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A Generic Assessment of Response Options

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Summary

This chapter reviews adaptation options, methane mitigation options, and the following categories of CO₂ mitigation options:

- Energy conservation and efficiency improvement;
- Fuel switching;
- Renewable energy technologies;
- Nuclear energy;
- Capture and disposal; and
- Enhancing sinks; forestry options.

There is broad consensus that *energy conservation and efficiency improvements* are attractive because of their energy and environmental benefits other than climate change (no-regrets). The scope for energy efficiency improvement appears to be largest in power production, transportation, steel and cement production, and the residential sector.

Estimates of the scope for "no-regret" energy efficiency improvements vary widely, depending on the discount rate. The potential in production is estimated at 10-40%; and in residential use at 10-50%. However, to achieve this potential will require policy intervention.

Relatively little information about the costs of *fossil fuel switching* is available. Estimates vary with the type of measure, the natural gas leakage during production and distribution, and the availability of coal reserves. The massive coal reserves in China and India could result in a transition from biomass to coal thus increasing the carbon-intensity.

Although *renewable energy* technologies are sustainable with respect to energy inputs, they are not always socially and environmentally benign.

Large differences exist in the technical and economic maturity of renewable options. Cost estimates diverge widely, due to the time horizon adopted, the discount rate, useful lifetime, site-specific factors, variability of supply, form of energy delivered, learning effects, economies of scale and the need for storage or transport.

The share of the technical potential not currently utilized varies from 50% (biomass), to 75% (hydro), to several thousand per cent for wind and solar.

Nuclear energy technology is well established except for the unresolved issue of the storage of nuclear waste. In addition, the long design/construction time (10-15 years) and the enormous capital cost of nuclear power plants make this a rather inflexible option. Hence, nuclear energy as a share of total energy is expected to increase only marginally during the next several decades.

Capture and disposal options are ultimately limited for technical reasons and because not all forms of disposal ensure a permanent storage of carbon. Practical applicability of such options is still a matter of debate because the environmental uncertainties of some types of disposal (eg. in aquifers, oceans) are unknown.

Forestry options offer the large expected potential, modest costs, low risk, and positive side-effects. However, estimates of net carbon release due to deforestation and land use changes and net carbon absorption due to afforestation are uncertain.

Forestry measures are generally considered relatively cost effective mitigation policies especially in developing countries. Estimates of the cost-effectiveness of forestry measures depend strongly on whether one takes a static or dynamic point of view. The cost assessment methodology has become more refined, so cost estimates have become more realistic. Costs tend to range from \$30 to \$60 tC, for large annual uptakes.

Halting or slowing deforestation is probably among the most urgent and most cost-effective options. However, social, political and infrastructural barriers may restrict this option as well as the scope of reforestation.

Methane emissions reveal wide variations among regions. Information about methane leakage and distribution is rather scanty and, in some regions, unreliable. Information on methane mitigation options cost functions is still in its infancy. The cost functions are not only time-specific, but also region- and context-specific. The few studies available provide only tentative results, but indicate that a significant share (probably more than half) of the lowest cost methane emission reduction potential lies outside the OECD.

Overall, the energy conservation and efficiency improvement, and forestry options seem to provide the largest potential for low cost emissions reductions. The potential of the forestry option is widely debated, however, because of the limitations of net absorption in time, and because much depends on forest exploitation and local acceptance. The potential for each option varies widely by region.

No systematic cost data are available for adaptation options, although information about the costs of land protection against flooding and sea level rise is rapidly increasing. Many efforts to reduce the vulnerability of agricultural production to climate change through adaptation are now underway.

Finally, introduction and application of the mitigation and adaptation options can pose particular difficulties for developing countries. Approaches to overcome these difficulties deserve a high priority on the research agenda.

1. Introduction

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

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

- to set up a structure so that the various options can be put into proper perspective and the assessment to be made can be truly generic (section 2);
- to discuss the various criteria that can be used in assessing the options, and the degree to which different criteria can produce different choices in terms of optimal use of the options (section 3);
- to review the various options in terms of (technical and practical) applicability, cost-effectiveness, and social acceptability, both as far as mitigation options (section 4), and adaptation options (section 5) are concerned. Special attention will be given to the case of the developing countries and countries in transition, because of their particular circumstances;
- to evaluate the scope for integrating response options, in particular with respect to mitigation options, on the basis of information about regional cost functions (section 6);
- to analyze to what extent currently available information about various options might provide a basis for international policy cooperation (section 7).

Sections 1-3 therefore provide the methodological base; sections 4-5 survey the mitigation and adaptation options, and sections 6-7 deal with response options and policy application. In this chapter the applicability, feasibility and cost-effectiveness of the various response options are surveyed; however, a (macro)economic effects assessment of the various options has here not been carried out (see in this respect also the sections in this report dealing with integrated response options).

2. A Conceptual Framework

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

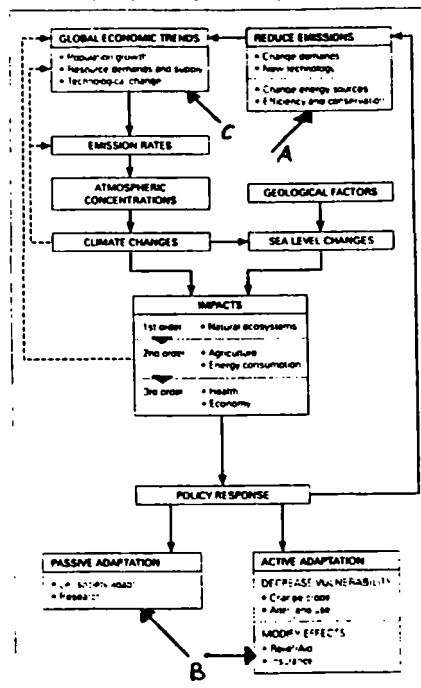


Figure 1. Schematic overview of available options to counter the greenhouse effect and their possible feedbacks.

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

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

a) mitigation options (block A in the figure), i.e. options that amongst others strive to prevent climate change, or combat any reinforcement thereof, by reducing the net emissions of greenhouse gases into the atmosphere either by reducing greenhouse gas emissions (source oriented measures), or by increasing the sinks for greenhouse gases (effect oriented measures) (see also chapter 8, section 2.2.2);

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

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

Obviously, the various types of options are not mutually exclusive, nor can they be fully separated. Indirect policy options, adaptation options and mitigation options may even reinforce each other, as the following examples may illustrate. A population policy, as part of a broader policy mix, resulting in slowing down population growth in a densely populated country may

contribute to finding cost-effective and acceptable opportunities for mitigation options. Similarly, if policies designed to decrease the energy and materials' intensity of economic activity are instituted in a country, many technically feasible options for emission reductions may become cost-effective. Technological progress will obviously improve the scope for adaptation options, etc. For conceptual reasons, however, the above distinction between the various types of options seems a useful starting point.

