertheless, as a whole, the IS92 scenarios do not reflect the range of policy scenarios and they should not be interpreted as policy scenarios. It is important to note that some sources of uncertainty are more subject to control by policy than others.

At the regional level there are several instances in which the IS92 scenarios do not suitably reflect the range of views represented by other scenarios. Notably, future emissions in Central and Eastern Europe and the Former USSR (EEFSU) are higher than in more recent scenario studies that take the effects of economic crisis into account. In addition, the IS92 base year (1990) estimate of CO₂ emissions is about 30 percent higher than the latest estimate. For the USA, the IS92 scenarios span a lower range than the full spectrum of scenarios available in the literature.

The analysis of energy scenarios does not provide any evidence that IS92a or any other individual IS92 scenario is a "medium" or "central" case. IS92a in particular sometimes covers well the "middle of the road" of alternative regional scenarios, but often is above or below the median of other scenarios.

The IS92 scenarios are within the range of most emission estimates and input assumptions of global energy scenarios. However, they are not always representative of the range of driving forces such as population and economic development, energy intensity, and carbon intensity, found in published *regional* scenarios. In some cases the IS92 scenarios span a much narrower range than other scenarios. For example, the IS92 scenarios assume a much narrower range of energy intensities in the USA and China plus Centrally Planned Asia, than

the range of published scenarios. In other cases, the IS92 scenarios fall outside the range of other scenarios. An example of this is the GDP growth rate assumed in IS92e which is higher for the USA and China plus Centrally Planned Asia, than any other scenario. The trend of driving forces in the IS92 scenarios also deviates in some circumstances from the other published scenarios, as in the case of Africa where the IS92 scenarios assume increasing energy intensity up to year 2020, and all but one other scenario assumes a downward trend. Thus the IS92 scenarios only partly reflect the range of regional views expressed in the published scenarios. It is important to note that regional perspectives can be included in global scenarios through a decentralized approach to scenario-building which includes the participation of scientists and policy makers familiar with national and regional circumstances. Examples of this are the scenario-building exercises sponsored by the World Energy Council, the Energy Modeling Forum, the International Energy Workshop, UNEP, and the CHALLENGE project of IIASA.

6.4 Comparison of Scenarios Related to Land Use

Very few scenarios of emissions related to land use and agriculture are available for comparison to the IS92 scenarios. However, in contrast to the energy-related scenarios, most of these scenarios include a range of greenhouse gas emissions rather than just CO₂. The scenarios reviewed in this section include:

- The previously described IS92 scenarios plus two sensitivity scenarios included in the IS92 document -- S1 (high estimates of deforestation and carbon content of vegetation) and S4 (low estimates of deforestation, high forestation rate).

- The U.S. Environmental Protection Agency (EPA, 1990) -- "Slowly Changing World" (SCW), "Rapidly Changing World" (RCW) and two "Stabilizing Policies" scenarios (SCWP and RCWP). These scenarios were developed from the Atmospheric Stabilization Framework (ASF) of the EPA which includes calculations from the global food system model, the "Basic Linked System" (BLS), developed at the International Institute for Applied Systems Analysis (IIASA),

- The IMAGE 2.0 "Conventional Wisdom" (CW) scenario (Alcamo et al., 1994.)

- The Asian Pacific Integrated Model (AIM) (Matsuoka and Morita, 1994).

- The three scenarios (H1 - H3) developed by Houghton (1991).

The scenarios S4, SCWP, and H3 assume policy intervention to reduce emissions, whereas the other scenarios can be considered "non-intervention" reference scenarios.

Because of time constraints of this evaluation, we focus in this section only on a few categories of land use emissions, namely, emissions of CO₂ from deforestation, CH₄ from wetland rice fields and enteric fermentation, and N₂O from soils underlying fertilized agricultural areas and soils underlying natural vegetation. These categories were selected because they illustrate the sensitivity of emission estimates to differences in input assumptions regarding agricultural variables. The scenario comparisons focus on both global scenarios and scenarios from Latin America, Africa and Asia. These regions are of particular interest because they are experiencing significant changes in the driving forces of land use emissions (e.g. agricultural expansion, agricultural productivity, deforestation, and population growth). The scenarios of CO₂ from deforestation include the fluxes of carbon resulting from changes in the area of forests, but not climatic feedbacks to the terrestrial carbon cycle.

For reference, Table 6.9 presents an overview of how each of the scenarios takes into

account driving forces of land use emissions. Table 6.11 summarizes other key assumptions of the scenarios. It should be noted that the IPCC methodology for national inventories for may differ from the IPCC scenario assumptions of emission factors, carbon contents of biomass, etc.

6.4.1 Results from CO₂ Global Scenarios

Before discussing scenarios of land use related CO₂ emissions, it should be noted that the scenarios substantially disagree on base year (1990) emissions, with estimates ranging from 0.7 to 2.5 Pg C a⁻¹. This reflects the lack of knowledge or agreement on how to represent the processes leading to CO₂ fluxes between the biosphere and atmosphere. Earlier it was noted that a similar situation exists for regional-scale energy-related emissions.

Most "non-intervention" scenarios show an upward trend until about year 2020, followed by a gradual decline (Figure 6.12). In comparison to energy-related scenarios which diverge up to year 2100, land use emissions show their greatest absolute differences around the middle of the next century (with a maximum range of about 0.8 to 4.8 Pg C a⁻¹), and then converge towards zero at the end of the century. Emissions decrease because either the driving forces of deforestation equilibrate or because forests are depleted.

The lower scenarios are IS92 a,b,e, AIM, and CW, and they all have similar decreasing global trends after 2010. Both H1 and SCW increase sharply until year 2050, but their magnitude of emissions is very different because they begin with very different base year emissions. The IS92 a,b,e scenarios show a net uptake of carbon from 2090 to 2100, resulting from assumptions about forest plantations in Africa and Asia. In most of the scenarios, the release of carbon by forest biomass burning greatly exceeds the amount of carbon taken up in plantations.

The range of cumulative emissions (of non-intervention scenarios) over the period 1990 to 2100 is 80 to 320 Pg C, indicating that the biosphere could continue to be a significant source of CO₂ in the atmosphere in the next century (Figure 6.13). The range in estimates of cumulative emissions (factor of four) is smaller than the maximum range of annual emissions (factor of six). This was also found to be the case for energy-related emissions. As noted earlier, this smaller gap between scenarios for cumulative emissions is significant from the point of view of climate impact analysis because of the integrative nature of the atmosphere-ocean system.

Cumulative emissions of the intervention scenarios assume considerable forestation and result in a significant net uptake of atmospheric CO₂ (30-150 Pg C).

The cumulative emissions of CO₂ from deforestation have an upper limit formed by the amount of carbon stored in the global terrestrial biosphere of about 600 Pg (Atjay, et al., 1979; Olson et al, 1983) assuming no forestation. According to the non-intervention scenarios reviewed in this chapter, deforestation in the next century may release between 15 and 50% of the carbon stored in the global terrestrial biosphere.

Summing up the discussion of global CO₂ scenarios from land use, their emission estimates vary by a maximum of a factor of six in the mid 21st century, and then converge to zero towards the end of the century because the driving forces equilibrate or forests are depleted. By comparison, the range of cumulative emissions is a factor of four.

Table 6.9: Major driving forces for land cover/use change

Process	IS92 (IPCC)	SCW/RCW	CW (IMAGE 2.0)
Deforestation	Proportional to population increase, with a lag time of 25 years.	External scenario based on Terrestrial carbon model (Houghton et al., 1983) for tropics only. Deforestation is not a result of demand for agricultural products.	Forest clearing results from change in demand for crop and animal products and industrial wood and fuelwood. Changes in land productivity take into account soil and changing climate.
Demand for agricultural products	See SCW/RCW	Demand consists of human consumption, feed, seed, industrial usage and waste. Human consumption is based on past trends (reflecting income, habits, tastes). Income changes allow changes in consumption. The model allows changes in arable land and pastures. Technical progress is captured in yield functions for 9 commodity classes.	Demand is determined by population and income through elasticities. This affects the required areas of both arable land and grassland. Arable crops are divided into 9 classes of vegetable products including rice and 5 classes of animal products.
Crop production	See SCW/RCW	Crop yields are function of fertilizer application. BLS extrapolates the trend in land use per capita from 2025-2050 to the period 2050-2100.	Crop yields change as a consequence of the additions of agricultural inputs, and technological development.
Rice acreage	See SCW/RCW	Various methods, e.g. China: based on past trends; India, Indonesia, US: based on relative profitability of rice compared to other crops.	Rice acreage is modeled from demand for rice, climate, and soil. The increase in harvested area is the result of increases in irrigated rice only, with the 1990 dryland area remaining constant.
Animal production and numbers	See SCW/RCW	The production of animal products is function of feeding intensity. For most regions the number of animals is not calculated explicitly.	In period 1990-2025 the production per animal increases along with GNP/capita to 1990 OECD-Europe productivity as GNP reaches 1990 OECD-Europe level. For industrialized countries increase in productivity is 10%. In 2025-2050 the increase in productivity is 50% of that in 1990-2025, in 2050-2100 the increase is zero.
Fertilizer use	Pre-specified. Scenario from Pepper et al. (1992).	Fertilizer use is explicit variable in most parts, except in regional models in BLS. In regional models agricultural production determines fertilizer use.	Fertilizer use is pre-specified, not a model result. Scenario for fertilizer use is from IS92a.

6.4.2 Results from CO₂ Regional Scenarios

The available regional scenarios of CO₂ (IS92, SCW and CW) show considerable differences (Figures 6.14a to 6.16a). The CW scenario for Africa greatly exceeds the other scenarios until about 2060, when Africa forests are depleted according to the scenario (Figure 6.14). After 2050, IS92 a,b,e show a net uptake in Africa resulting from forest plantations.

In Latin America, the SCW scenario is much higher than the others because it assumes a higher forest exploitation rate, while CW is much lower than the others because it computes a stabilization of driving forces that have led to deforestation (Figure 6.15).

Table 6.11. Assumptions of land use scenarios of emissions

Source	IS92a	SCW/RCW	CW
CO ₂ from deforestation and forestation	Low estimates of biomass based on OECD (1991)	Based on clearing rates and on low biomass estimates in vegetation and soils from Houghton (1991). High and low biomass values are specified for 6 types of forest (disturbed and undisturbed moist, seasonal and dry forests) and for 3 continents. The SCW scenario uses the low biomass estimates.	Carbon contents are result of soil and climate using BIOME model and Klein-Goldewijk et al. (1993).
CH ₄ from wet rice cultivation	38 g m ² a ⁻¹	75 g m ² a ⁻¹	38 g m ² a ⁻¹
CH ₄ from animals	Crutzen et al. (1986); Lerner et al. (1988). Emissions per unit of product decrease with productivity.	Crutzen et al. (1986); Lerner et al. (1988). Emissions per unit of product decrease with productivity.	Gibbs and Leng (1993); Crutzen et al. (1986). Emissions per unit of product decrease with productivity.
CH ₄ from animal waste	1990 emission of 26 Tg a ⁻¹ (source not specified)	Not included in calculations	Based on Gibbs and Woodbury (1993), giving total of ~13 Tg a ⁻¹ for 1990.
Biomass burning emissions (CH ₄ , CO, NO _x , N ₂ O, VOC)	Crutzen and Andreae (1990)	Various literature sources (Cicerone and Oremland, 1988; Seiler and Crutzen, 1980 and other references)	Crutzen and Andreae (1990)
N ₂ O from fertilizer and animal excreta;	Fertilizer induced emission of 2.6% of applied mineral fertilizer-N. Background and animal excreta not considered.	Fertilizer induced emission of 2.5% of applied mineral fertilizer-N. Background and animal excreta not considered.	Fertilizer induced emission 1% of applied mineral N and 1% of N in animal excreta, based on Bouwman et al. (in prep.). Background emission from arable lands and pastures are based on climate and NPP.
N ₂ O from natural ecosystems	6.1 Tg N a ⁻¹ , constant in time.	6.0 Tg N a ⁻¹ , constant in time.	Depending on temperature, precipitation, NPP (Based on Bouwman et al. (1993).
N ₂ O from gain in agricultural land	Luizao et al. (1989) for current flux of 0.8 Tg N a ⁻¹ .	Bolle et al. (1986) for current flux of 0.4 Tg a ⁻¹ .	Modelled, based on Keller et al. (1993) and Bouwman et al. (in prep).
Other sources	Calculated as complement to assumed global source	Calculated as complement to assumed global source	Calculated as complement to assumed global source.

For Asia, the SCW and CW scenarios show the largest differences to the IS92 and AIM scenarios (Figure 6.16). Part of the differences may be caused by differences in the definition of regions. For example, the deforestation estimates in IS92 and SCW do not include China, although computed deforestation in the CW scenario which does include China is considerable. For Asia, the CW scenario peaks around year 2000, mainly caused by high deforestation rates in India. Both the IS92 and CW scenarios assume that wood from forest clearings are not burned in China and Centrally-Planned Asian countries. Hence deforestation in this part of Asia is assumed to result in a low, long-term flux of carbon from enhanced soil respiration, rather than a higher short-term flux due to wood burning of cleared forests. Hence, although the global results for CO₂ fluxes are consistent, the regional results show a much greater disagreement.

Summing up the discussion of regional CO₂ scenarios from deforestation, the differences in their emission estimates are quite large, with most important inconsistencies/differences occurring for Africa and Asia. However, some of these regional differences apparently offset each other so that differences in global results of the scenarios are not as great.

6.4.3 Factors Affecting CO₂ Emissions from Deforestation and Forestation

The main factors used to estimate CO₂ emissions from deforestation are: (i) the rate of deforestation, (ii) the carbon content of vegetation, and (iii) the allocation of the cleared biomass to different carbon pools on the deforested land. The last factor will influence the timing of the release of CO₂ but will have only a small effect on the cumulative emissions. Hence, the following sections will only discuss the first two factors. Table 6.9 describes the driving force assumptions made in various scenarios to compute CO₂ emissions from land use. Table 6.11 makes a qualitative comparison of the scenario assumptions of deforestation, forestation, and carbon content.

6.4.3.1 Deforestation and Forestation Rates

The IS92 and CW scenarios have similar global average deforestation rates, but differ within regions (Figures 6.14b, 6.15b, 6.16b). The IS92 scenarios for Africa increase up to 2020, and decline slowly afterwards (Figure 6.14b). The CW scenario increases more quickly than IS92, but also peaks around 2020. Afterwards the rate of deforestation declines at a faster rate than the IS92 scenarios, reaching zero around 2070 when all African forests are depleted. In the meantime, the AIM scenario peaks somewhat earlier than the other two scenarios, and also maintains a lower rate of deforestation throughout much of the period.

For Latin America the deforestation rate of the IS92 scenarios gradually decreases towards 2100 (Figure 6.15b). Meanwhile, the net rate of the CW scenario decreases much more rapidly, reaching zero in 2005. Afterwards, there is a net forestation of abandoned agricultural and rangeland until 2050 when net forestation also reaches zero. The AIM scenario parallels the trend of the IS92 scenarios, but at a lower rate.

Deforestation in Asia slowly decreases in the IS92 scenarios, reaching near zero in 2100 (Figure 6.16b). Again the AIM scenario follows the trend of the IS92 scenarios, but with a lower deforestation rate. The CW scenario is very different from these scenarios, peaking around the year 2000 in China and India, and then rapidly decreasing by 2045 as forests are depleted.

Most scenarios base their deforestation rates on population estimates, under the assumption that population is related to demand for agricultural and forestry products which, in turn, leads to deforestation. The population scenarios used in the IS92 and CW scenarios (World Bank, 1990), SCW and RCW (USBC, 1987), AIM (UN, 1992) are only slightly different in their estimates of population trends to the year 2100. These small differences cannot explain the significant differences in deforestation rates between some of the published scenarios. Houghton (1991) does not report the population estimates used for scenarios H1 and H2.

The IS92 and AIM scenarios set deforestation rates proportional to population increase, with a 25 year time lag. Hence, as population growth declines (which it ultimately does according to the assumed population scenarios), deforestation rates also decline.

The SCW and H1 scenarios have similar emission trends, and it is presumed that their underlying deforestation assumptions are similar. Deforestation in the SCW scenario is a function

of population growth, while in H1 it is extrapolated from historical trends of tropical deforestation in FAO/UNEP (1991).

As compared to the SCW and H1 scenarios, the deforestation rates of the RCW and H2 scenarios are based on higher rates of agricultural productivity, which leads to lower rates of agricultural expansion and deforestation. The CO₂ emissions estimated by the two scenarios differ because of different assumptions about carbon content of vegetation rather than different assumed deforestation rates.

Deforestation rates are computed indirectly in the CW scenario: population and GNP scenarios are used to compute regional agricultural demands which are then used to estimate the expansion or abandonment of agricultural and rangeland on a geographically-detailed basis for the whole world. Expansion of land for crops or livestock leads to a certain amount of forest clearing from which a deforestation rate can be derived.

Some non-intervention scenarios assume forestation. For example, for IS92 a,b,e a constant rate of forestation of 1.3 Mha a⁻¹ was assumed, while abandoned agricultural land is converted to its natural ecosystem in CW.

Box 3. Uncertainties in Estimating CO₂ from Deforestation: An Indonesian Example

Country estimates help illuminate the uncertainties in estimating the driving forces of CO₂ emissions from deforestation. The report JEE(1993) estimates an Indonesian deforestation rate of 1.3 Mha a⁻¹ for the period 1982-1990. Deforestation was attributed to a combination of expansion of agricultural land, infrastructure, and urban centers; as well as shifting cultivation, forest fires, and logging. The carbon content assumed for Indonesian forests was 45-90 t C ha⁻¹ (JEE, 1993). The integrated flux is 60 to 124 Tg C a⁻¹ (1989/90) for Indonesia. This can be compared to Houghton's estimate of 192 Tg [t] C a⁻¹ (Houghton, 1991) which is based on assumptions about the carbon content of different types of vegetation.

The carbon uptake of vegetation was estimated by JEE (1993) to be around 103 to 224 Tg C a⁻¹ based on an annual carbon uptake of 3.0-6.6 t C ha⁻¹ a⁻¹ for 17 Mha of forest fallow and 4 Mha of forest plantations. This total area is equivalent to about 20% of the total forested area in Indonesia estimated by Myers (1991).

6.4.3.2 Carbon Content of Vegetation

Another major factor influencing the range of CO₂ emission estimates is the uncertainty of carbon content of vegetation. Pepper et al. (1992) and EPA (1990) point out the sensitivity of the IS92 and SCW and RCW scenarios to this uncertainty (See also Box 3).

There are two different methods to estimate the carbon content of vegetation. Higher estimates are obtained by destructive sampling of biomass, usually covering small areas. Lower values for the carbon content are obtained by estimating timber volumes and wood densities for forest stands, usually derived from inventories covering large forest areas. The mean carbon content of all tropical forests is about 65% higher for destructive sampling than for wood volume based estimates (Houghton, 1991). The scenarios reviewed above use different premises for their estimates of carbon content of vegetation. The IS92 scenarios use OECD (1991), which are mid-ranges of values based on estimates of wood volumes used by Houghton (1991). The H1 to H3 scenarios are based on the mean of the two methods --destructive sampling and estimation from wood volumes; while the SCW, RCW, SCWP, and RCWP scenarios are identical to the low

estimates of Houghton (1991). The continental mean carbon content of vegetation in CW is similar to the low estimates in the IS92, RCW and SCW scenarios. However, unlike the other scenarios, carbon content of vegetation in the CW scenario changes with time in accordance with changes in climate and atmospheric CO₂ concentration. Hence, the scenarios reviewed contain various combinations of assumptions for deforestation rate and carbon content.

Summing up the discussion of factors influencing the estimation of CO₂ emissions from deforestation -- there are comparatively few studies to compare, and their assumptions about deforestation rates vary considerably. However, the scenarios agree that deforestation will diminish by the end of the 21st century because of equilibration of the driving forces of deforestation or the depletion of forests. The carbon content of vegetation is another important assumption in estimating CO₂ emissions, and the various scenarios use a wide range of estimates for this variable.

6.4.4 Results from Global Scenarios of non-CO₂ Greenhouse Gases

The scenarios IS92, SCW and CW include global and regional estimates of emissions other than CO₂. This section highlights global scenarios of some of the more important emission categories of these gases.

For CH₄ from rice fields, the SCW scenario assumes a base year (1985) emissions that is twice as large as the IS92 and CW scenarios (Table 6.12). However, the temporal trend of the SCW scenario is close to that of the IS92 scenario in that it increases until around the middle of next century, and declines slowly afterwards. The CW scenario, by comparison, declines until around 2025, and then slightly increases to the end of the century. These trends reflect the harvested area of wetland rice assumed in the scenarios. This issue will be discussed later in this chapter.

The scenarios for CH₄ from enteric fermentation agree on base year (1985) emissions and trends up to 2000 (). Afterwards, emission estimates of the IS92 and SCW scenarios increase up to the end of the century, although the SCW does so at a slower rate. By contrast, the CW emissions peak around 2050 and decline afterwards. The lower emissions of the CW scenario result from its assumptions about increases in the meat productivity of animals which leads to estimates of lower numbers of animals than the other scenarios.

The various scenarios of N₂O emissions from soils of natural vegetation (not shown) differ greatly. The IS92, RCW, and SCW scenarios have constant global emissions, while the CW scenario slowly increases. Part of the difference in scenarios arises because the CW scenario takes into account climatic feedback to N₂O emissions. By comparison, scenarios of N₂O emissions from soils of fertilized agricultural areas do not vary as much because they are all based on the same global scenario of fertilizer use. In this case the difference between scenarios stems from differences in assumed emission factors.

6.4.5 Results from Regional Scenarios of non-CO₂ Greenhouse Gases

With regards to CH₄ from rice production, this paragraph focuses on scenario results for Asia where about 90% of the world's rice is produced. The three available scenarios differ very

Table 6.12: Emissions of CH₄ from wetland rice cultivation in Tg CH₄ a⁻¹

	1985	1990	2000	2010	2020	2025	2050	2075	2100
SCW									
Africa	2.6		3.9			5.5	6.6	7.6	7.8
Asia	96.0		110.0			131.6	148.5	155.3	148.1
LA	6.0		6.5			7.1	6.8	6.8	6.5
World	109		125			149	165	176	169
CW									
Africa	1.2	1.4	1.8	2.4	3.5	4.2	8.2	11.9	15.7
Asia	53.8	54.3	46.8	40.7	38.5	38.5	39.4	38.3	37.7
LA	2.5	2.4	2.6	2.6	2.5	2.4	2.5	2.7	3.0
World	58	59	53	48	46	47	52	55	54
IS92 a,b,e									
Africa	1.4	1.6	2.0	2.5	2.8	2.9	3.4	3.9	4.1
Asia	50.5	52.9	58.0	62.9	66.7	69.2	78.2	76.3	74.2
LA	3.1	3.1	3.4	3.7	3.7	3.7	3.4	3.3	3.2
World	58	60	66	69	76	78	87	86	84

Table 6.13: Emissions of CH₄ from enteric fermentation in Tg CH₄ a⁻¹

	1985	1990	2000	2010	2020	2025	2050	2075	2100
SCW									
World	75		94			125	151	172	179
CW									
Africa	8.1	8.5	11.2	14.9	21.5	25.4	40.5	43.5	47.5
Asia	22.8	24.1	38.9	53.6	68.0	75.1	82.3	69.9	63.1
CP Asia	6.7	7.2	16.1	24.2	31.4	34.8	31.1	27.5	24.8
LA	8.1	17.7	19.5	19.0	18.5	18.2	13.8	9.7	7.5
USA	5.8	5.6	4.3	3.2	3.0	2.9	2.8	2.8	2.2
World	75	79	96	112	131	142	161	147	142
IS92 a,b,e									
Africa	8.6	9.8	13.2	16.5	20.2	22.6	33.1	42.4	48.1
Asia	22.0	23.8	28.6	34.1	40.3	43.7	61.1	66.5	69.9
CP Asia	4.9	5.2	5.7	6.2	6.8	7.0	8.6	8.5	8.7
LA	16.0	18.0	22.0	26.0	30.0	32.0	40.0	42.0	43.0
USA	7.1	7.8	8.8	8.9	9.3	9.2	6.6	6.0	6.0
World	77	84	99	114	129	138	173	188	198

considerably. Base year (1985) emissions of SCW are nearly twice as high as the CW and IS92 scenarios (Table 6.12). The IS92 scenarios show a 24 Tg CH_4 a^{-1} increase by year 2100, as compared to a 52 Tg CH_4 a^{-1} increase for the SCW scenario, and a 4 Tg CH_4 a^{-1} decrease of CH_4 from rice fields in the CW scenario. However, both the SCW and IS92 scenarios project an increase of about 50% in CH_4 emissions, because of their identical assumptions about the increase in harvested rice area (Table 6.12). The IS92 scenarios indicate a nearly constant emissions levels for China plus Centrally Planned Asian countries (not shown), while the CW scenario estimates a reduction by a factor of 2 caused by a major increase in rice yields per hectare. Emissions from India (not shown) also decrease by 20% in the CW scenario by 2100 because of faster increases in rice yields per unit area than in rice demand.

With regards to estimates of CH_4 emissions from enteric fermentation, there are large differences between the IS92, SCW, and CW scenarios for Asia, but smaller differences for Africa (Table 6.13). For example, in the China plus Centrally Planned Asia, the IS92 scenario has low and nearly constant emissions as compared to the CW scenario which has a rapid increase between 1985 and 2025, and a decline of 30% between 2025 and 2100.

The IS92 scenarios of Latin America for CH_4 from enteric fermentation show a large increase from 16 Tg to 43 Tg CH_4 between 1985 and 2100, whereas the CW scenario gives a doubling in emissions between 1990 and 2025, and a decline thereafter (Table 6.13).

Regional results for N_2O from soils underlying natural vegetation are only provided by the CW scenario, which estimates that increases will be most important in temperate climates because of the importance of climate feedbacks there.

With regards to N_2O from fertilized soils -- different regional assumptions of fertilizer use lead to different estimates of N_2O emissions. For example, the growth in fertilizer use and associated N_2O loss for Africa is higher in IS92 a,b,e than in CW. The increase in fertilizer-related N_2O is similar for Asia as a whole, but different for e.g. in Centrally Planned Asian countries. For Latin America the growth of N_2O emission from N-fertilizer is faster in CW than in IS92 a,b,e.

6.4.6 Factors Affecting non- CO_2 Emissions from Land Use

For reference, the main driving forces of non- CO_2 emissions from land use are reviewed in Table 6.9 and key assumptions of the scenarios in Table 6.11.

6.4.6.1 Factors Affecting CH_4 From Rice Production

This section discusses the assumptions of different scenarios leading to estimates of CH_4 emissions from rice fields. The main factors influencing the estimation of emissions are the assumed rate of CH_4 emissions per unit area of rice field, and the total area of rice fields. The area of rice fields is in turn, influenced by the assumed rice yield per ha. The scenarios reviewed in this report all assume that the emission rate of CH_4 does not change with time.

The RCW and SCW scenarios give emission rates for wetland rice that are twice as high as the value used in the IS92 scenarios. The CW scenario uses the same wetlands emission rate as in the IS92 scenarios, but unlike the IS92 scenarios, distinguishes between wetland and

dryland rice areas. This contributes to the difference between the IS92 and CW scenarios. In addition, the IS92 scenarios estimate the area of rice fields based on *a priori* assumptions about per capita rice consumption and rice yield per ha, whereas the estimate of rice area in the CW scenarios is based on economic and technological development. The rice yields of the IS92 scenarios are similar to those of the CW and SCW scenarios for South and Southeast Asia (Figure 6.17b), but are lower than those of the CW scenario for China and Centrally Planned Asia (Figure 6.17a). The higher yields in the CW scenario lead to smaller areas of rice fields as compared to the IS92 scenarios, and hence to lower CH_4 emission estimates. In India, the CW scenario shows that rice yield improvements exceed the increase in rice demand up to 2025, leading to a decrease in rice area and CH_4 emissions. After 2025 demand exceeds the yield improvement, and both rice area and CH_4 emissions increase. Emissions in the IS92 scenarios are relatively constant up to 2100.

The global yield increase of rice is assumed to be about $0.9\% \text{ a}^{-1}$ in the IS92, SCW and RCW scenarios for the period 1990-2010. FAO (1993) assumes a global yield increase of $1.5\% \text{ a}^{-1}$ and increase in harvested area of $0.5\% \text{ a}^{-1}$ for the period 1990-2010 leading to a rise in production of $2\% \text{ a}^{-1}$. The total yield increase over the period is about 35%. This is even more optimistic than the yield increase of 25% for Asia assumed by CW, and substantially different from the IS92, SCW, and RCW scenarios. For the period beyond 2010 it is not certain whether high growth rates in rice yields of the order of 1.5% can be maintained, and it has been suggested that for continued growth a genetic breakthrough is needed.

National projections can be used to examine the assumptions for different regions. For example, in Indonesia a number of different scenarios were developed to analyze different combinations of development in rice yields and harvested and planted rice area (DOAI, 1993). The highest yield increase was $1.5\% \text{ a}^{-1}$, with an increase in harvested area of $0.6\% \text{ a}^{-1}$ to arrive at a $2.2\% \text{ a}^{-1}$ growth in rice production. The same $2.2\% \text{ a}^{-1}$ rise in production could also be achieved with a yield increase of $0.9\% \text{ a}^{-1}$ combined with an increase of $1.2\% \text{ a}^{-1}$ in harvested area. The latter scenario was based on historical increases in rice yield and is much less optimistic about rice yields than FAO (1993), IPCC IS92 scenarios, CW and RCW and SCW. This Indonesian example shows the important effect of assumptions about rice yields on the development of harvested area.

6.4.6.2 Factors Affecting CH_4 from Enteric Fermentation

Estimates of CH_4 emissions from enteric fermentation depend on assumptions about the number of animals, and this in turn depends on the size of the demand for meat and dairy products and the amount of meat and dairy products produced by each animal (animal productivity).

The major difference between the IS92 and CW scenarios is the estimation of demand for meat and dairy products. This depends on demographic, economic and technological factors in CW, and on *a priori* assumptions in the IS92 scenarios.

Of the scenarios reviewed, only the CW scenario makes explicit assumptions about meat productivity. Over the period 1990-2010, the CW scenario assumes a 0.2 to $1.5\% \text{ a}^{-1}$ increase in developing regions, whereas FAO (1993) assumes a much higher 0.9 to $1.9\% \text{ a}^{-1}$ for the same period. Scenarios of animal populations are linked to these productivity assumptions. For the period 1990-2010 the CW scenario shows an increase in the number of cattle by a factor of 1.9

for Africa, 2.2 for the Middle East, 5.6 for China, 1.2 for India and 1.3 for Latin America. The corresponding estimates from FAO (1993) are much lower, namely, 1.3 for Africa, 1.4 for Middle East, 2.3 for East Asia (including China), 1.2 for South Asia (including India) and 1.1 for Latin America.

6.4.6.3 Factors Affecting N_2O from Fertilized Agricultural Soils

The amount of N_2O from fertilized soils depends on the amount of fertilizer used and the N_2O loss rate from soil. It was already pointed out that the scenarios reviewed here assume the same amount of future fertilizer use. Hence most differences between scenarios arise from different assumptions about N_2O loss rates from soils.

The assumed growth of fertilizer up to 2010 is substantially lower than given in FAO (1993). For the period 1990-2010, FAO assumes a 3.3 to 4.8% a^{-1} growth in fertilizer use in Africa, Latin America and Asia.