2.1 Mitigation Options

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

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

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

- a. measures concerning CO₂
 1. energy conservation and efficiency improvement
 2. fossil fuels switch
 3. renewable energy
 4. nuclear energy

(1-4 = source-oriented)

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

(5-6 = sink-enhancement)

b. measures concerning other greenhouse gases, such as phasing out HFCs (in addition to (H)CFCs, via the Montreal Protocol), and reducing emissions of methane (CH₄), nitrous oxide (N₂O), and other greenhouse gases.

Since the energy sector (in terms of both energy production and consumption) is the single largest source of carbon, much of the CO₂ mitigation effort can be concentrated here. Options 1-4 each address elements of the energy conversion process from primary energy to end-use services.

Energy conservation and efficiency improvement have in common that both measures aim to

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

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

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

2.2 Adaptation Options

Adaptation options have two purposes:

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

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

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

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

2.3 Indirect Policy Options

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

This poses two fundamental dilemmas when assessing the various response options to climate

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

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

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

An effective climate change response strategy should therefore pay attention to possibilities to join climate change response options with responses to other socio-economic transition phenomena, so as to increase the probabilities of actual implementation.

Examples of the latter can especially be found in applications of the integrated systems approach. For instance, at present in many developing countries crop agriculture is highly dependent on energy use, both directly and indirectly, for much of which farmers have to depend on outside sources; in addition, such agricultural systems like those based on high-yielding varieties of wheat and rice are often monocultures. Other options, like low-external input sustainable agriculture, are proclaimed not only to lower the need for external and energy-intensive inputs, but also to increase productivity in farming, while at the same time taking care of any concern for national food security (Reijntjes et al., 1992). Still, another example of a 'multi-functional system' is wave-energy. In that case the production of energy is combined with other functions, such as the protection of the shore against erosion, water desalination, and the protection for a harbour or for aquaculture. These systems can be particularly interesting if applied at a small scale in developing countries.

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 these 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, which should not be confused with the distinction - which has drawn a lot of attention in the literature - between top-down and

bottom-up modelling (see also chapter 8). 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 (other categorizations of the assessment approach are also conceivable; in chapter 8, for instance, the assessment is differentiated depending on the level of aggregation, e.g. the aggregate national level or the level of a single project; however, such a differentiation was not considered crucial for the topic of the present chapter, which is to provide a generic assessment of the various response options).

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

However, if the welfare economic approach is taken, the overall assessment may be quite different. By using the land for afforestation purposes, the possibility to use the same land for agricultural purposes is foregone. It therefore matters a great deal if the area has agricultural potential or not. If so, the local population may well be forced to migrate or else to suffer income losses. Moreover, the afforestation program if applied at a large scale may have additional impacts, either positive or negative, e.g. through its effect on the local climate and soil fertility, on the social and cultural life, on the infrastructure, on tourism, etc. In the assessment attention can also be paid to the distortionary impact of government measures, such as subsidies and taxes, on the efficiency of the forestry option. If all the direct and indirect welfare consequences of the envisaged afforestation program are going to be assessed, an extensive and complicated social cost-benefit type of analysis may well be called for, because not all aspects can be quantified or monetized (see also chapter 4).

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 monetary 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 inside and outside the societies concerned, including the external effects, and of the social and political acceptability of options.

In actual practice, even public agents may not be fully aware of the various externalities and indirect, immaterial and distributional impacts of the application of response options. For one reason they may not want to take the various aspects into account, for instance under the influence of particular pressure groups; for another reason the information required for a full welfare assessment may simply be insufficient, so that decision making is hampered. What is

more, even if all information for assessing the various options is available, obstacles in setting up the institutional capacities can pose serious bottlenecks, so that appropriate action will not follow, a process which may also contribute to explaining the existence of private no-regrets options.

As was explained already rather extensively in the former chapters, the practical obstacles for a welfare economic assessment of climate change response options are large, particularly in the developing countries. 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 data collection, processing and communication; vice versa policies dealing with externalities may fail to reach part of the local population for various reasons. Three, most developing countries face a severe lack of institutional and human capacity to deal with these issues.

The general impression arises that optimism about the 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 various aspects of the economies of scale concept:

- a) average costs may decrease at a larger scale of application (internal economies of scale);
- b) costs may decrease at a larger scale of application of other options, because of positive external effects (external economies of scale);
- c) costs may decrease 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. afforestation projects often provide a clear example;
- e) costs may increase, because achieving the required rate of diffusion of technologies, public education and lifestyle changes may become increasingly difficult at larger scale. This may be particularly relevant if technologies require a high level of technical expertise.

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

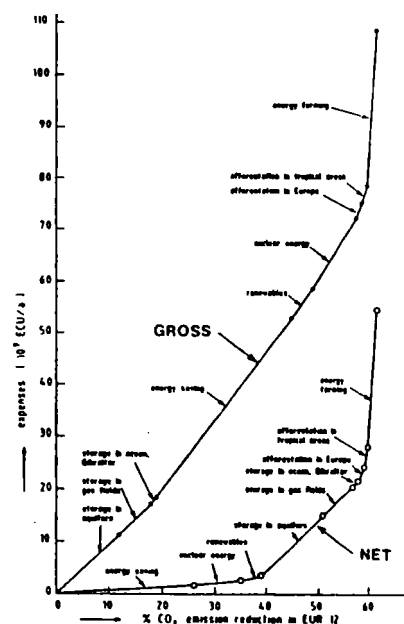


Figure 2. Options for CO₂ emission reduction in the EU, net and gross costs, and effectiveness.

Source: TNO, 1992, p.5.

A comparable issue is how costs have to be ascribed to the various reductions that are achieved with the help of the investment made. More often than not, investments made for economic and/or environmental reasons, have changes in greenhouse gas emission as a side-effect. Many no-regrets options belong to this category. The question then becomes how precisely to relate the investment costs to the greenhouse effect.

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

In other chapters (esp. 8 and 9) the need to reconcile the various types of analyses of the costs of energy related greenhouse gas mitigation has been underlined. There is indeed a growing convergence of detailed (bottom-up) analyses of technological options and more aggregate (top-down) analyses of economic effects, so that differences in results can increasingly be attributed to differences in input assumptions rather than to differences in model structure. However, notwithstanding the current progress in greenhouse related modelling, there still is a lack of understanding of how models have to be developed and applied that are particularly suited to

study the greenhouse problematic in economies in transition or developing country economies. In view of the structural changes that are underway in these regions, further improving the understanding of the greenhouse gas emissions reduction/absorption potential in economies in transition and developing countries economies - recognizing all relevant aspects and especially the sensitivity of the outcomes for the economic and technological development path - is imperative.

4. Mitigation Options

This section will treat mitigation options, as listed in section 2.1, in some detail along with their costs and potential.