Summing up the discussion of factors influencing the emissions of non- CO_2 gases from land use - The scenarios reviewed take a wide variety of different approaches in estimating future emissions. This reflects the lack of knowledge or agreement on how to represent emission-generating processes. In general, the IS92 scenarios only partly cover the range of input assumptions found in other published scenarios.

6.4.7 Discussion

Different clusters of scenarios for CO_2 emissions from deforestation are distinguishable. Starting with global scenarios, the IS92 and AIM scenarios make similar assumptions about the relationship between population growth and emissions. Consequently, as population growth slows, they estimate similar downward trends in emissions. The CW scenario takes into account growth of population, GNP, as well as technological development and other factors, and calculates a global emissions trend close to the IS92 and AIM scenarios. These scenarios are also in the lower range of non-intervention scenarios. The remaining non-intervention scenarios, SCW, RCW, H1, and H2, extrapolate past trends in deforestation and estimate much higher emission rates than the other scenarios.

For regional scenarios, the CW differed greatly from the IS92 and AIM scenarios because of differences in methods for estimating future trends in deforestation. Although nearly all scenarios relate the deforestation rate only to population growth, it is known that deforestation is more precisely related to pressure for agricultural land, wood products, settlement policy, and other socio-economic factors (Turner, et al. 1993). Accounting for these factors would permit the construction of more diverse scenarios of CO_2 emissions. Moreover, including these socio-economic factors would tend to dampen the rapid rates of deforestation found in nearly all scenarios.

Much of the variation between scenarios on both the global and regional basis can be attributed to different estimates of base year emissions. This indicates the lack of scientific agreement on the processes leading to CO_2 fluxes from deforestation. Another important source of variation is differing estimates of carbon content of vegetation and soil. For example, the SCW and H1 scenarios differ only because of their different assumptions of carbon content of forests.

The scenarios for CH₄ emissions from rice fields and enteric fermentation are sensitive to assumptions about future technological improvement of rice and animal productivity, and herd composition. Estimates of the different scenarios disagree with FAO (1993) and perhaps should be re-evaluated. Another source of uncertainty for CH₄ estimates from rice fields is the rate of emissions per unit area of rice field. Although the scenarios surveyed in this report assumed a global, constant emission factor, the rate of emissions is known to depend on site conditions, rice variety, and crop management. Some of this knowledge should be built into new scenarios.

A drawback of the IS92 and other scenarios is that they do not take into account important climatic and atmospheric feedbacks to land use emissions (e.g., N₂O from soils and CO₂ from soil respiration). The only scenario to do so is the CW scenario, although there is of course great uncertainty in its treatment of these feedbacks.

From the land use emissions perspective, the IS92 scenarios are on the low side of the wide range of global scenarios for CO₂ from deforestation, and overlap with the few regional scenarios that are available. They also partly overlap with the few scenarios available for N₂O and CH₄ emissions. In addition, the IS92 scenarios cover most of the greenhouse gases originating from land use and agriculture, as well as precursors of ozone and sulfate aerosol. Emissions are reported for four world regions and by source and sector.

With regards to reproducibility of the IS92, SCW and RCW land use scenarios -- Their documentation of certain land use assumptions is not quite adequate to reproduce the scenarios. For example, it would be helpful to have a more detailed description of the assumptions about forestation, rice production, and animal production. There are few published sensitivity analyses of land use emissions. In one of the few studies available, Pepper et al. (1992) analyzed the effect on CO₂ emissions of assumed carbon content of the cleared vegetation and the rate of deforestation. Although this analysis was not strictly a sensitivity analysis, it illustrates the simplicity of the assumptions. The calculated CO₂ emissions are directly related to the carbon content of the cleared vegetation, population growth and deforestation rates in previous periods. The carbon content is specified for 3 forest types and for 3 continents. The deforestation rates in IS92 scenarios are calculated from human population growth and the deforestation rate, with a lag time of 25 years.

There is no analysis of the sensitivity to input assumptions of deforestation rates presented for SCW and RCW in EPA (1990) and AIM (Matsuoka and Morita, 1994). Zuidema et al. (1994) examined the sensitivity of changes in land cover of the CW to changes in crop and animal productivity, showing that deforestation rates are more sensitive to crop yields than to animal productivity. Table 6.9 indicates that the CW scenario of deforestation is based on the assumption that deforestation is driven by the demand for food and wood products. Hence, in the CW deforestation depends on human population, on GNP through income elasticities of food products, and on the land's productivity. Land productivity is based on grid-based maps of land cover, climate, soils and region-specific management factors. Further sensitivity analysis should include all these factors.

In closing this section, we note that one reason for the large differences in land use scenarios of CO₂, CH₄ and N₂O emissions is the lack of dependable geo-referenced information on land cover and land use. Systematic land cover and land use mapping is needed to decrease this uncertainty, to improve emission scenarios, and to develop cost-effective mitigation measures.

6.5 Discussion and Recommendations

In this section, we discuss the IS92 scenarios in light of the purposes for scenarios laid out in Section 6.1. It should again be emphasized that time constraints led to a narrowing of the focus for the evaluation. Also, in fairness, we note that we did not judge other scenarios by the criteria with which we judged the IS92 scenarios. Therefore the reader should be aware that any shortcomings of the IS92 scenarios identified in this evaluation may or may not apply to other scenarios.

As a method for judging whether the IS92 scenarios comply with criteria in Section 6.1, they have been compared to other scenarios. This comparison does not answer all questions about requirements of the scenarios, but provides important information about the relative position of the IS92 scenarios with regards to other work in the scientific community. In this chapter we first examine the uses and limitations of the IS92 scenarios and then discuss the need for new scenarios, as well as the procedure for developing them.

6.5.1 What Are the Uses and Limitations of the IS92 Scenarios?

In our judgement, the IS92 scenarios clearly fulfill the criteria for Purpose 1 listed as "very important" in Table 6.14. Specifically, it is shown in Sections 6.2 through 6.4 that their global results and many input assumptions span the range of results of other scenarios; in this way it can be said that the scenarios reflect the current range of views about future emissions, at least on the global level. (For particular regions, however, there are many cases in which the IS92 scenarios are not representative of the range of views.) Moreover, the IS92 scenarios are among the most comprehensive scenarios available in their coverage of all important greenhouse gases and precursors of ozone and sulfate aerosol. Also the scenarios are sufficiently documented in reports and in digital form to allow their comparison with other scenarios, and to be used as input files for climate models. As a consequence, they are useful for Purpose 1, namely as input to atmosphere/climate models for examining the environmental/climatic consequences of not acting to reduce greenhouse emissions.

It is noted that the IS92 scenarios do not fulfill all of the "important" and "desirable" requirements for Purpose 1 listed in Table 6.14. With regards to the criterion of reproducibility -- the documentation of land use assumptions having to do with forestation, rice production and animal production may not be adequate enough to allow other researchers to reproduce the IS92 calculations. Related to reproducibility, we note that the ASF model used to generate the scenarios is not readily available. With regards to the criterion of sensitivity analysis of the IS92 scenarios -- only a limited amount of work is reported in Pepper, et al. (1992). The criterion of internal consistency of the scenarios could not be evaluated because we did not have access to the ASF model.

Although these shortcomings should be addressed in new scenarios, we do not believe that they take away from the current usefulness of the IS92 scenarios as input to atmospheric/climate models.

Table 6.14: Suggested Criteria for Using Emission Scenarios for Different Purposes

Criteria	Purpose of Scenario (See Box 2 -- Sec. 6.1)			
	1	2	3	4
<i>Comprehensive.</i> The scenarios take into account all important greenhouse gases including precursors of ozone and sulfate aerosol.	xxx	xxx	xxx	xxx
<i>Documentation of Output.</i> Sufficient detail is provided for emissions by type, region (if available) and sector, in order to allow comparisons with other scenarios.	xxx	xxx	xxx	xxx
<i>Emission Estimates and Input Assumptions of the Scenario Reflect a Range of Views.</i> A single reference scenario is inadequate for this purpose. Instead, a range of scenario results are presented that take into account the uncertainties of basic driving forces of the scenarios. Data on driving forces, as well as parameters in the case that a model is used, reflect the current range of views. In addition, derived variables, for example, carbon intensity of the economy, also reflect current understanding.	xxx	xxx	xxx	xxx
<i>Reproducible.</i> Input data and methodology are documented adequately enough to allow other researchers to reproduce the scenarios.	xx	xx	xx	xxx
<i>Sensitivity Analysis.</i> Information is provided on the sensitivity of scenarios output to variation and uncertainty of input data and model parameters (if a model is used).	xx	xx	xx	xxx
<i>Internal Consistency.</i> The various input assumptions and data of the scenarios are internally consistent. For example, assumptions about biomass in the energy sector are consistent with assumptions in the land use sector.	xx	xx	xxx	xxx
<i>Documentation of Assumptions about Policy Intervention.</i> All assumptions about policy actions are documented adequately enough to allow policy interpretation of the scenario results.	NA	xxx	xxx	xxx
<i>Disaggregation of Data.</i> Input and results of scenarios are sufficiently disaggregated into sectors and geographic regions to allow analysis of policies. The geographic breakdown is the country level, but the regional level may be adequate as a first step.	x	x	xxx	xxx
<i>Documentation of Input Data and Methodology.</i> Input data and methodology are sufficiently documented to allow analysis of feasibility and costs of reduction measures.	NA	NA	xxx	xxx
<i>Reference Scenario.</i> The set of emission scenarios include a "Reference Scenario" for comparison with the policy scenarios in order to ensure consistency.	NA	xxx	xxx	xxx
<i>Temporal Calculations.</i> The scenarios describe the time aspect of implementing mitigation measures. This is critical information for assessing costs of control.	NA	x	xxx	xxx
<i>Range of Policy Actions.</i> The set of scenarios include a wide range of policy alternatives.	NA	x	x	x

xxx **Very Important**
 xx **Important**
 x **Desirable**
 NA **Not Applicable**

Even though the IS92 scenarios were designed with Purpose 1 in mind, it is interesting to examine whether they are useful for the other purposes of scenarios. Table 6.14 ranks the importance of different criteria to fulfill these purposes. We now briefly review the suitability of the IS92 scenarios to fulfill them.

Purpose 2. To evaluate the environmental/climatic consequences of intervention to reduce greenhouse gas emissions. For this purpose an intervention scenario is devised, and then input to a climate or similar model to evaluate the scenario's environmental/climatic consequences.

This is basically the same as Purpose 1 except that the emissions scenario takes into account climate policies for reducing greenhouse gas emissions. For example, the scenario might assume that a carbon tax is imposed in order to reduce CO₂ emissions, or that a program to reduce CH₄ leakage in natural gas pipelines is carried out.

With regards to Purpose 2 (evaluating the consequences of intervention to reduce emissions), the IS92 scenarios make assumptions about controlling local air pollution problems and these measures would also have an affect on greenhouse gas emissions. Moreover, the IS92b scenario includes information available in 1992 about emission commitments of OECD countries. This information, however, must be updated with the latest information on commitments in connection with the Climate Convention. In general, it was found that emission estimates of the IS92 scenarios are substantially higher than policy scenarios published in the literature. Hence, they should not be used as intervention scenarios.

Purpose 3. To examine the feasibility and costs of mitigating greenhouse gases from different regions and economic sectors, and over time. This can include setting emission reduction targets, and developing scenarios to reach these targets. It can also include examining different driving forces of emissions and sinks in order to identify the driving forces which can be influenced by policies.

This purpose requires more information about the scenarios than the preceding two purposes because its goal is a realistic assessment (technical and financial) of mitigation measures. This requires estimation of all important greenhouse gases from specific economic sectors and geographic regions. Input assumptions must also be described in this detail. Under ideal circumstances, these data would be available on the country-level, although for preliminary calculations the scale of world regions may be adequate.

Analysing the feasibility and costs of mitigation also requires that the scenario have a high level of internal consistency, so that costs can be accurately assessed. In addition, since the evaluation of mitigation measures must take into account the time period over which measures are put into place, a scenario must provide information about changing emissions over time, rather than for a single point in the future (e.g. year 2025). To enhance the usefulness of scenarios for Purpose 3, it is also recommended that a *range* of policy alternatives be explored.

Scenarios that fulfill Purpose 3 will also fulfill Purpose 2, but a scenario that fulfills the requirements for Purpose 2 will not necessarily have enough detail to comply with Purpose 3.

The IS92 scenarios are inadequate for Purpose 3 primarily because they do not include 5 out of 6 scenarios do not include climate policies to reduce greenhouse gas emissions (they

were also not intended for that purpose). In addition, they have somewhat limited use as reference scenarios for mitigation studies because their regional emission estimates and regional input assumptions are in many cases outside the range of views found in published scenarios.

Purpose 4. As input for negotiating possible emission reductions for different countries and geographic regions.

To achieve this purpose a scenario must gain broad international acceptance by being based on widely acknowledged and accepted input assumptions and methodology. Consequently this scenario has the most stringent requirements.

It is our opinion that Purpose 4 is difficult to achieve at this time because of the high uncertainty of current greenhouse emissions from many emission categories and in many countries (especially CO₂ in non-energy sectors and other greenhouse gases from virtually all sectors). This is one reason why the IS92 scenarios are not appropriate for this purpose, although it can help set the context for negotiations by indicating the possible range of emissions if no mitigation takes place.

We note that scenarios for Purpose 4 will soon be needed for discussions related to the Climate Convention.

6.5.2 The Question of New Scenarios

At this time, it is recommended that researchers use the IS92 scenarios as input to atmosphere/climate models for examining the consequences of not intervening to reduce greenhouse gas emissions (Purpose 1).

As to the use of one IS92 scenario over another -- In some ways the IS92a scenario is intermediate among the scenarios. Its global CO₂ emissions fall near the middle of other scenarios at least up to year 2050, and some of its input assumptions are intermediate. For example, its population assumptions are equal or close to the medium projections recently published by three different international organizations. Although sensitivity analysis showed that there are no strong reasons for selecting it as the "medium case" scenario.

However, being an intermediate scenario is not the same as being the most likely scenario. Indeed, we believe that at this time there is no objective basis for assessing the likelihood of one scenario versus another. Considering the degree of uncertainty about future emissions, it is recommended to use the full range of IS92 scenarios as input to atmosphere/climate models rather than any single scenario.

Users of the IS92 scenarios are cautioned, however, that the lowest scenario (IS92c) has the emission levels and some input assumptions more characteristic of an intervention scenario rather than a reference scenario.

In general, because the IS92 scenarios were not designed and are not suitable for Purposes 2, 3, and 4, new scenarios may be needed to fulfill these purposes. It is worth repeating that the evaluation did not judge the suitability of non-IS92 scenarios to satisfy these purposes.

New scenarios, if developed, should especially include improvements in the estimation of baseline and future non-CO₂ emissions, particularly from the land use sector.

Although we did not judge the adequacy of all currently available scenarios, it is still likely that new reference scenarios will be needed for the following:

- to take into account the latest information on economic restructuring, especially in the CIS, Eastern Europe, Asia, and Latin America, (we note that restructuring in Eastern Europe and the CIS was partly taken into account in the IS92 scenarios, but it would be worthwhile to include more recent information about this restructuring)
- to evaluate the possible consequences of the Uruguay Round amendments to the General Agreement on Tariffs and Trade
- to explore a variety of economic development pathways, for example, a closing of the income gap between industrialized and developing regions.
- to examine different trends of technological change.
- to take into account the latest information about current emission commitments in connection with the Climate Convention.

The current commitments to stabilize emissions under the Climate Convention (See Box 4) could result in large reductions of emissions in certain regions, but on a global basis a reduction of 10% or less is expected in CO₂ emissions (in annual emissions relative to the IS92a scenario). Current commitments will have no effect on the lowest IPCC scenario (IS92c) because emissions in this scenario are lower than would be expected by current commitments.

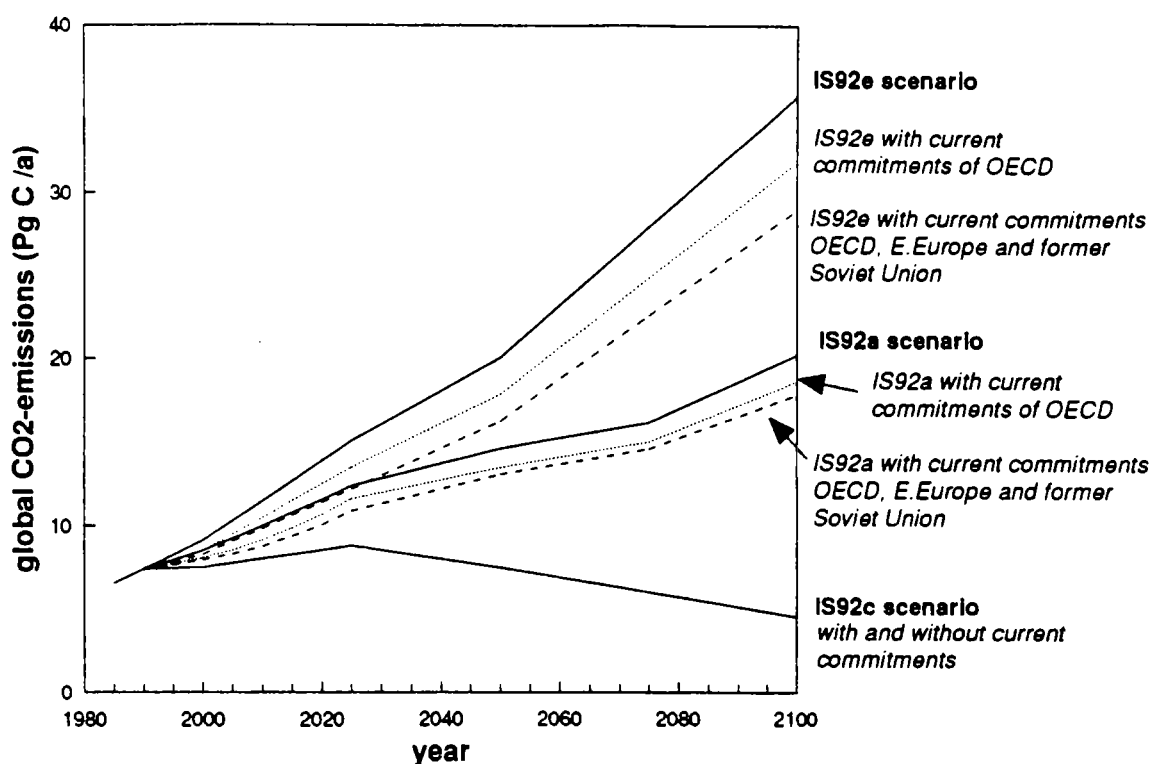
New scenarios are also needed that are consistent with limits on atmospheric concentrations of greenhouse gases by a specified date. These should be related to the carbon stabilization modeling exercises being performed by IPCC Working Group I.

6.5.3 The Process of Developing Scenarios

If new or updated scenarios are developed it is recommended that the following approach be taken to develop these scenarios. The IPCC or other suitable organization should act as an "umbrella" under which different groups can develop comparable, comprehensive emission scenarios. The process for developing scenarios should draw on current experience in harmonizing scenarios and model calculations, by emphasizing the following:

- *Openness*. Scenario development should be open to the wide participation of the research community, particularly from developing countries. This requires extensive documentation of modeling assumptions and inputs;
- *Pluralism*. A diversity of groups, approaches and methodologies should be encouraged, although they should be harmonized as noted below;
- *Comparability*. Reporting conventions of input and output should be standardized.
- *Harmonization*. Input assumptions and methodologies of the scenarios should be harmonized in order provide a common benchmark for scenarios from different groups.

Box 4. Scenarios of Current Commitments



This graph shows scenarios of global CO₂ emissions that could follow from current commitments under Article 4 of the Framework Convention on Climate Change. The current commitments scenarios are compared to the lowest, highest, and an intermediate IPCC scenario. For each reference scenario two cases of current commitments are shown. *Case 1*: All OECD countries comply with commitments noted in *Climate Change Policy Initiatives, Volume 1 OECD Countries, 1994 Update* (OECD, 1994); *Case 2*: All OECD countries comply with their commitments as in Case 1, plus countries in Eastern Europe and the former Soviet Union stabilize their emissions in year 2000 at the their 1990 levels. These cases show the *maximum* reductions that might be expected from current commitments (especially since some former republics of the Soviet Union have made no commitments under the Convention). CO₂ emissions are reduced by about 8 to 12% relative to the intermediate (IS92a) reference scenario of IPCC. Current commitments have no effect on global emissions of the IS92c scenario because emissions in this reference case are lower than they would be for either Case 1 or 2.

6.5.4 Integrated Scenarios

To accomplish Purpose 3 of emission scenarios (estimation of feasibility and costs of mitigation measures) it is not only important to analyze the costs of emission reductions, but also to assess the costs and benefits of the impacts of emissions on the natural environment and society. Therefore, the next generation of emission scenarios should be coupled with their impact on environment and society in the form of consistent, comprehensive *integrated* scenarios of global change. These scenarios would cover not only the trend of emissions, but also changes in the atmosphere and ocean, and the impact of these changes on society, the terrestrial environment, and the marine environment. We recommend that the IPCC encourages the development of integrated scenarios.

6.5.5 Dissemination of Scenarios

Current and new scenarios should be widely disseminated to countries, international organizations, non-governmental organizations and the scientific community. As part of this effort, a central archive should be established to make available the results of new scenarios to any group. The archive should also make available some aspects of the models and input assumptions used to derive scenarios. In addition, special effort is needed to improve the capabilities of researchers to analyze and develop scenarios, especially in developing regions. The IPCC can play a role in these activities.

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Appendix 6.1 Scenarios reviewed in this report

Code	Scenario Identification	Type (*)	Reference
1-1	IS92a IPCC 1992	G R	Leggett et al. (1992)
1-2	IS92b IPCC 1992	G R	Leggett et al. (1992)
1-3	IS92c IPCC 1992	G R	Leggett et al. (1992)
1-4	IS92d IPCC 1992	G R	Leggett et al. (1992)
1-5	IS92e IPCC 1992	G R	Leggett et al. (1992)
1-6	IS92f IPCC 1992	G R	Leggett et al. (1992)
1-7	IS92 S1: IPCC 1992 Sensitivity 1 (High Deforestation, High Biomass)	G R	Leggett et al. (1992)
1-8	IS92 S4: IPCC 1992 Sensitivity 4 (Halt Deforestation, High Plantation)	G R	Leggett et al. (1992)
2-1	Nordhaus 50th% (50th percentile)	G	Nordhaus et al. (1983)
2-2	Nordhaus 95th% (95th percentile)	G	Nordhaus et al. (1983)
2-3	Nordhaus 5th% (5th percentile)	G	Nordhaus et al. (1983)
3-1	Edmonds 50th% (Scenario B, 50th percentile)	G R	Edmonds et al. (1986)
3-2	Edmonds 95th% (Scenario B, 95th percentile)	G R	Edmonds et al. (1986)
3-3	Edmonds 5th% (Scenario B, 5th percentile)	G R	Edmonds et al. (1986)
4	Rogner	G R	Rogner (1986)
5	Mintzer	G R	Mintzer (1988)
6-1	Methane Economy Efficiency Scenario	G	Ausubel et al. (1988)
6-2	Methane Economy Long-wave scenario	G	Ausubel et al. (1988)
7-1	EPA Slowly Changing World (SCW)	G R	Lashof et al. (1990)
7-2	EPA Rapidly Changing World (RCW)	G R	Lashof et al. (1990)
7-3	EPA RCW with Accelerated Emissions (RCWA)	G R	Lashof et al. (1990)
7-4	EPA High Reforestation (Halt Deforestation, High Plantation)	G R	Lashof et al. (1990)
7-5	EPA SCW with Stabilization Policies	G R P	Lashof et al. (1990)
7-6	EPA RCW with Stabilization Policies	G R P	Lashof et al. (1990)

(*) G = Global, R = Regional (National), P = Policy Scenarios

Appendix 6.1 (continued)

Code	Scenario Identification	Type(*)	Reference
8-1	IPCC 1990 (SA:Scenario A)	G R	IPCC (1990)
8-2	IPCC 1990 (Scenario A, High)	G R	IPCC (1990)
8-3	IPCC 1990 (Scenario A, Low)	G R	IPCC (1990)
8-4	IPCC-EIS Energy Industry Sub-group 1990 (reference)	G R	IPCC (1990)
9	Ogawa (Institute of Energy Economics, Japan)	G R	Ogawa (1990)
10	Bach	G	Bach (1991)
11-1	Edmonds-Reilly (Scenario 1)	G R	Barns et al. (1991)
11-2	Edmonds-Reilly (Scenario 2)	G R	Barns et al. (1991)
12-1	GREEN (1991)	G R	Burniaux et al. (1991)
12-2	GREEN (1992)	G R	Burniaux et al. (1992)
12-3	GREEN (1993) reference	G R	Oliveira, Martins (1992)
12-4	GREEN (1993) 200 \$/tc carbon tax	G R P	Oliveira, Martins (1992)
13-1	Global 2100 (Scenario 1)	G R	Manne et al. (1991)
13-2	Global 2100 (Scenario 2)	G R	Manne et al. (1991)
13-3	Global 2100 (1992 Scenario)	G R	Manne (1992)
14	TEC	G R	Okada et al. (1991)
15	Anderson (World Bank)	G R	Anderson et al. (1992)
16-1	CHALLENGE reference	G R	Schrattenholzer (1992)
16-2	CHALLENGE 200 \$/tc carbon tax	G R P	Schrattenholzer (1992)
17	CRTM	G R	Rutherford (1992)
18	ECS '92 (Dynamics as usual)	G R	Messner et al.(1992)
19-1	IEA 1992	G R	Vouyoukas (1992)
19-2	IEA 1993	G R	Vouyoukas (1993)

(*) G = Global, R = Regional (National), P = Policy Scenarios

Appendix 6.1 (continued)

Code	Scenario Identification	Type(*)	Reference
20-1	IEW 1991	G R	Manne et al. (1991)
20-2	IEW Poll 50th percentile	G R	Manne et al. (1994)
20-3	IEW Poll 84th percentile	G R	Manne et al. (1994)
20-4	IEW Poll 16th percentile	G R	Manne et al. (1994)
21	ITF-D4	G R	Shishido (1992)
22	AGE	G R	Manne et al. (1993)
23-1	AIM High Scenario	G R	Morita et al. (1993)
23-2	AIM Low Scenario	G R	Morita et al. (1993)
23-3	AIM land use emission scenarios	G R	Matsuoka et al. (1994)
23-4	AIM sulfur emission scenarios	G R	Matsuoka (1992)
24	CETA	G R	Peck et al. (1993)
25	DICE	G	Nordhaus (1993)
26	FUGI 7.0	G R	Onishi (1993)
27-1	IMAGE 2.0 1993	G R	Alcamo et al. (1993)
27-2	IMAGE 2.0 CW (Conventional Wisdom Scenario)	G R	Alcamo et al. (1994)
27-3	IMAGE 2.0 No Biofuels (No Biofuels Scenario)	G R	Alcamo et al. (1994)
28-1	Manne-Richels-50th%-(50th percentile)	G R	Manne et al. (1993)
28-2	Manne-Richels-95th%-(95th percentile)	G R	Manne et al. (1993)
28-3	Manne-Richels-5th%-(5th percentile)	G R	Manne et al. (1993)
28-4	Global 2100, 1994	G R	Manne et al. (1994)
29	MERGE	G R	Manne et al. (1993)
30-1	12RT reference	G R	Manne (1993)
30-2	12RT 200 \$/tc carbon tax	G R P	Manne (1993)

(*) G = Global, R = Regional (National), P = Policy Scenarios

Appendix 6.1 (continued)

Code	Scenario Identification	Type(*)	Reference
31-1	WEC reference (Scenario B)	G R	WEC (1993)
31-2	WEC A High Growth	G R	WEC (1993)
31-3	WEC C Ecologically Driven	G R P	WEC (1993)
32	NES current policies	R	National Energy Strategy (1991)
33-1	ESCAPE	G R	Rotmans et al. (1994)
33-2	ESCAPE S1 (Business as Usual)	R	ESCAPE (1991)
33-3	ESCAPE S3 (Emission Control)	R P	ESCAPE (1991)
34-1	Bashmakov-Base (Russia)	R	Bashmakov (1993)
34-2	Bashmakov-Efficiency	R P	Bashmakov (1993)
35-1	Sinyak DAU (Dynamics as Usual Scenario)	R	Sinyak et al. (1992)
35-2	Sinyak Efficiency (Energy Efficiency Scenario)	R P	Sinyak et al. (1992)
36-1	EMF-12	R	Gaskins et al. (1993)
36-2	EMF-12 lowest/highest reference scenarios	R	Weyant (1993)
36-3	EMF-12 20% 20% emission reduction case	R P	Gaskins et al. (1993)
36-4	EMF-12 20% -20% emission reduction case	R P	Weyant (1993)
37	He et al. (Gradual Changing Scenario)	R	He et al. (1993)
38-1	UNEP-base (Baseline Scenario)	R	Christensen et al. (1994)
38-2	USEP-abate (Abatement Scenario)	R P	Christensen et al. (1994)
39-1	Houghton-Population*	G	Houghton (1991)
39-2	Houghton-Exponential Extrapolation*	G	Houghton (1991)
39-3	Houghton-Reforestation*	G	Houghton (1991)
40	RIGES (Renewable Intensive Global Energy System)	G R P	Johansson et al. (1993)
41	FFES (Fossil Free Energy System)	G R P	Lazarus et al. (1993)

(*) G = Global, R = Regional (National), P = Policy Scenarios

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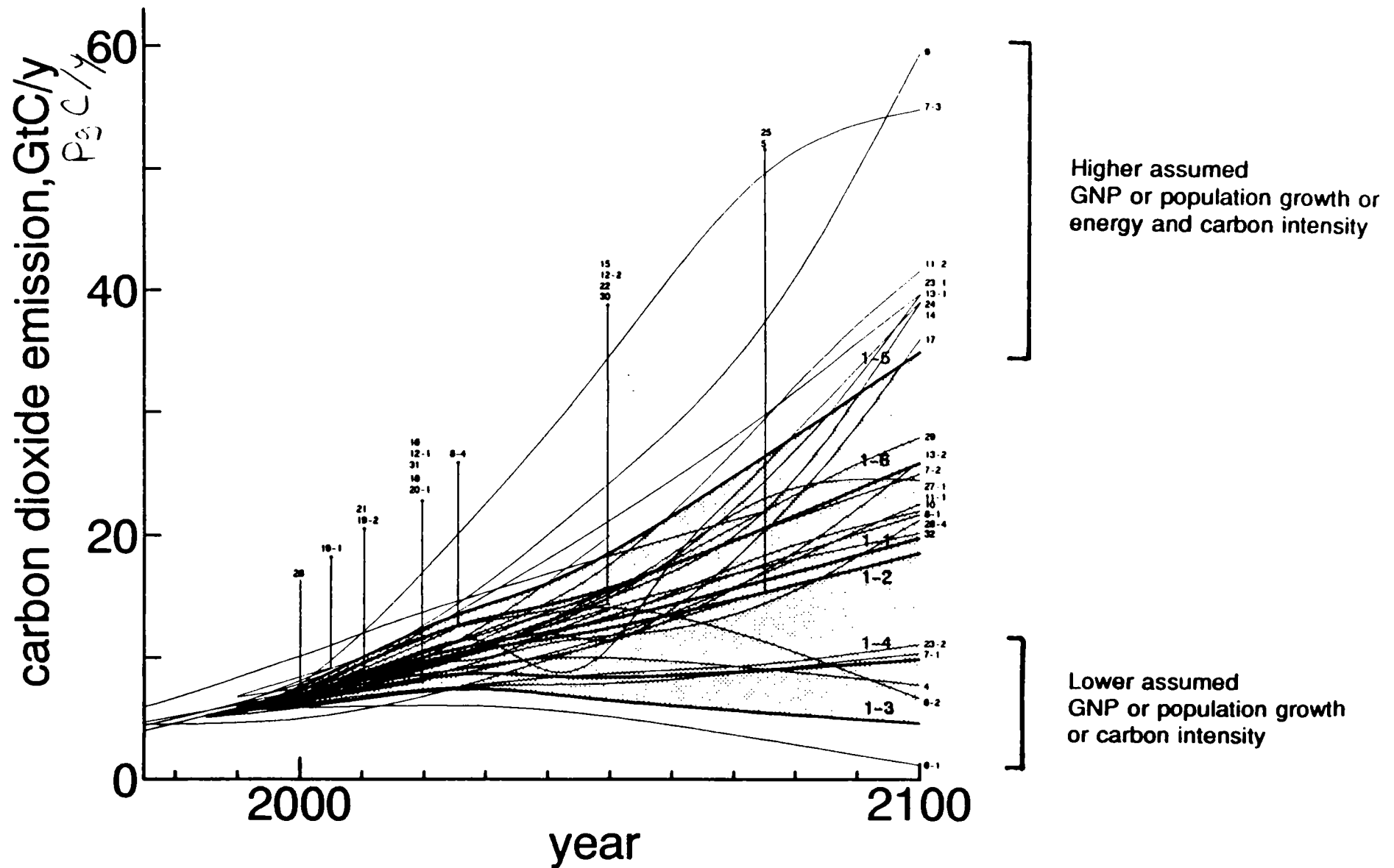


Figure 6.1: Trends of energy-related global CO₂ emissions of various scenarios. Shaded area indicates coverage of IS92 scenarios. Numbers correspond to list of scenarios in Appendix 6.1.