4.1 Energy Conservation And Efficiency Improvement

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

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

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

If population growth is given and the future levels of GDP per capita are predetermined, a given CO₂-emission reduction target can only be achieved by a reduction in carbon intensity (CO₂/E) and/or energy intensity (E/GDP). The need to reduce carbon and energy intensities becomes stronger, the higher the growth rate of population and the more ambitious targets are set with respect to GDP increase. The latter points obviously reinforce the need to pay specific attention to developing countries.

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

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

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

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

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

The two underlying factors of reduced energy intensities are improved energy efficiency of individual production processes and structural changes in the economy (in particular, the increasing weight of less energy intensive sectors and the energy efficiency of the spatial structure). Only a few studies explicitly incorporate the impact of structural changes (most focus on energy efficiency measures).⁴ For example, it was estimated that energy efficiency improvements were responsible for about three-quarters of the 26% reduction in US energy intensity during 1973-1986 (Schipper, Howarth and Geller, 1990).

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

Among virtually all studies, there is broad consensus on the virtue of energy efficiency improvement. Moreover, it is seen as directly beneficial irrespective of whether greenhouse warming will take place or not so emissions reductions are achieved at a negative net cost (no-regrets policy).

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

53% in the industrialized countries). This suggests that the scope for energy efficiency improvement is particularly promising with regards to increasing useful to final energy. Efficiencies are lowered further if seen from an 'energy' point of view, i.e. if the actual services (work) supplied by the energy source are related to the corresponding inputs minimally required: energy 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 technologies would be disseminated throughout the world, global primary energy requirements would come down by 17% from 12 to 10 TWyr/yr; if instead the best available technologies would replace instantaneously the current energy system worldwide, without altering the energy system structure, global annual primary energy requirements would decline to 7.2 TWyr/yr (Nakicenovic and Grübler, 1993). A similar exercise assuming that Japanese industrial efficiency levels would diffuse globally, shows an estimated industrial carbon reduction potential of some 730 MtC worldwide, mainly in steel, chemical and cement industries (Matsuo, 1991).

Clearly, energy end use is the least efficient part of energy systems, and it is in this area that improvement would bring the greatest benefits. Most studies suggest that a large potential exists in many sectors and regions, while at the same time acknowledging that institutional, economic, and social barriers may delay or inhibit the achievement of full efficiency potentials in the near future. A review of twelve studies of long-term energy efficiency potential found that in many regions of the world, full adoption of cost-effective energy efficiency measures could reduce carbon emissions by 40% or more over the medium- to long-term compared to business-as-usual trends (Geller 1994). An illustrative example which is related to the OECD area is IEA/OECD (1991) as shown in table 1. In this respect it should be mentioned that there have recently been considerable policy and regulatory reforms which have begun to address some of these barriers. In the US, for example, more than 30 States have adopted or experimented with regulatory reforms since 1989 to promote demand-side management (DSM) and to encourage integrated resource planning (IRP).

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

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

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 C).

4. Energy use only.

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

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

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

Much of the discussion seems to increasingly focus on the issue to what extent improved energy efficiency and conservation serves the dual purpose of being now economically viable as well as saving energy and reducing CO₂ emissions (no-regret). Optimism about the scope for no-regret options generally is much greater among proponents of the bottom-up approach, than amongst those adhering to top-down methodologies.³

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

The choice of a (financial) discount rate is an important factor in evaluating the cost-effective energy efficiency potential in a particular sector or region. Studies that have tried to assess the implicit consumer discount rates of household investments in energy efficiency reveal ranges varying (depending among others on income classes) from a few percentages only to well over 50%. Train (1985), in his survey, found ranges of: 10-32% for improvements of thermal integrity of buildings; 4-36% for space heating and fuel type; 3-29% 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.

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 ^a
<i>Market economies</i>				
Efficiency improvement	15	45	84	144
Structural change/recycling	95	n.a.	25	120
Fuel substitution	6	n.a.	n.a.	>>6
Process technology change	0	2	98	100
<i>Reforming economies</i>				
Efficiency improvement	48	53	n.a.	>101
Structural change/recycling	165	50	n.a.	>215
Fuel substitution	10	n.a.	n.a.	>>10
Process technology change	0	10	48	58
<i>Developing countries</i>				
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
<i>World</i>				
Efficiency improvement	75	139	84	5298
Structural change/recycling	279	>79	>25	>383
Fuel substitution	10	n.a.	n.a.	>>10
Process technology change	0	20	200	220

^aTotal reduction potential could be higher because not all measures have been assessed.

n.a. = Not assessed.

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

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

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

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

Notwithstanding the above, a host of studies has emerged suggesting a considerable scope for no-regrets options, especially in the household and tertiary sector: e.g. Springmann (1991), Mills et al. (1991), Rubin (1992), Jackson (1991), Blok et al. (1993), UNEP (1993 draft), Robinson et al. (1993 draft).

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

4.2 Fossil Fuels Switch

According to most studies the present dominance of fossil fuels in global (primary and non-commercial) energy consumption (1990: 77%) will continue to exist in the next decades to come, e.g. varying between 76 and 66% in 2020 according to the recent, authoritative WEC scenarios⁶ (WEC Commission, 1993, p. 106) (table 3 next).

	1990	1990	in 2020			
			A	B ₁	B	C
Coal	14	23	49	38	30	21
Oil	10	28	48	45	38	29
Natural Gas	0.4	1.7	3.6	3.6	3.0	2.5
Nuclear	—	0.4	1.0	1.0	0.8	0.7
Large Hydro	0.15	0.5	1.0	1.0	0.9	0.7
"Traditional"	0.5	0.9	1.3	1.3	1.3	1.1
"New" Renewables	—	0.2	0.8	0.8	0.6	1.3
Total	3.3	8.8	17.2	16.0	13.4	11.3

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

Source: WEC Commission, 1993, p.106.

All the scenarios reflected in the table show: fossil energy to remain dominant; the share of natural gas, environmentally the least damaging of the fossil fuels, to increase from the present quarter to one third at most; the share of nuclear to remain modest; the relative potential of the presently modest "new" renewables to be not insignificant, as opposed to the limited size of the projected shifts for large hydro and "traditional" energy sources (see in this respect also chapter 9).

The remaining dominance of fossil fuels is due to the large resource base⁷, the strongly vested position in the current vintage of technologies and price distortions that externalize the environmental costs. Estimates point out that total identified fossil fuel reserves will suffice to provide for current (1990) levels of energy consumption for the next 130 years.⁸ Obviously, this time span may become considerably shorter as energy use in the developing countries will increase rapidly.

Of the three fossil fuels, natural gas is least and coal is most carbon-intensive.⁹ Additional environmental advantages of natural gas are for instance minimal sulfur emissions and virtually no airborne particulates (World Resources 1994-95). Therefore, a switch from coal and/or oil to natural gas is to be seen as a response option with multiple benefits. Current estimates of the natural gas resource base, which will likely be revised upwards in the future, allow for a massive switch-over for the next century or so to come. If so, the entailed transition of the 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 H₂, a considered potential (massive) renewable energy later in the next century.¹⁰

Costs of this fuel stem from retrofitting or replacing the current vintage of energy technology and in some cases building additional transport grids to connect (remote) urban areas with gas fields. Estimates of the costs of switching even without extending the existing networks, vary to a large extent depending on the type of measure. Switching building electricity use from electric resistance heat to natural gas heating (improving overall efficiency by 60-70%) on the one hand would, according to Rubin et al. (1992), yield a net benefit of \$¹⁹⁹⁰ 90/CO₂ (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 \$¹⁹⁹⁰ 60/CO₂.