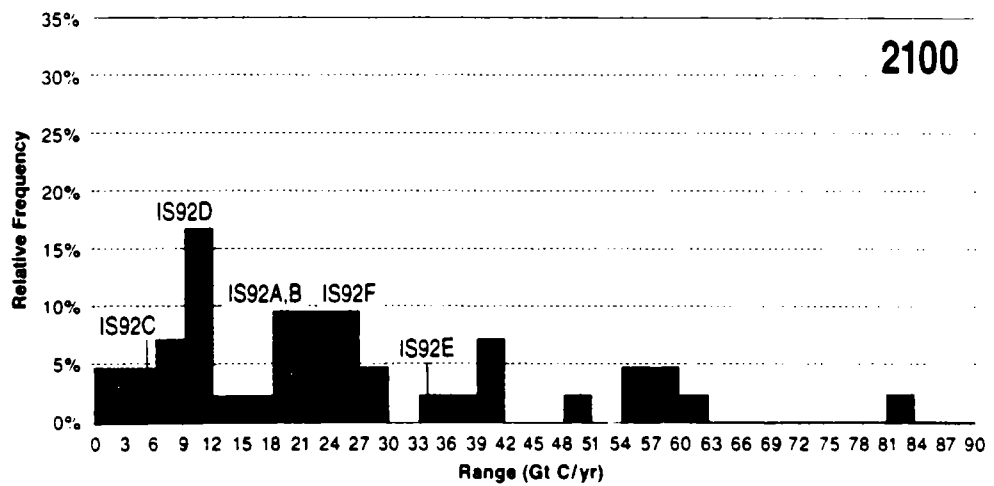
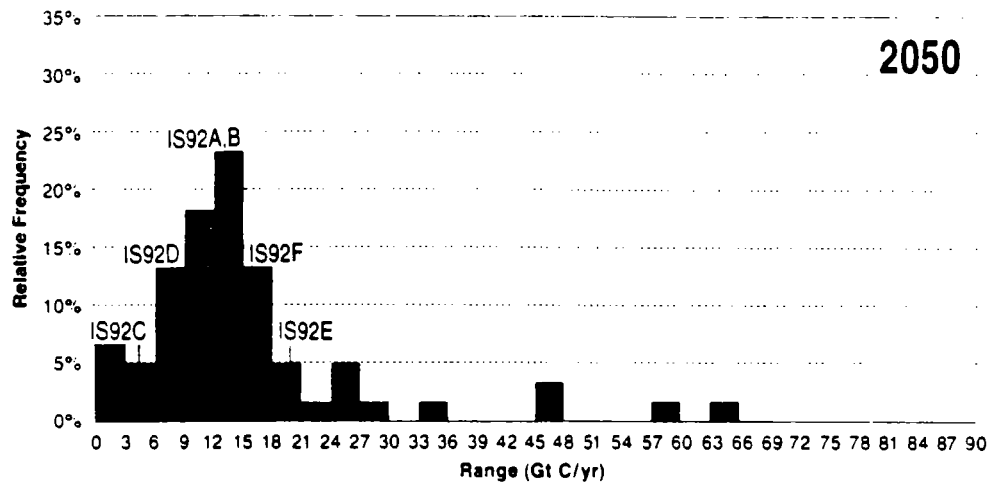
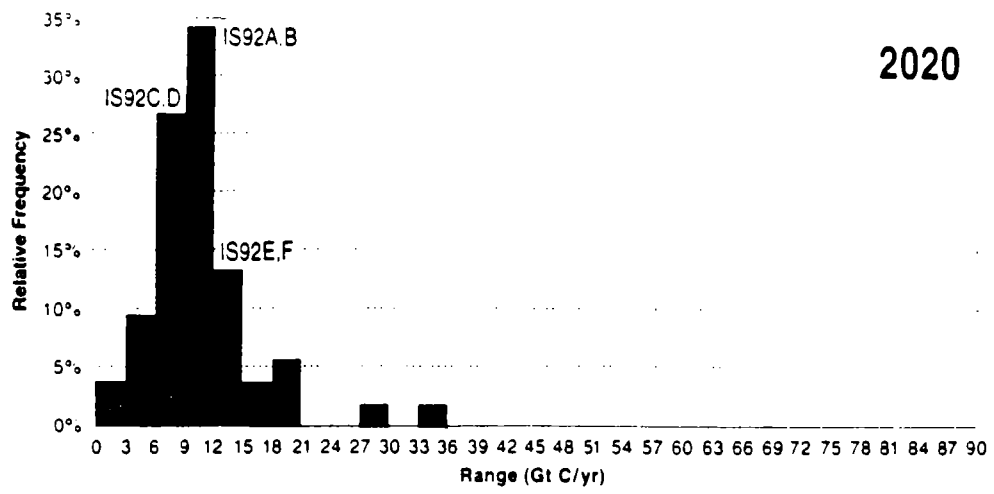


Figure 6.2: Histograms depicting distribution of different scenario estimates of energy-related global CO₂ emissions for three scenario years.

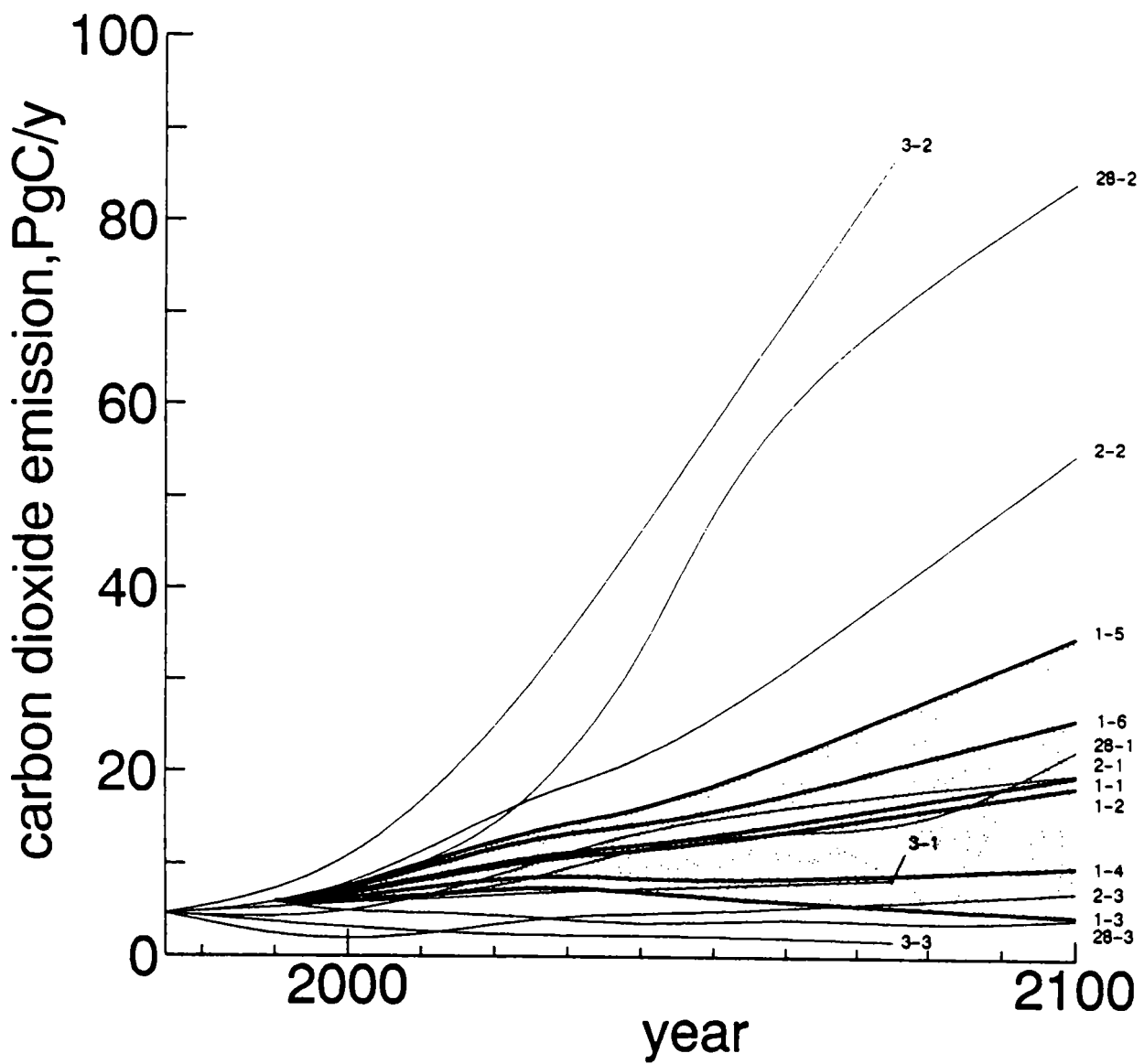


Figure 6.3: Results from uncertainty analyses showing 5th and 9th percentile of global CO₂ emissions. Also shown are IS92 estimates (code numbers beginning with "1"), with their range indicated by the shaded area (IS92 results are not from uncertainty analysis). Numbers correspond to list of scenarios in Appendix 6.1.

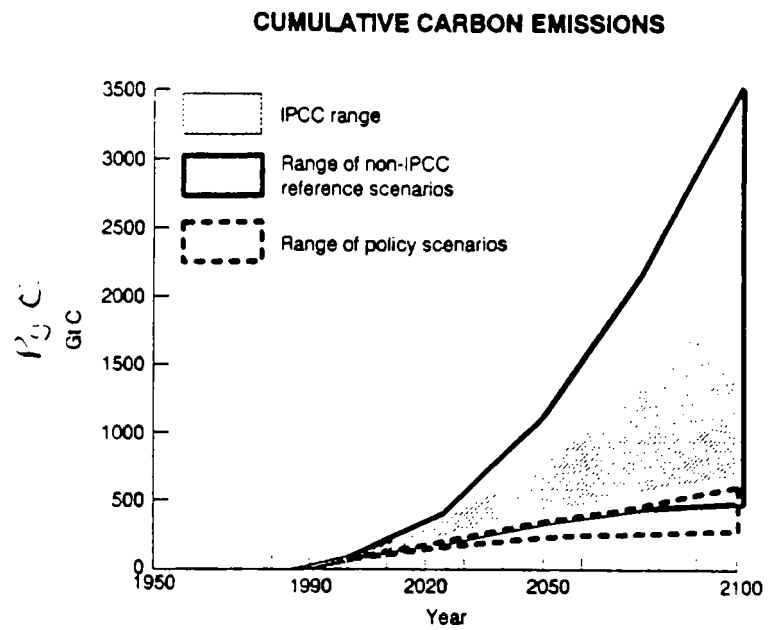


Figure 6.4: Range of cumulative energy-related global CO₂ emissions from IS92 and other published scenarios.

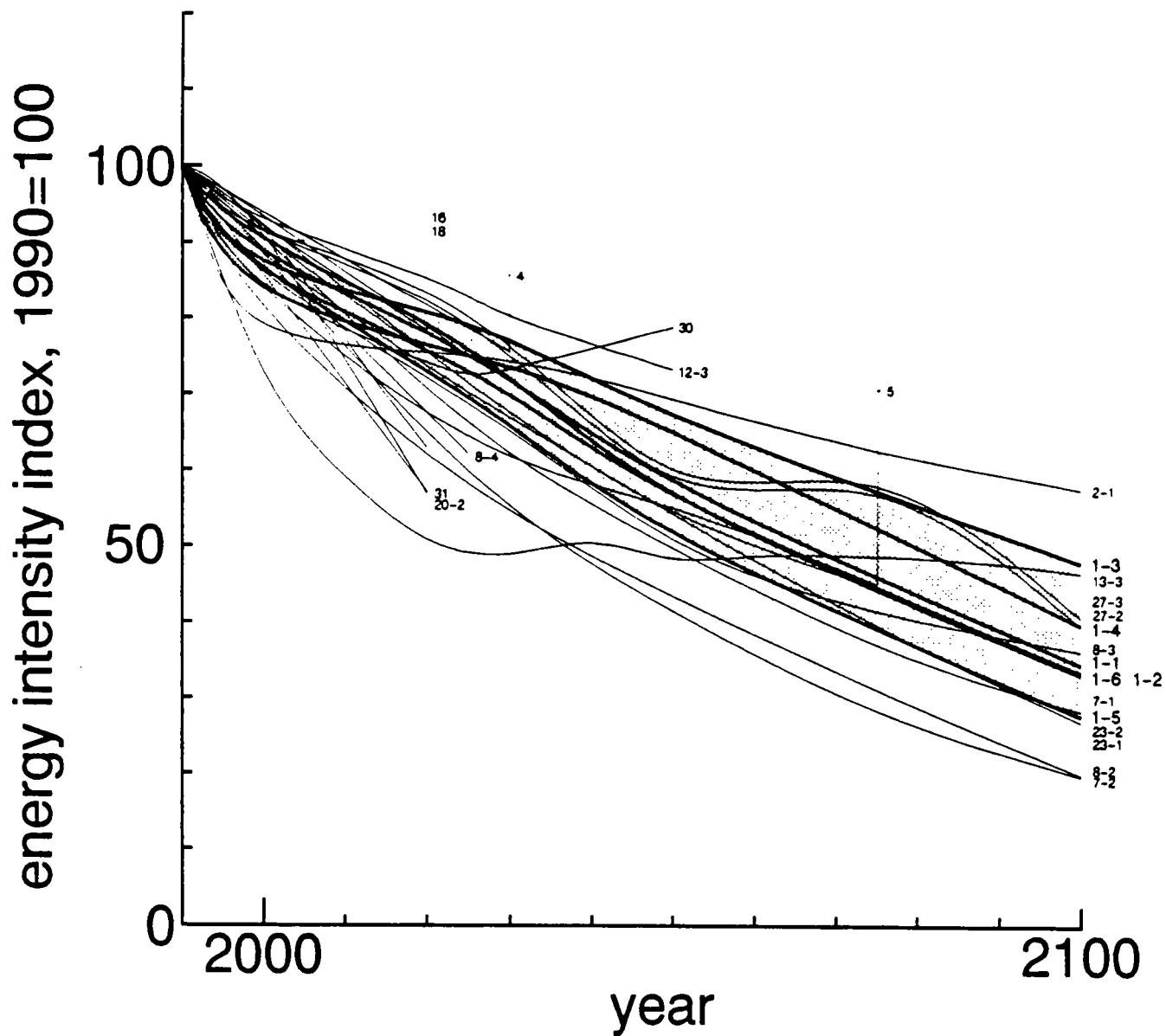


Figure 6.5: Trends of energy intensity for various global scenarios. Shaded area indicates range of IS92 scenarios. Numbers correspond to list of scenarios in Appendix 6.1.

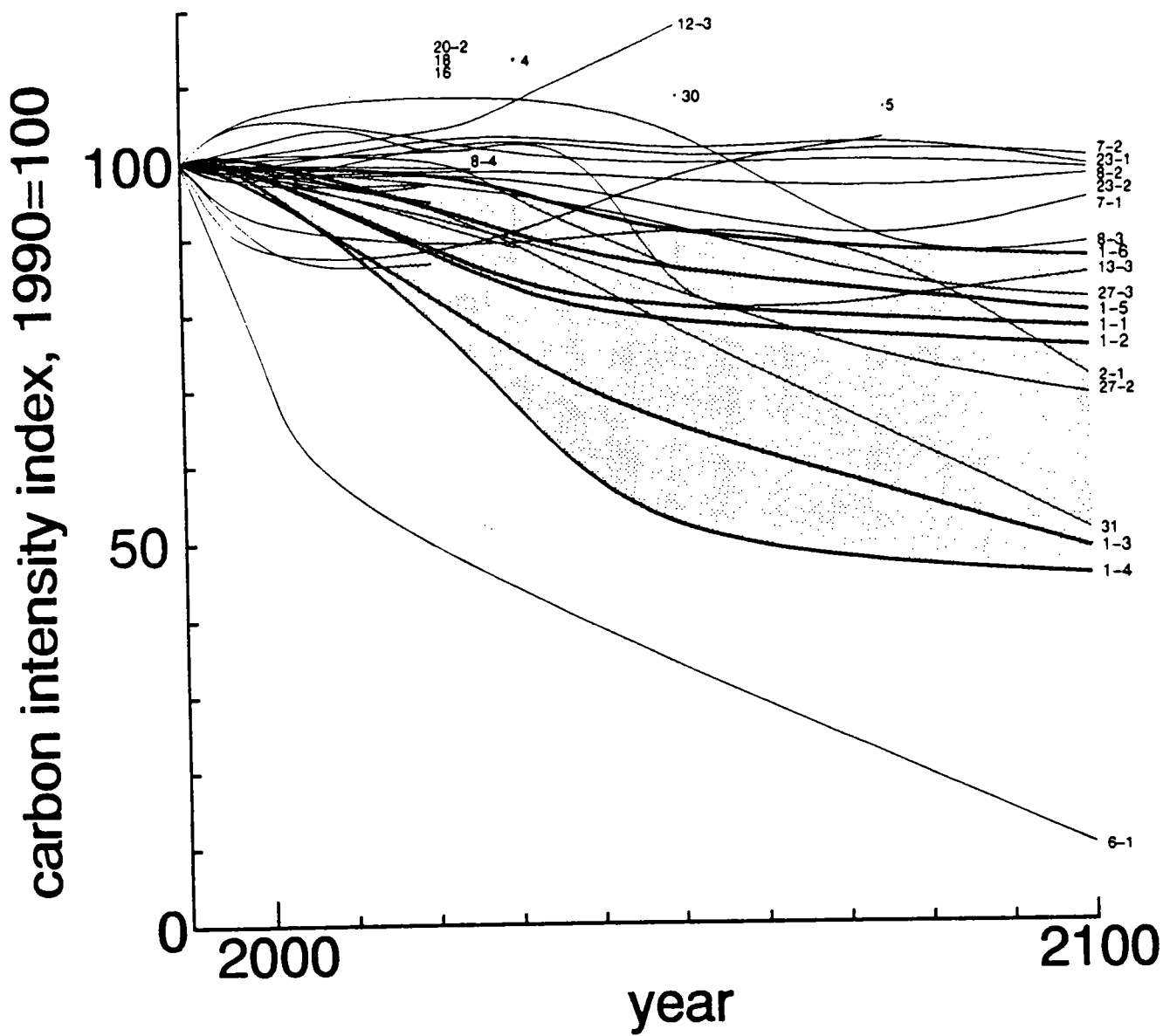


Figure 6.6: Trends of carbon intensity for various global scenarios. Shaded area indicates range of IS92 scenarios. Numbers correspond to list of scenarios in Appendix 6.1.

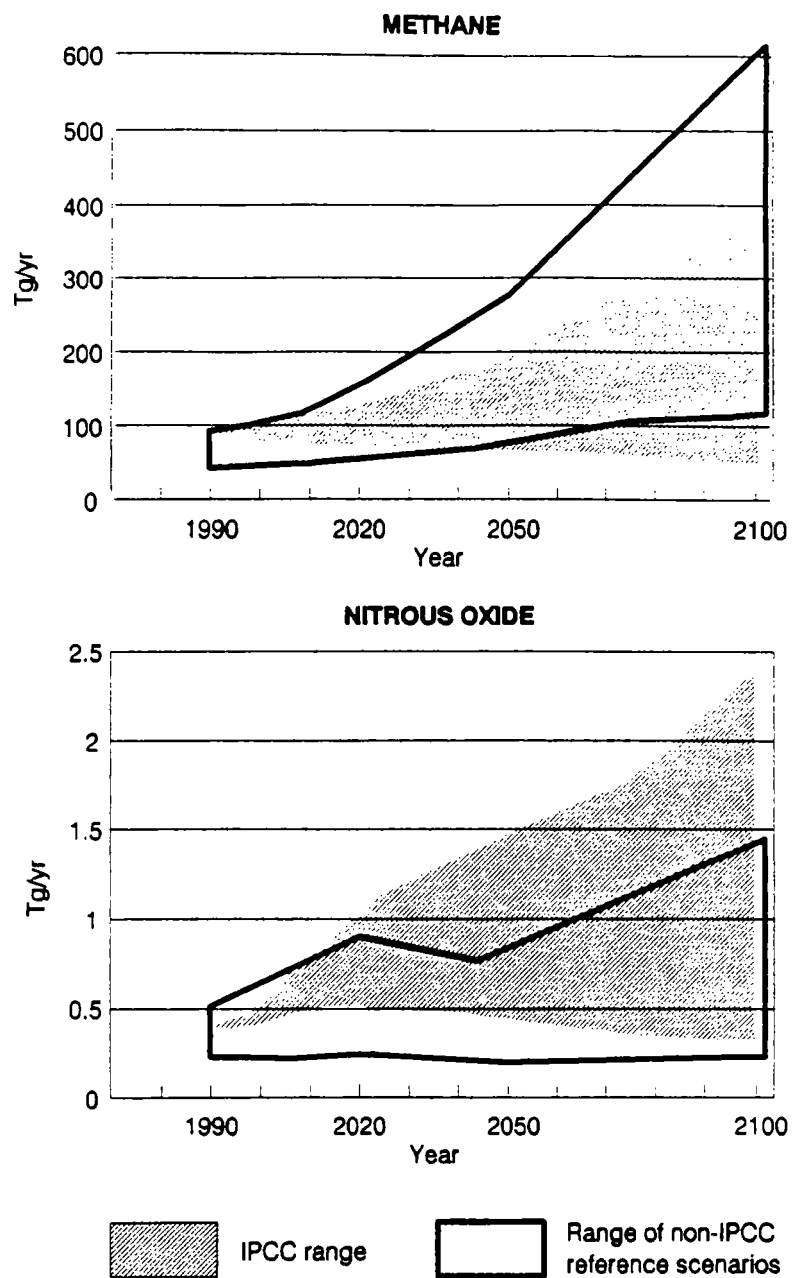


Figure 6.7: Range of CH_4 and NO_x energy-related global emissions from IS92 and other published scenarios.

REGIONAL CARBON EMISSION SCENARIOS

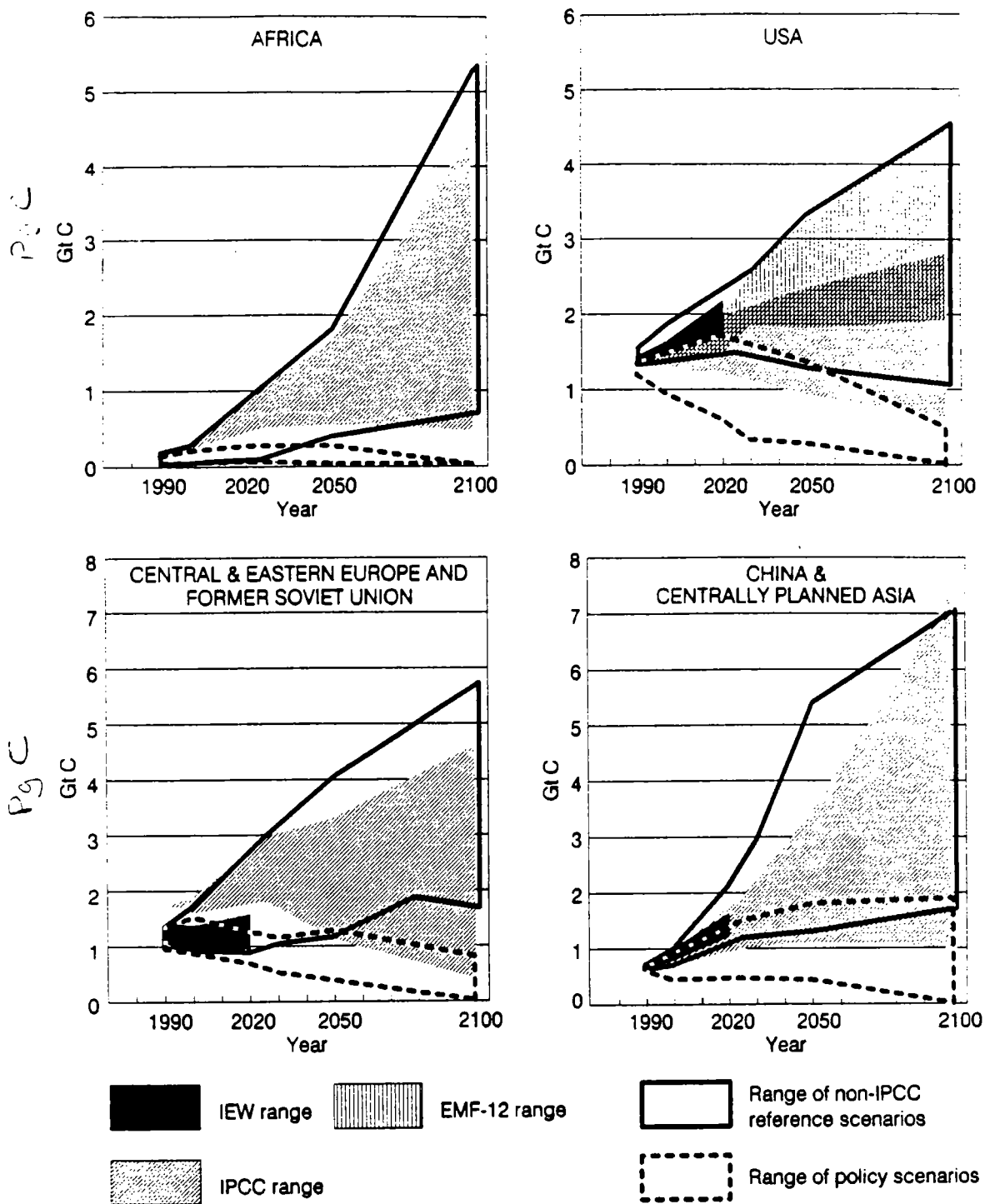


Figure 6.8: Range of regional CO₂ emissions from IS92 and other published scenarios.

REGIONAL ENERGY INTENSITY SCENARIOS

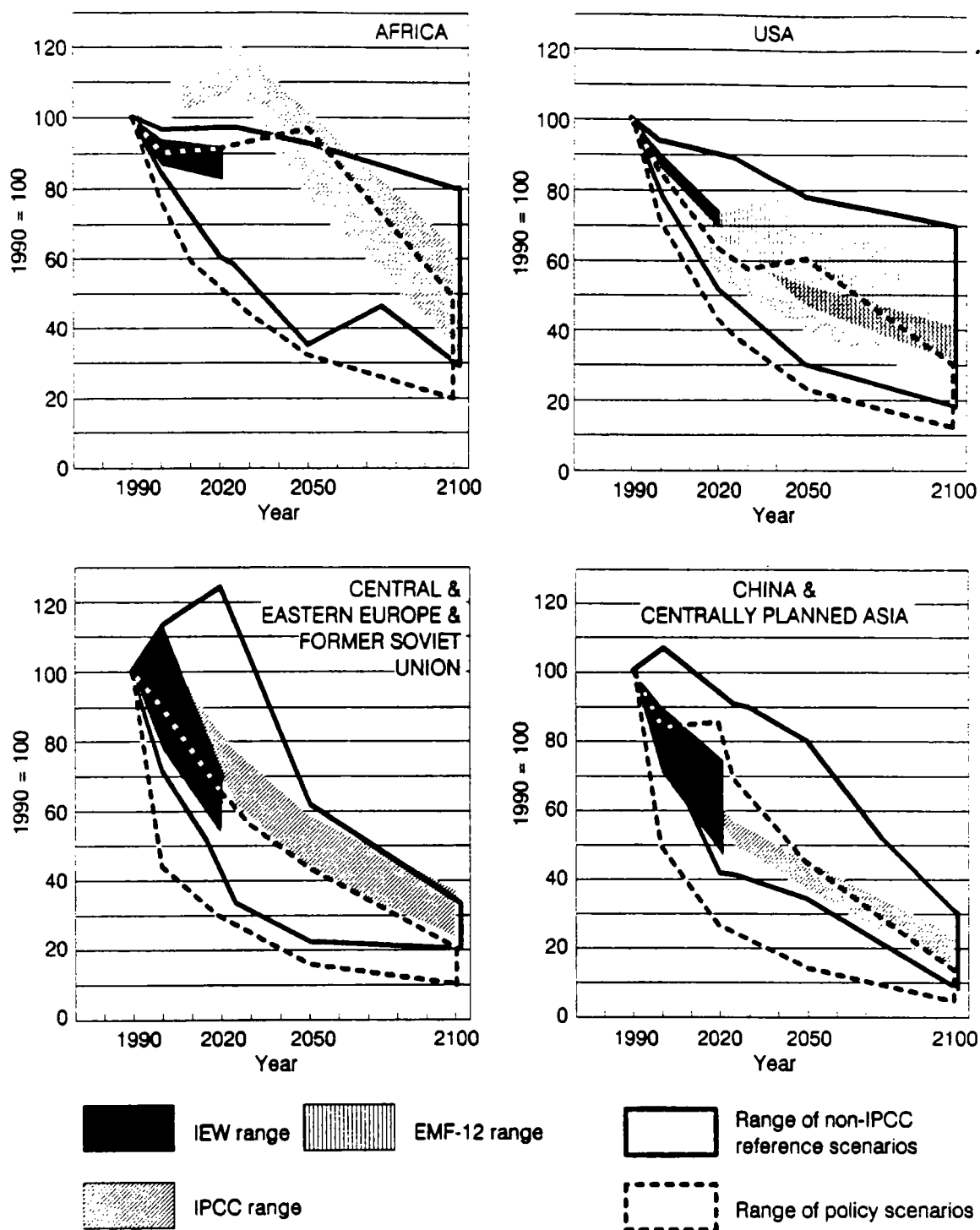


Figure 6.9: Range of regional energy intensities from IS92 and other published scenarios.