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 24.5 times that of CO₂.¹¹ Estimates of common current leakage rates range from 0.3 to 4% for distribution and from 0.13 to 6% for production (Simpson and Anastasi, 1993).¹² 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%¹³ for switching from coal to gas and at 4% for switching from oil to gas (adopting a global warming potential index of CH₄ of 21). These figures point to the need of severely controlling leakage rates.¹⁴ Additional questions are, what happens to leakage rates in case of a large-scale fuel switch and whether leakage rates of newly built and/or additional grids, i.e. marginal leakages, can be reduced.

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

4.3 Renewable Energy Technologies

Today many technologies have been developed to provide energy on a sustainable basis, in the sense that they harness energy resources that are practically unlimited and require relatively little additional energy input. Moreover, exploitation of renewable energy resources with appropriate technologies has the advantage of releasing relatively little (net) carbon.¹⁵ So, a switch from fossil fuels to renewables will result in reduced absolute greenhouse gas emissions.

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

The following classes of renewable energy resources are commonly distinguished: solar, wind, hydro, geothermal, ocean, and traditional and modern biomass.¹⁶ To understand the main factors underlying costs and potential of renewables as a group, a detailed treatment of their diversity is required.¹⁷ 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 well-developed, whereas some ocean technologies are still in a demonstration

stage, though this may in the shorter term be left by tidal and wave technologies. Solar, modern biomass and geothermal are in between, and photovoltaics may 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.

* Includes fuel wood and dung

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

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

Some estimates of 'practicable'¹⁸ potentials (relative to current use) are given in table 5. It clearly shows, how small current use is when related to various estimates of 'practicable' potential, whatever discrepancies thereof may exist. Notable exceptions are (large) hydro and (traditional) biomass, that, according to the data presented, are exploited at about a quarter to half of probable capacity. Judging on these figures only, the scope for renewables is promising. However, a truly comprehensive assessment cannot do without a glance at the costs involved.

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

As for 1), the time horizon adopted, the level of discount rate chosen and the capacity and useful life time assumed are important factors. As for 2), costs are strongly influenced by site-specificity and (temporal) variability of supply as mentioned above, and by the form of final energy delivered.¹⁹

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

Current prices of hydro, wind and some solar and biomass technologies as listed in table 6 are already competitive with conventional resources. Looking ahead, substantial cost reductions for virtually all major classes are to be expected within the next few decades.²⁰ However, whether they will actually become competitive, is also related to: local conditions that shape a renewable's attractiveness, and complementarity between renewables.

In contrast to fossil fuels' mobility, renewable energy consumption currently seems to be more

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

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

1. in 2020

2. in 2030

3. in 2020

a. Source: Johansson et al. (1993), WEC (1993), Swisher et al. (1993).

b. includes 81.7 TWh/yr for small hydro.

c. includes 211-308 TWh/yr for small hydro.

d. 4170 TWh/yr for traditional and 543 for modern biomass.

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

Source	solar	wind	hydro	geothermal	ocean	biomass electric	fuel (\$/GJ)
IEA ²	0-14 ^a 7.6-41.9 (15- 174) ^b 5.2-26 (22.61) ^c 5 (50) ^d (all 1984 £c)	3.5-4.2 ^b (4.48-7.62) (20) ⁱ	-	(3.6-9.2)	5-20 ^e (p/kWh) (11.5-50) 6.7-8 ^a	-	7.58-12.80 (11.85-16.68) ^a 12.70-20.85 ^a 15.64-23.70 ^a
Johansson et al. ²	4.5-11.7 (7.5- 32.8) ^f 4.9-9.4 (8.5- 28) ^g	3.13-4.46 (4.29-8.4)	-	3-12 ^h 0.15-2.5 ⁱ	(5-30) ^m 12-25 ⁿ 22-30 ^o	-	1.86-2.73 (2.73-3.86)
Swisher et al. ³	5-10 ^f (12) 4-8 ^g (25) 4-8 ^g (30)	3-6 (7)	5-10 (5)	-	8-10 ^m	5	6 ^f (8) 7 ^g (13) 10 ^g (15) 1 ^g
WEC ⁴	no storage 0.4-2.5 (0.5- 10) ^f 1-11 (1.2-28) ^g 4-14 (28-45) ^g	3-9 (5-10)	-	n.a.	(5-12) ^m (5-7) ⁿ (12) ^o (10-14) ^o	n.a.	n.a.

1. current costs in parentheses; 2. 1984; a. passive solar; b. active solar; c. solar thermal (line focus); d. solar thermal (point focus); e. solar thermal-electric; 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. sub gradient; p. ocean thermal; q. ethanol from corn; r. ethanol from sugar; s. ethanol from wood; t. methanol from wood; u. methanol from herbages; v. biomass.

Sources: IEA (1987); Johansson et al. (1993); Swisher et al. (1993); and WEC (1993)

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

Conversely, what often makes up the main part of a renewable's promise are its large potential and modest price on the spot relative to availability and prices of conventional resources. Moreover, by using local renewables countries could reduce dependence on imported fossil fuels and reduce foreign exchange constraints; in addition, in the case of biomass, local communities could significantly benefit from small-scale applications and their net positive side-effects. In a way parallel to energy efficiency measures, this could come to a no-regrets policy.

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

The above discussion implies that the future role of renewables is hard to predict precisely. Though differences exist in optimism, renewables' share in the 2020 energy mix will according to various scenarios probably not exceed 25%.²¹ 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 Energy²²

Nuclear energy now accounts for about 5% of all primary energy production or about 20% of the world's electricity generation. Its production, comparable to that based on renewables, causes overall relatively little CO₂.²³ Moreover, its technology has passed the demonstration stage except for the still unresolved main issue of the storage of nuclear waste. In addition, further dissemination could be strongly prohibited by the lack of public acceptance due to major concerns about reactor safety, the risk of theft of nuclear technologies or materials, the proliferation of weapons-grade nuclear materials and the final storage of fission products.

Bearing these serious limitations in mind, nuclear energy (for comparison with gross costs, see also figure 2), if evaluated on the basis of the engineering efficiency approach, can 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 the long design/construction time (10-15 years) and the enormous investment costs of nuclear power plants, the nuclear option is rather inflexible. According to Mills et al., 1991, p. 540 (see table 7; note that the figures in the table are based on average existing rather than new plants), costs to produce electricity with nuclear energy (\$/kWh) which seem to have been rising and not falling (MacKerron, 1992), are still less than with many of the renewable options considered next.