REGIONAL CARBON INTENSITY SCENARIOS

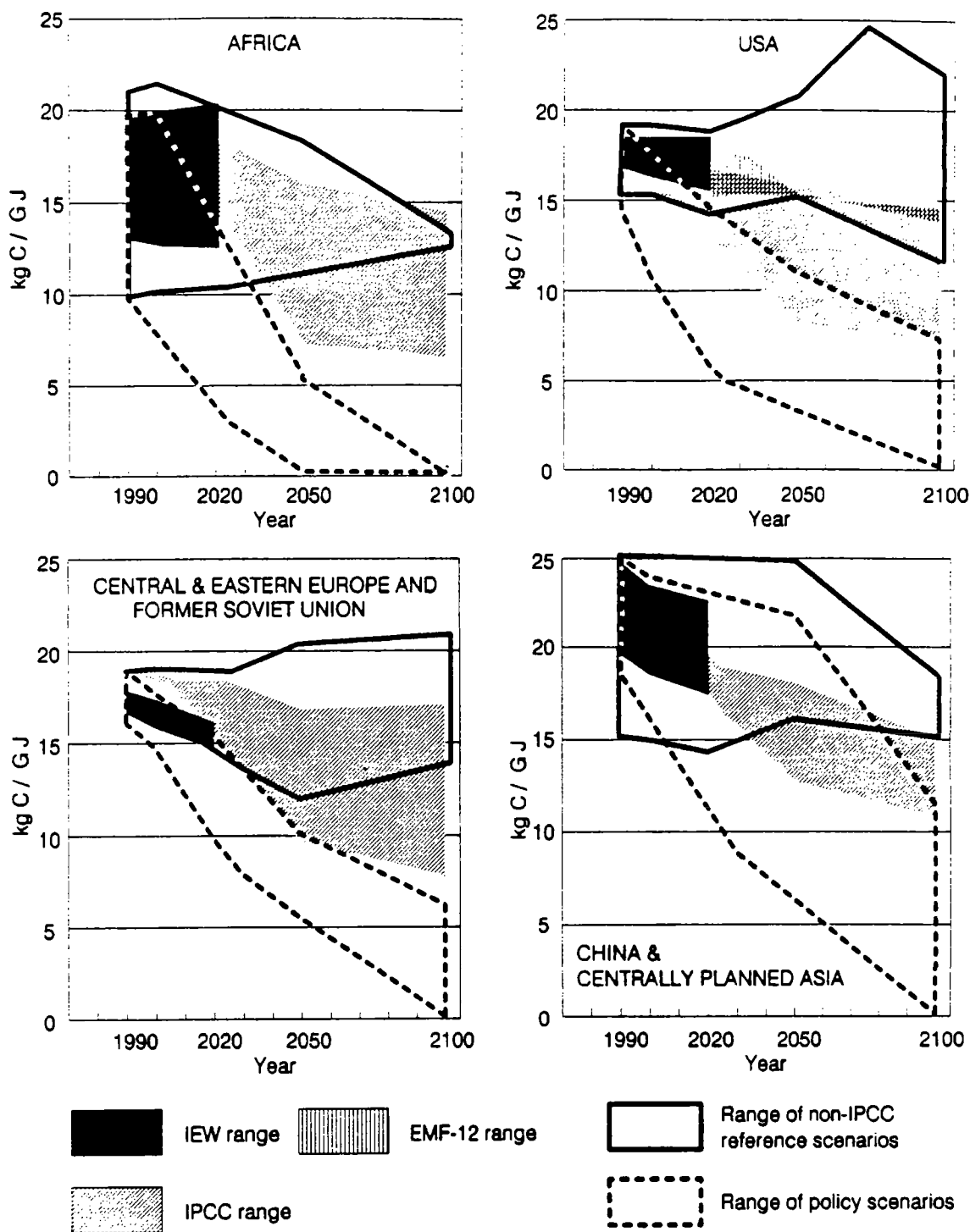


Figure 6.10: Range of regional carbon intensities from IS92 and other published scenarios.

SENSITIVITY ANALYSIS OF ENERGY-RELATED CARBON EMISSIONS COMPARED TO IS92a

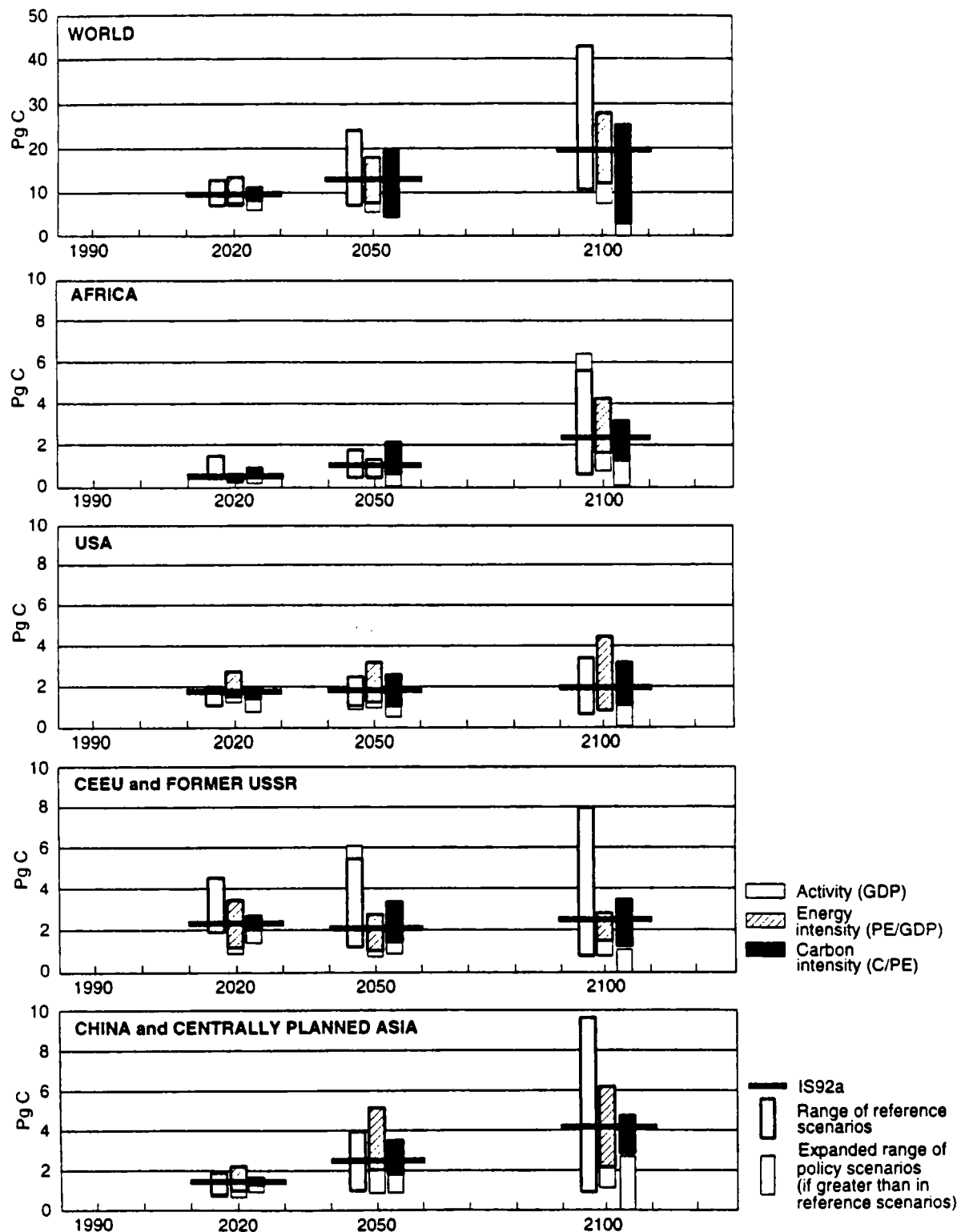


Figure 6.11: Uncertainty analysis of energy-related CO₂ emission estimates relative to the IS92a scenario.

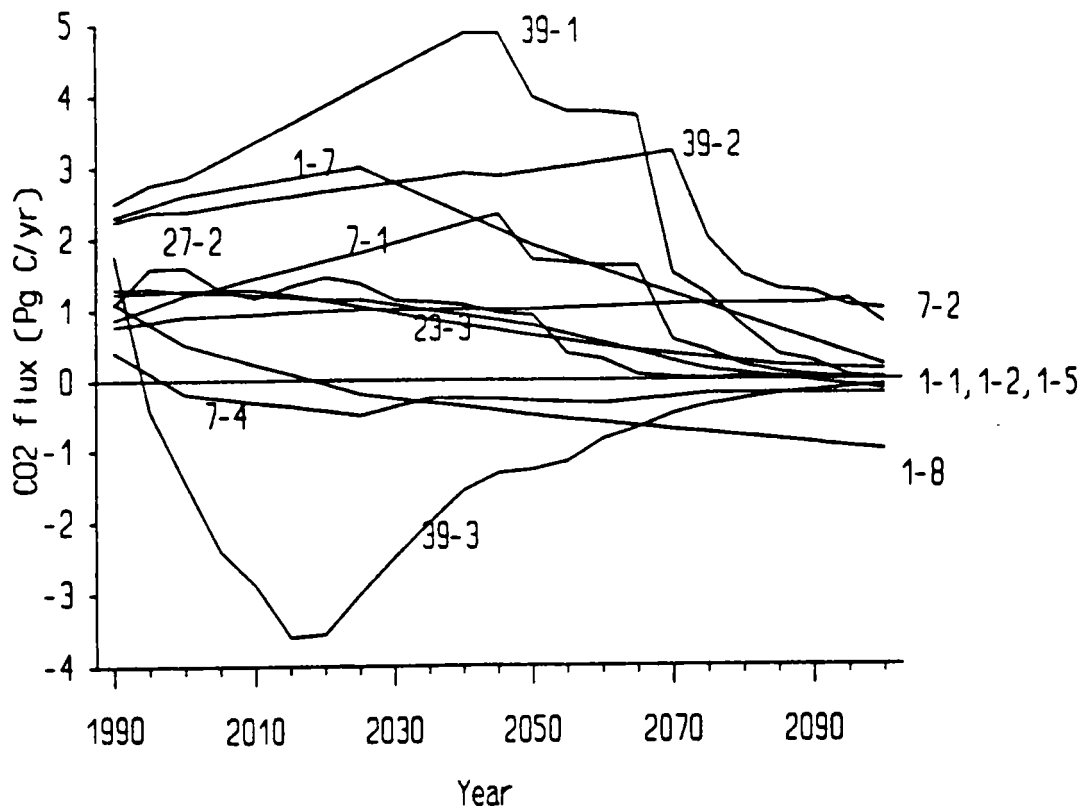


Figure 6.12: Comparison of global scenarios of CO₂ fluxes from deforestation. Numbers correspond to list of scenarios in Appendix 6.1.

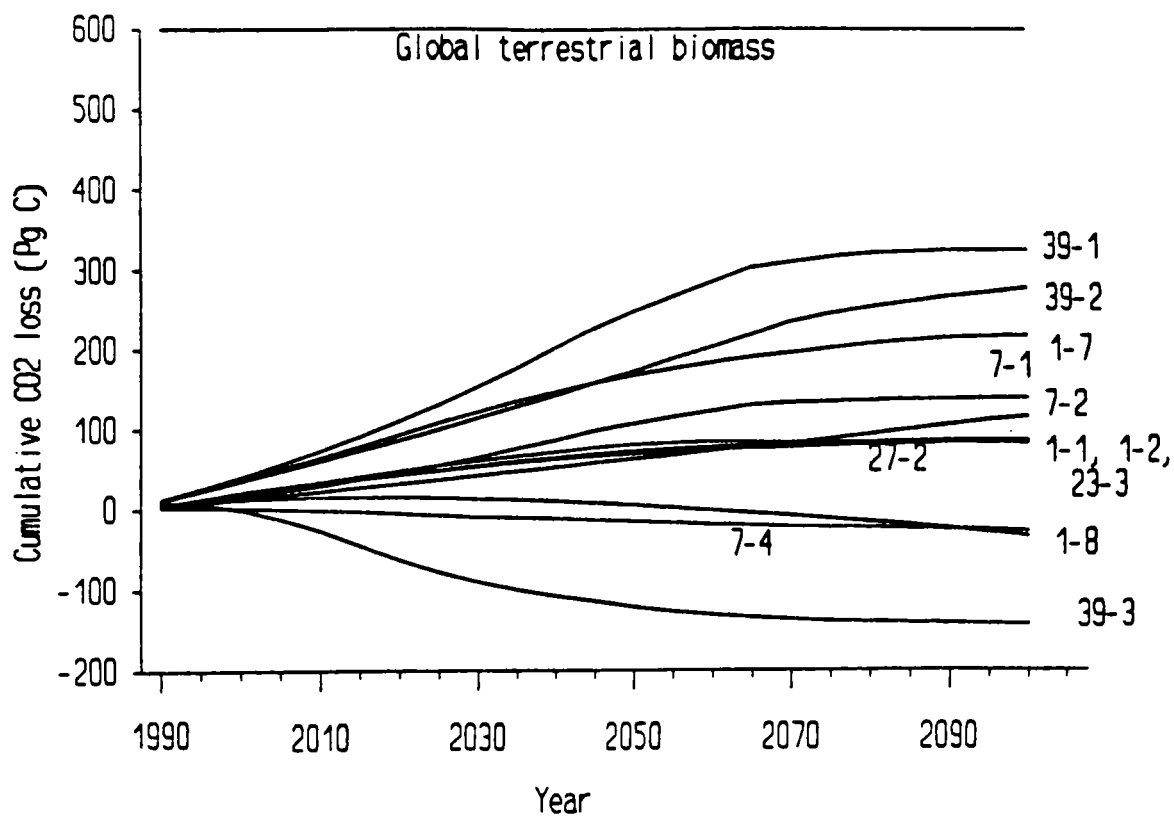


Figure 6.13: Comparison of cumulative global CO₂ fluxes from deforestation for different scenarios. Numbers correspond to list of scenarios in Appendix 6.1.

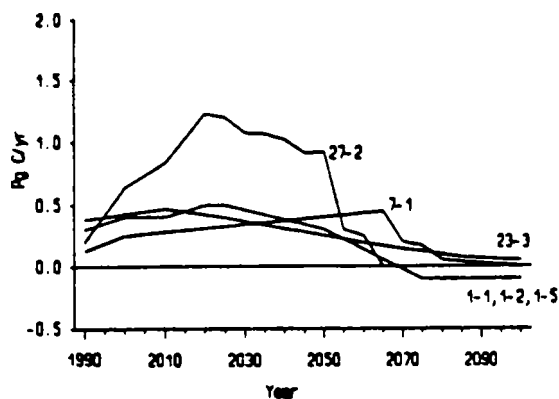


Figure 6.14a: CO₂ fluxes from deforestation for Africa for different scenarios. Numbers correspond to list of scenarios in Appendix 6.1.

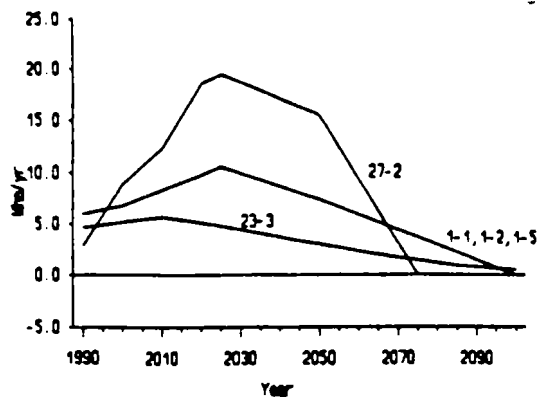


Figure 6.14b: Deforestation rates for Africa for different scenarios. Numbers correspond to list of scenarios in Appendix 6.1.