However, if the nuclear option is assessed from the welfare economic point of view, the final assessment becomes much more uncertain because the lack of public acceptance and the various risks and uncertainties now also have to be taken into account explicitly. This not only holds in the industrialized countries, but probably even more so in the developing countries and the countries in transition. In addition, any future use of nuclear energy will, like any fuel switching to

Table 7.

Examples of avoided emissions and their costs: electricity.				
Electricity ^a (Cost of avoided resource (coal): \$0.44/kWh)	Measure Resource cost (\$/kWh)	Avoided emissions (g Carbon-eq/kWh) (%)	Cost of avoided carbon-equivalent (\$/tonne)	
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 (bushar costs)				
Available technologies				
Biomass steam-electric (woodfuel)	0.041	318	100	-9
STIG (gasified coal)	0.041	9	3	-313
STIG (natural gas)	0.027	163	51	-103
Wind (1980)	0.054	318	100	33
Solar thermal electric (1980)	0.114	318	100	221
Solar photovoltaics (1980)	0.231	318	100	508
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
(2020)	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: ^a 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 €1.89/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 costs.²⁰ (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).²¹ Variable-speed motor drive: ABB Corporate Research (personal communication, Lars Gertmar, 1988). Capital cost \$104/kW (750 kW motor). Heat-pump water heater: equal to 8% of capital cost; 15-year lifetime; 4 000 hours/year; 35% reduction in electricity requirement. US field data, multi-family space heating: includes measured data from 42 actual projects in the USA.²² STIG (Steam-injected gas turbine) for gasified coal: 2 × 50 MW steam-injected gas turbine (STIG), air-blown gasifier, hot-gas clean-up, 35.6% efficiency, \$1 300/kW capital cost and €0.71/kWh O&M costs; STIG for natural gas: 4 × 51 MW, 40% efficiency, \$410/kW capital cost and €0.29/kWh O&M costs; Chemically recuperated gas turbines: assumes 34% efficiency, \$500/kW capital cost, 70% capacity factor.²³ O&M costs assumed same as for gas-fired STIG systems. Biomass-steam \$1 500/kW capital cost, \$0.005/kWh O&M, \$1.5/GJ fuel cost, wind, solar, thermal, and solar photovoltaics.²⁴ These prices are based on the RD&D intensification scenarios developed by five US National Laboratories: Nuclear; see, *op. cit.* Ref. 15. ISTIG (intercooled STIG) coal, 110 MW, 42.1% efficiency, \$1 030/kW capital cost and €0.60/kWh O&M costs; gas, 114 MW, 47% efficiency, \$400/kW capital cost and €0.29/kWh O&M costs; Fuel choice: the coal base-case is gasified coal + natural gas.²⁵ Gasified coal + biomass 111 MW BIG/ISTIG system.²⁶

non-fossils, depend on the underlying cross price elasticities and energy price assumptions, inflation, public policy, and technological progress. Recognizing all this - i.e. the fact that there is no established technology for decommissioning nuclear plants, that there are hidden external costs regarding nuclear power relate damage, and that efforts are being made to develop intrinsically safe nuclear reactors - the IEA projects the share of nuclear energy in total energy use by 2010 at 6.1%; the WEC C-scenario (see also note 7) projects the share of nuclear at 6.2% in 2020.

4.5 Capture And Disposal

CO₂ capture and disposal is understood as any sequence of processes in which carbon is recovered from an energy conversion process and disposed of at sites other than the atmosphere. It should be noted though, that disposal capacity is ultimately limited, both for technical reasons, and because not all forms of disposal ensure a permanent prevention of carbon reentering the atmosphere. However, assuming sufficient and feasible disposal, the further development of these technologies combined with coal gasification is considered of significant intermediate potential, especially for coal-rich countries such as China. Indeed, should China actually consume 2 billion tons of coal per year in the next century as some scenarios suggest, it might render almost useless the other efforts to reduce CO₂ emissions globally (Nakicenovic and Victor, 1993, p. 534; see in this respect also the outcomes of the OECD Model Comparison Project as discussed in chapter 8).

Since places of recovery do in general 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.²⁸ To date, most research effort was spent on power plants. For these, two types of recovering technologies exist:²⁹ separation of the CO₂ from the flue gases (scrubbing) with or without prior modifications in the energy conversion process. Technologies of the former type, which are now in experiment, are an Integrated Coal Gasifier Combined Cycle (ICGCC), modification of the boiler and modification of the gas turbine.³⁰ The main separation options are chemical or physical absorption, the use of membranes, and cryogenic fractionation. Of these, chemical and physical absorption is most developed and membrane separation and cold distillation least.³¹

Depending on the place of disposal, transport will take place onshore or offshore. Onshore, pipelines are most economical. Estimated costs vary between \$1-4/tCO₂ over 100 km, depending on 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 decreasing 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, i.e. the mean retention time is large compared to the about 120 years residence time of CO₂ in the atmosphere (not all applications ensure entire or long-term storage of the carbon).³²

Disposal can occur in two ways: either it is utilized in (long-lived) productive activities,³³ or it is stored underground, in aquifers (almost unlimited potential to store), or in the ocean.³⁴ Especially in the latter cases environmental risks seem to be involved, however.

4.6 Enhancing Sinks: Forestry Options³¹

Unlike removal options, in options enhancing sinks carbon is removed after dispersion in the atmosphere. Much more carbon is stored in soils (some 700 GT C) than in forests (< 100 GT C). This suggests significant attention for the range of measures to promote soil conservation, reduce carbon mobilization from soils to air, and increase soil storage of atmospheric carbon through the action of soil micro organisms. Nevertheless, 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 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).³² The large amount of uncertainty that exist on net carbon release figures of deforestation and land use changes stems from: the extent of the area deforested; the carbon content of biota and soils in the deforested land; and the dynamic release profile of biotic and soil carbon after disturbance.

The following subclasses of forestry measures are commonly distinguished: halting or slowing deforestation, reforestation, afforestation,³³ and sustainable forest exploitation cum sequestration of carbon in long-lived forest products.³⁴ The first three measures intend to sequester carbon by increasing the standing inventory of biomass, or by preventing a decrease thereof. This comes to a once-for-all uptake of carbon. In contrast, the fourth measure aims at continuing to break the carbon cycle, thereby in principle enabling permanent application; this option becomes the more efficient and attractive if the timber is used to substitute for the more CO₂-emission intensive products, such as bricks, concrete, steel, and plastics at a large scale.

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

In assessing the global potential of halting or slowing down deforestation and of reforestation, there are four main fields of uncertainty: 1) the potential for slowing deforestation depends on resolving complex problems which are linked with the large-scale encroachment of human settlers into the (tropical) forests or policy distortions (e.g., below-cost sales of timber on government lands) leading to deforestation in industrial countries; 2) the potential of the option depends on the amount of area globally available for some kind of forestry measure (see also IPCC, WGII, Chapter III.F, section 4.1 and 4.2, 1995 *forthcoming*) and 3) of the incremental (i.e. annual) and net cumulative carbon uptake/ha³⁵ for the main forest species³⁶; 4) large-scale

monoculture forestry may not be acceptable to many environmentalists; moreover the local ecosystems may be destabilized.

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

ad 2. Tropical deforestation rates vary widely among the various sources, partly due to different definitions of both tropical forests and deforestation (for a discussion, see Jepma, 1994). According to FAO (1991), annual tropical deforestation for the late 1980s amounted to some 17 million ha; other estimates vary between 3 to 20 million ha. Estimates of global annual biotic carbon fluxes from closed forests during the late 1980s show an equally large variety: ranging between 600 MtC (IPCC, 1992) and 2800 MtC (WRI, 1990) (for an overview see 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. According to Sedjo and Solomon (1989), annually 2.9 GtC of excess atmospheric carbon could be sequestered by approximately 465 million ha of (fast-growing) plantation forests at a cost of about \$186-372 billion (without employing fast-growing species the area needed 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 at present globally 265 million ha would be available and suitable for forest plantations and 85 million ha for agroforestry. Other sources (Winjum et al., 1992, and Centeno, 1992) suggest significantly larger (some 400-1200 million ha) areas, however. These figures are in sharp contrast with the potential in the OECD countries, amounting 15-50 (in future) mln. ha in the EU, mainly due to redundancy of farm lands, and 30-60 mln. ha in the US. Carbon sequestered in global annual wood production is currently estimated at some 1 GtC (TNO, 1992, p. 110). This gives some indication of the potential of carbon sequestration through wood products, depending on the price, product life time and the trend in timber demand (commonly projected to rise). Some authors argue that a considerably higher demand for wood could be achieved if it is used to produce electricity (and liquid fuels such as methanol), thereby replacing fossil fuel CO₂-emissions with a system in which net emissions are zero, provided the wood is grown on a sustainable basis (for a feasibility study, see BTG, 1994).

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

4.6.1 Costs

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

The major part of the studies, dealing with the costs of 1) afforestation or 2) halting or slowing down 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), including 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 down deforestation probably belongs to the category of both the most urgent and cost-effective options (Grübler et al., 1993b, p. 499). This impression is reinforced by the fact, that experience with the closest alternative, reforestation, has so far produced mixed results. On the one hand some success stories can be told about reforestation projects in Sweden, Finland and parts of Canada. On the other hand, however, large losses occurred in Angola, Nigeria, Morocco, and several other countries, whereas in China the rate of survival of reforestation efforts is estimated to be not higher than 20% (Nakicenovic and John, 1991).

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

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

However, even if afforestation with 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 reforestation rates very modest (Trexler, 1991). Indeed, 'tropical forestry programs undertaken with global climate change mitigation in mind will need to be integrated into the social, environmental, and economic contexts and needs of the countries (and local communities, ed.) in which they are undertaken. Failure to understand this has brought about the failure of many tropical forestry efforts intended to solve fuelwood and other problems. The same could easily occur with forestry efforts intended to mitigate global climate change' (Brown et al., 1993).

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

ad 1. So far most effort has been spent on deriving point estimates from average costs. Some selected cases are given in table 8 and 9. Note that the estimates generally assume 'tree cemeteries'. Tables 8 and 9 show relatively low carbon sequestering costs through tree planting, in many cases under \$10/tC and rarely over \$30/tC. Other studies with similar results, stressing various aspects of the problem, include Trexler et al. (1989), Swisher (1991), Winjum and Lewis (1993) and Faeth et al. (1993). For a detailed assessment see Turner et al. (1993) and IPCC, WGII, chapter III.F, section 5 (1995, *forthcoming*).

Source	Tropical Agroforestry - Plantation	Temperate Plantations	Boreal Plantations - Protection
Andrianto (1993)	3-5	3-6	0-1
Dixon et al. (1993)	4-16	6-60	3-30
Krakballe and Dixon (1993)		1-7	1-8
Houghton et al. (1991)	3-12	4-37	1-3

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

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

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

Forest Type/ Practices	Median \$/tC	Median \$/ha
Boreal:		
Natural Regeneration	5 (4-11)	93 (83-126)
Reforestation	8 (3-27)	324 (127-455)
Temperate:		
Natural Regeneration	1 (<1-1)	9 (9-100)
Afforestation	2 (<1-5)	259 (41-444)
Reforestation	6 (3-29)	357 (257-911)
Tropical:		
Natural Regeneration	1 (<1-2)	178 (106-238)
Agroforestry	5 (2-11)	454 (255-699)
Reforestation	7 (3-26)	430 (303-1183)

Interquartile ranges (middle 50% of observations) in parentheses

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

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

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

- diminishing uptakes as less suitable or less well-managed land is forested, resulting in a lower carbon uptake per ha;
- increasing public resistance and social and legal objections of the local population against interference with present land use.
- rising establishment costs due to higher opportunity costs as plantation establishment moves from fallow land to land suitable for alternative uses;²⁷
- no or negligible economies of scale in operating and maintenance costs;

All but d) tend to enhance marginal costs; the potential of d) to offset the trend is generally absent. Hence, *marginal* costs will generally increase as more area is being forested. Exceptions to this rule might only occur if the amount of land needed for agriculture shows a declining trend. Clearly this is almost nowhere the case in developing countries, 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.²⁸ This way also more 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	700
	\$/ton			
Moulton/Richards (1990)	\$16.37	20.69	23.24	34.73
Adams et al. (1993)	18.30	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 higher levels, divergence rapidly grows wider. Therefore, the conclusion seems justified, that point estimates though valid for small areas, seriously fail to describe actual costs for larger areas.

ad 2. Recently, a number of forestry studies have begun to appear employing a somewhat more sophisticated methodology than before. These include Moulton and Richards (1990), Adams et al. (1993), and Parks and Hardie (1992). These studies 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 until recently virtually ignored 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 a justified generalization to state that the newer research is tending to find a somewhat steeper increase in costs than did the earlier studies, with the costs per tC roughly doubling, from about \$30 to \$60/tC, for large annual uptakes.

Finally, it is increasingly recognized that there are probably limits to the extent to which the global system can maintain forest stocks. However, at the same time one recognizes the potential long-term contribution of sustainable forest management to providing a continuous flow of substitutes for net-emitting energy carriers, such as coal.

4.7 Methane

After CO₂, methane (CH₄) most likely accounts for the largest anthropogenic contribution (about 18%) to greenhouse warming, although there is still considerable uncertainty about methane emissions.²⁹ Major sources of anthropogenic methane are: losses from the production and distribution of natural gas, releases from coal mining, from ruminant animals and from paddy rice production. For natural gas in distribution most of the losses occur from leaks in the pipe work. The remaining losses stem from routine maintenance, pressure release valves and non-efficient end-use applications. In production losses are due to leakage at wellheads and gas treatment plants, venting and incomplete flaring operations and exploration and drilling activities.