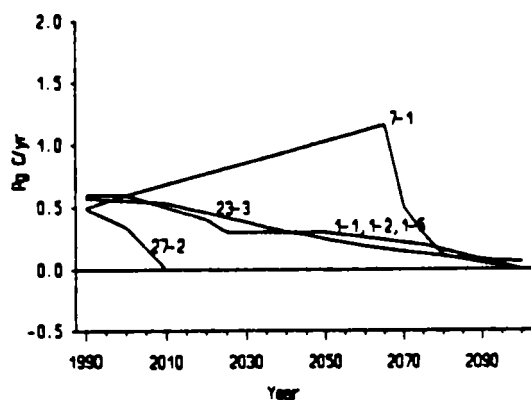


Figure 6.15a: CO₂ fluxes from deforestation for Latin America for different scenarios. Numbers correspond to list of scenarios in Appendix 6.1.

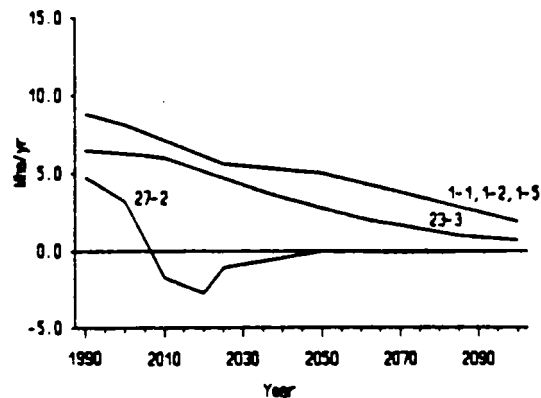


Figure 6.15b: Deforestation rates for Latin America for different scenarios. Numbers correspond to list of scenarios in Appendix 6.1.

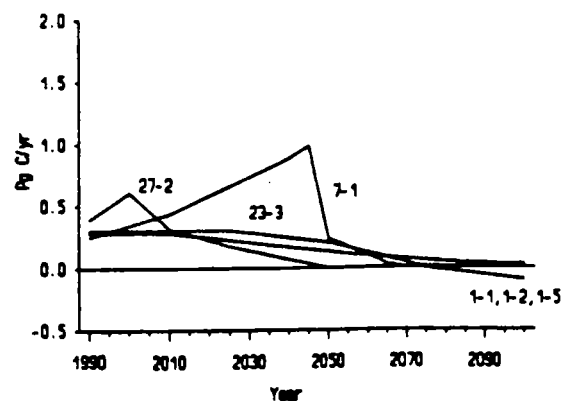


Figure 6.16a: CO₂ fluxes from deforestation for Asia for different scenarios. Numbers correspond to list of scenarios in Appendix 6.1.

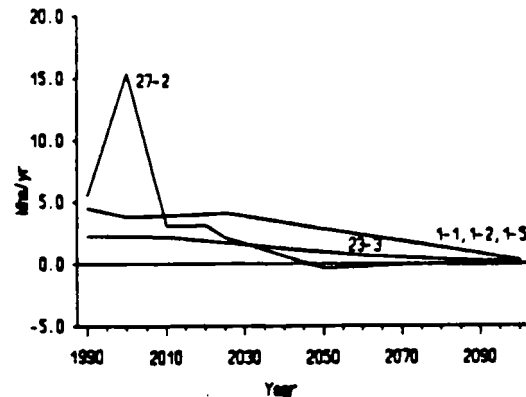


Figure 6.16b: Deforestation rates for Asia for different scenarios. Numbers correspond to list of scenarios in Appendix 6.1.

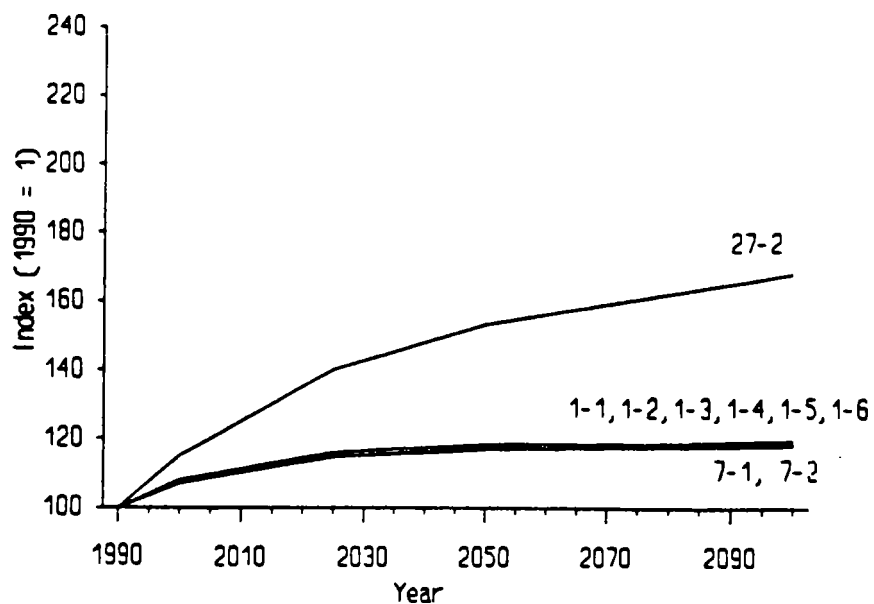


Figure 6.17a: Comparison of development of rice yields for China and Centrally Planned Asian countries for different scenarios. Numbers correspond to list of scenarios in Appendix 6.1.

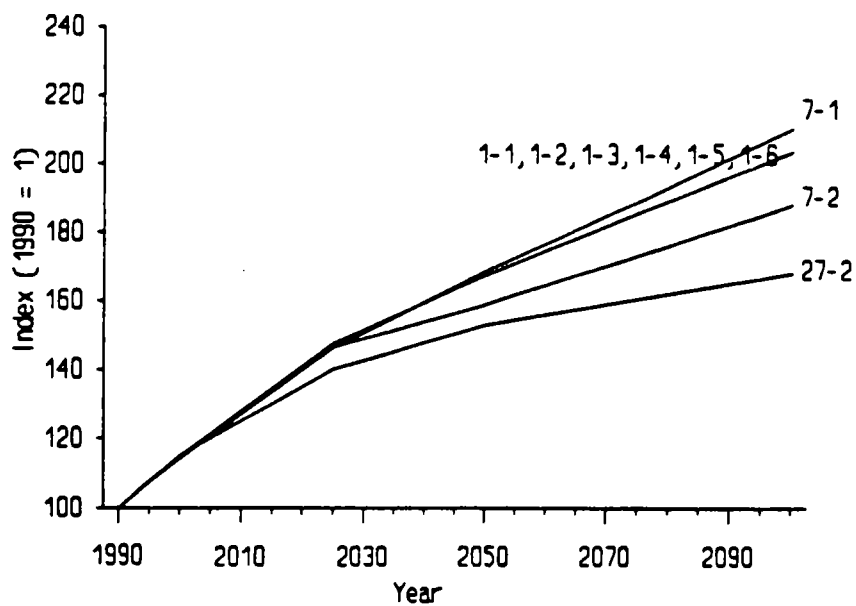


Figure 6.17b: Comparison of development of rice yields for South and Southeast Asia for different scenarios. Numbers correspond to list of scenarios in Appendix 6.1.

emissions will require sustainable development policies in all countries, both developed and developing. Neither the Convention nor Joint Implementation will be considered successful if they promote continued growth in emissions by the North while striving to slow emissions growth in the South and East.

If a management structure can be developed to assure that the JI regime meets these eight criteria, then JI could surely make a contribution to sustainable development. ■

JI Survey: II Supporting North-South Cooperation

— Jyoti Parikh, *Indira Gandhi Institute of Development Research, Goregaon (East), Bombay 400065, India*

Joint implementation (JI) could open the way to reducing global greenhouse gas emissions by providing the North with cost-effective opportunities for limiting emissions in other countries. If handled correctly, this could be done without compromising the needs of developing countries — in fact, it could even help to catalyse development in the South. Furthermore, while an increase in developing-country emissions is generally considered inevitable, this increase could be minimised if JI projects promote technological and financial transfers from the North to the South.

Priority projects

JI now seems poised for a pilot phase. This pilot phase must be carefully thought out if it is to succeed. In particular, it must be decided what types of projects should be selected. The areas chosen should be non-controversial and beneficial to both parties. The emissions reductions should be immediate, and it should be possible to account for them clearly. The projects should also be replicable elsewhere.

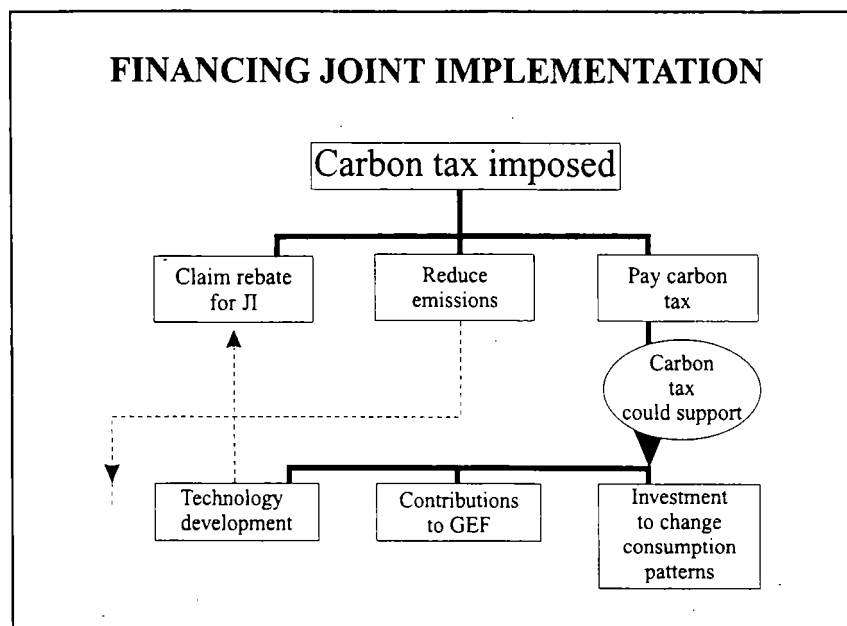
Projects for reducing emissions through increased efficiency are clearly a priority for developing countries. Appropriate projects could include those that achieve the following:

- * Introduce more efficient technologies that save imported oil or electricity, which in turn reduces the need for energy-related investments and imports;
- * Modernise power supply systems to cut power losses and increase generating efficiencies;
- * Conserve domestic fossil fuel resources such as coal and gas;
- * Reduce methane emissions from gas flaring, coal mining, and gas pipeline leaks;
- * Reduce methane emissions from sewage and waste-water treatment plants, or harvest the methane for productive uses;
- * Improve ruminant digestion of livestock to reduce methane emissions;
- * Reduce biomass burning by providing or developing more efficient cooking stoves or replacement fuels such as biogas or kerosene; and
- * Develop less carbon-intensive technologies for the transport, construction, industrial, and agricultural sectors.

Such emissions-reduction projects should have priority over projects for enhancing sinks through, say,

afforestation. For one thing, sink projects would take too many years to achieve results. They would also raise too many questions about what would happen at the end of the project. Who would the wood belong to? What if the host country decided that it now needs the land for other purposes? It might be difficult to calculate how the partners should share the credits from the project. There are also uncertainties and risks due to fire and blights, and potential conflicts with development priorities, especially land-use. Finally, sink projects tend to merely postpone the problem of greenhouse gas emissions rather than solve it and, given colonial-era conflicts involving land rights, such projects could also be viewed as neo-colonialism.

Though there is clearly a need to preserve forests, this may be best done by the countries themselves. We must recognise that the mix of species needed to support biodiversity as well as economic activity is not the same as, and may even conflict with, the best mix for carbon sequestration. The Convention on Biodiversity is therefore a more suitable forum for this issue. It recognises the complexity of forest ecosystems and would value them appropriately, rather than treating them merely as carbon sinks. Since the climate change and biodiversity treaties both



IPCC Calendar of Events

1994:

July 18-22 Nairobi

IPCC Working Group III. Workshop on Equity and Social Considerations

September TBD

IPCC Working Group III. Workshop on Cost-Benefit Analyses and Decision-making

September 6-7 Geneva

IPCC Working Group III. Second Session

September 13-16 Maastricht, The Netherlands

IPCC Working Group I. Fourth Session

September 19-23 TDB

IPCC. Workshop on Droughts and Desertification

October 17-21 Fortaleza, Brazil

IPCC. First Workshop on Article 2 (objective) of the Climate Change Convention.

November 8 UNEP, Nairobi

IPCC Working Group II. Second Session

November 10-12 UNEP, Nairobi

IPCC. Tenth Session

1995:

TBD Greece

IPCC. Second Workshop related to Article 2 of the Climate Change Convention.

June-August

IPCC Working Group I. Fifth Session
IPCC Working Group II. Third Session
IPCC Working Group III. Third Session

September 26-29 Geneva

IPCC. Eleventh Session

For more information, contact *IPCC Secretariat, c/o WMO, C.P. 2300, 1211 Geneva 2, fax (41-22) 733 1270.*

Convention Calendar

1994:

Aug 22 - Sept. 2 Geneva

INC/FCCC. Tenth Session

1995:

Jan. 30- Feb. 17 New York

INC/FCCC. Eleventh Session

March 28 - April 7 Berlin, Germany

Conference of the Parties (COP) to the Climate Change Convention, First Session.

For more information, contact the *UNFCCC Interim secretariat, Geneva Executive Center, 11-13 chemin des Anémones, 1219 Châtelaine, Switzerland, tel. (41-22-) 979 9111, fax. (41-22) 979 9034, e-mail: secretariat.unfccc@unep.ch*

currently rely on the GEF, there is no special advantage to handling forest projects under the Climate Change Convention.

The carbon tax link

How can we ensure continued support for JI on a long-term basis? How is it possible to raise additional funds when the industrialised countries already complain about the paucity of funds available even for the GEF?

To bring about the required reduction in their carbon emissions, these countries may have to levy a carbon tax. If Northern countries impose national carbon taxes and give tax rebates to investors in JI projects with the South, fossil-fuel consumers would have three options (see figure): carry out JI and claim a tax rebate, reduce their emissions, or pay the full tax.

Thus, depending on the level of a carbon tax, JI could attract private capital in abundant measure. In addition, the tax receipts could support GEF, technology

development, government-to-government JI projects, or emissions reduction projects in the home country (e.g. mass transit).

Institutional mechanisms

If an experimental or pilot phase for JI projects that reduce emissions in developing countries is initiated, the projects must of course be analysed closely to see what lessons can be learned. In particular, it is as yet unclear how we should account for carbon reductions. A number of alternative schemes will have to be analysed before an agreement can be reached.

While private parties will want to negotiate among themselves, JI would require some institutional mechanisms at the national level for registering, endorsing, and monitoring projects. At the international level, we will need a council or committee (such as the Subsidiary Body for Scientific and Technological Advice established by the Convention) with experts and Government representatives from the

South and the North. This council would need administrative and policy support from the Convention secretariat and the COP.

In addition, technical committees should be set up to establish guidelines for each specific type of project (e.g. power systems, or gas flaring and leaks). Since electricity and gas flow are metered continuously, they could provide a reasonable indication of how effective a particular project is in saving CO₂ or methane. This category of JI could, therefore, begin early. Setting technical ground rules for estimating reductions in other types of projects may be more challenging. As and when there is demand for new types of JI projects, new ground rules could be developed by new technical committees following the council's overall guidelines.

Of course, technical issues are just a beginning. Decisions concerning JI projects should be taken only after careful consideration of all socio-economic, scientific, political, environmental, and administrative issues. ■