Data available for 1984 on the fraction of vented and incompletely flared gas released during

production of natural gas reveal wide discrepancies between the various regions: 1% in North America, 2% in Europe and CIS, 11% in Asia and Australia, 18% in Central and South America, 40% in Africa and 61% in the Middle East (!) (Fung et al., 1991).

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

According to Van Amstel et al. (1993), currently available techniques allow for a 70% reduction of methane emissions from coal mining (particularly gassy mines). Future techniques may increase the figure up to 90%. For oil and natural gas production many techniques are available as well.

Rubin et al. (1992) estimate the costs: of eliminating US paddy rice production at about \$0.5/CO₂; and of reducing US ruminant animal production by 25% at \$2/CO₂ (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). There is a lack of similar cost information of, for instance, reducing methane from rice production or from ruminant animals in developing countries.

5. Adaptation Options

There are no comprehensive surveys of the various adaptation options and their costs, probably because adaptation covers such a broad range of potential action and also because of the large uncertainties surrounding these options. Therefore, no more than fragmentary information can be provided.⁴¹ In any case, it is clear that society now already incurs large costs in adapting to climate extremes; climate change will just increase these costs.

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

5.1 Adaptation to what?

Climate change may cause accelerated sea level rise, possibly attended with floods or hurricanes, changes in regional temperature, an increase in storminess and changes in the runoff of river water 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 sea level rise is increasingly being carried out (Tol, 1994; Nordhaus, 1993; Cline, 1992a; Fankhauser, 1992, 1993, 1994a and 1994b). The World Coast Conference 1993 (IPCC, 1994) has pointed to the need to integrate responses to long-term threats such as climate change and associated sea level rise with existing planning and management efforts so as to arrive at Integrated Coastal Zone Management. 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, little research has yet been carried out 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 ground water 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) accommodation, or c) protection.

a) Retreat will cause loss of dry land and loss of wetlands. IPCC (1994) computes that a one meter sea level rise could threaten 170,000 km² (or 56%) of global coastal wetlands. Loss of dry land means losses in agriculture, in forestry, in species and in physical assets and implies migration of people. Attempts to estimate these losses can be found in Ayres and Walter (1991), Rijsbergen (1991), Fankhauser (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.

TABLE 11.

region/scenario ^a	Agricultural Yield Changes 2xCO ₂ (percent of Gross Agricultural Product) ^b									
	UKMO			GISS			GFDL			diff. avg. 1 ^c 2+3 ^d avg. ^e
	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
S&SEA	-20.0	-20.0	-10.0	-10.0	-10.0	0.0	-10.0	-10.0	0.0	-8.83 -13.33 -4.50
CPA	-7.5	+7.5	+7.5	+7.5	+22.5	+22.5	+7.5	+22.5	+22.5	+17.50 +2.50 -15.00
AFR	-20.0	-20.0	-20.0	-7.5	-7.5	+7.5	-15.0	-15.0	0.0	-6.67 -14.17 -7.50

Notes:

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

Source: Tol (1994), p.5

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

1 All estimates 1990.

Source: Tol (1994, p.50).

Table 12. Annual costs of sea level rise.

Not all estimates include the side-effects of resettling people that used to live on the lost land. These costs involve the costs of taking up refugees on the one hand, and of (the hardship of) people leaving on the other hand. By combining various sources of information, Tol estimated the global annual costs of relocating due to sea level rise at some \$14 billion. These costs vary between 0.01-0.03% of GDP for the OECD and the countries in transition, and some 0.3-0.8% for the developing regions (Tol, 1993, p.52).

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

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

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

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

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

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

shifts per region, are presented in table 11.

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

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

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

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

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

v) aquaculture. Climate change affects ocean circulation in the upper layers, upwelling and ice extent, all of which affect marine biological production and hence marine fisheries. One way to adapt is to intensify efforts to develop aquaculture. Integrating aquaculture with 'controlled environment agriculture' has a great potential: recently, dramatic advances in marine biotechnology have been made. The almost sterile, nutrient rich bottom water from Ocean Thermal Energy 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 for marginal groups the risks of damages due to climate change will become larger the more unequal the land distribution system is. Changes in land tenure may therefore, as a side-effect, reduce these risks and can be viewed as an indirect adaptation option in itself.

5.3 Adaptation measures in developing countries

In developing countries, adaption depends on the type and intensity of the impacts of climate change that may occur. Depending on these impacts, adaptation may be applied immediately or be delayed. In case of the African countries, however, no real adaptation studies have yet been carried out. Current bilateral and multilateral activities are expected to lead to a more systematic assessment of adaptation options and their costs.

The quest for adaptation options, however, already existed long before the global debate on climate change started. On the one hand, countries tried to find long- and short-term responses to recurrent droughts in arid and semi-arid zones. Countries in heavy rainfall regions and those affected by storms and cyclones in their coastal areas, on the other hand, tried to (non-)structurally deal with recurrent floods.

The short-term responses to recurrent droughts included improvement in drought preparedness, and primarily focussed on drought relief and drought recovery activities. With respect to drought relief one can think of supplementary food programmes and programmes to protect and replenish the national livestock. Drought recovery entails such activities as the provision of seed and land preparation supplements to farmers after a period of drought. However, even for these

short-term responses no systematic studies have been carried out.

Long-term measures included regional and national research efforts on drought resistant crops and the breeding of hardy livestock. Incorporation of drought and salt resistance in crop varieties is, thus, already a major item on the research agenda in some developing countries. Further activities, particularly those strengthening the research capacity, including increased flows of financial resources, are necessary and will almost certainly prove to be cost-effective. In areas where water resources management will become crucial because of large changes in the characteristics of rainfall regimes, e.g. increased frequency and severity of floods and droughts, an improved and more environmentally-sound infrastructure will be necessary, while policies encouraging water conservation (e.g. pricing mechanisms in which prices reflect social scarcity) will need to be introduced.

The electricity generation sector, which will also be heavily affected by changes in climatic patterns, has received responses from outside the climate change activities of the current global effort. Facing massive river and dam silting and below average precipitation to replenish hydroelectric installations, nations have sought to develop alternative base load systems, such as coal thermal. A more systematic assessment of these responses will prove to be crucial, particularly in the light of the indicated importance of decarbonizing the fuel base to reduce emissions.

5.4 Modelling Adaptation

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

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

6. An Integrating Approach

A major part of the literature on the response options focuses on the various technologies and their cost-effectiveness within a specific option. Options are then not assessed on the basis of mutual comparison. The main explanation why the 'partial' approach dominates, is probably the limited availability of reliable and accepted data about the options' costs and benefits. Moreover, one increasingly recognizes that the costs of the various options critically depend upon the assumptions one employs about the efficiency of the baseline scenario one uses in the analysis (see in this respect also chapter 8 and 9).

Nevertheless, a truly generic assessment would require an integrating framework that allows a simultaneous evaluation of the various technologies. If emission reduction targets are to be achieved in an optimal way, also in terms of flexibility and spreading of risks, a full picture of all the alternatives should be available, so that an integrated portfolio of options can be determined which minimizes costs of a given level of reduction of the carbon concentration (the integrating

approach in this chapter should not be confused with the integration of costs of a given option, nor with the integrated modelling approach treated elsewhere in this report).

The need for such an integrating approach is reinforced by the fact that evidence suggests that many of the options' cost functions show internal economies of scale (for some evidence with respect to forestry options see e.g. Moulton and Richards (1990), Adams et al. (1993), Parks and Hardie (1992), and Qureshi and Sherer (1994); with respect to energy technologies, see e.g. Kram (1994b), and Southern Centre/Risö (1993); for some broader analysis, see e.g. TNO (1992)). For the implication is that the most efficient option after reaching a certain scale of application, will become more costly than another option and so on (on marginal costs of CO₂ abatement, see also chapter 8 and 9).

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

A number of studies have been carried out in the tradition of the integrating approach, some of which in the sphere of a 'top-down' approach, aiming at completeness and based on generalized estimates of options' cost functions (McKinsey&Company, 1989; Nordhaus, 1991a; Jepma and Lee, 1994); others more in the 'bottom-up' tradition, commonly pursuing a greater level of detail (Jackson, 1991; Rubin, 1992; Mills et al., 1991; Kram, 1994b).⁴²

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

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

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

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

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

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

A detailed integrating response study in the bottom-up tradition is Kram (1994b). Here an overall assessment is made on the basis of long-term bottom-up country models (MARKAL) for nine Western countries, with more than seventy types of technologies (more than 30 supply technologies and more than 40 end use technologies), which are then integrated. A range of targets for CO₂-emission reductions by 2020 was tested to determine the mix of energy technologies that would produce the reductions at least total energy system cost. The results revealed considerable diversity among these countries in their optimal path, in terms of mix of energy technologies toward CO₂-emission reduction and in the cost and amount of reductions that could be achieved. This diversity turned out to depend on the various countries future energy needs, existing energy system, natural resources, technology options, and energy policies especially with regard to hydro-electric and nuclear power.

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

Table 13. Base case simulation

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;100)	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).

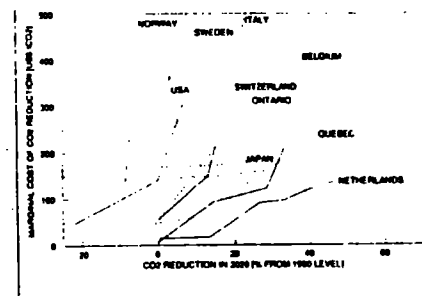


Figure 3. Marginal costs of CO₂ emission reduction for a number of OECD countries.

Source: Kram, 1994a, p. XIV.

There appear to be no similar detailed integrating response studies dealing with the developing countries. Given that the level of economic development and other circumstances vary greatly among developing countries, the marginal costs of emission reduction are likely to be here very much context-specific.

7. Regional Differences and International Cooperation

Though the industrialized countries constitute only 25% of the world's population, they account for 72% of the current global energy-related carbon emissions, whereas most of the historical cumulative carbon emissions, i.e. some 80-85%, are also due to them (Fujii, 1990). Clearly, this advocates for industrialized countries to assume their historic responsibility, which has been translated into the concept of 'common but differentiated responsibilities' mentioned in FCCC, Article 3.1 and elaborated in Principle 7 of the Rio Declaration: "... The developed countries acknowledge the responsibility that they bear in the international pursuit of sustainable development in view of the pressures their societies place on the global environment and of the technologies and financial resources they command."

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

- The GNP per capita varies from \$440 for Asia to \$17,473 for the West; the ratio is 1:40. The differences can also be large within regions: sub-Saharan Africa has a per capita GDP of \$322 as against \$1,507 for North and South Africa together (1:5).
- The relative use of traditional energy (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 57% of total energy use for Africa to 98% for the Middle East; within Africa it amounts to 30% for sub-Saharan Africa and 92% for North plus South-Africa (1:3).
- The relative use of nuclear plus renewables varies from 1% for the Middle East to 22% for Latin America. Within Africa it amounts to 3% for North plus South and 9% for sub-Saharan

Table 14.

Region	Tr (%)	Co	Oil	NG	EF	AI (%)	SEner (Mtoe)	Popul (million)	GNP (billion US\$)	GNP (\$ per capita)	Toe per capita	Toe per thousand US\$
<i>West</i>	1	22	41	19	82	16	4 296	849	14 840	17 473	5.06	0.29
North America	2	22	38	24	83	15	2 289	276	5 738	20 809	8.30	0.40
Western Europe	1	22	43	16	80	19	1 456	430	5 901	13 726	3.39	0.25
JANZ	1	21	51	12	84	16	551	144	3 202	22 279	3.83	0.17
<i>East</i>	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
<i>North</i>	1	23	38	24	85	14	6 040	1 263	17 888	14 163	4.78	0.34
<i>Africa</i>	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
<i>Asia</i>	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
<i>Latin America</i>	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
<i>Middle East</i>	1	1	64	32	98	1	233	129	370	2 860	1.81	0.63
<i>South</i>	17	31	33	10	74	10	2 624	4 029	2 835	704	0.65	0.93
<i>World</i>	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; Oil = Oil; NG = natural gas; EF = total fossils; AI = 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.

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Africa.

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

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

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

Most scenarios suggest that during the next decades the growth in carbon emissions will increasingly take place in the developing countries. According to the data summarized in chapter 12 of this report, the mean world annual growth rate of CO₂-emissions for over twenty scenarios is 1.56%, the corresponding mean rate for China is 2.83%, for Eastern Europe and ex-USSR 0.76%, and for Africa 3.85%. Consequently the share of developing countries in global CO₂-emissions is projected to 46% according to ECS'92 (compare OECD 34% and countries in transition 20%); however, according to the various WEC scenarios the developing countries' share in 2020 would be much larger, over 60%. In any case, it seems most likely that the developing countries as a group will start to become the major CO₂ emittant within a few decades. This picture is reinforced if the emissions of CH₄ from wetland rice cultivation and from enteric fermentation are also taken into account.

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

The literature on adoption and diffusion of technology clearly indicates that while profitability is probably the most straightforward determinant of the adoption of a new idea, technology or equipment, various other factors may also be important. A review of recent research of diffusion of energy technologies in developing countries shows that there are many financial, institutional and other factors which influence the successful adoption of these technologies (Barnett, 1990; Ghai, 1994). Often the initial awareness about such benefits and new opportunities may be

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

contingent upon such factors as, say, winning over women to introduce more energy efficient cooking stoves. To give another example, research into drought-tolerant crops have had limited diffusion success in Africa due to social resistance.

Moreover, one necessary ingredient for adaptation of technology, namely a pool of local skills to draw upon, may be lacking or be inadequate in many cases so that even proven technologies may spread rather slowly in these countries. For all these reasons an adequate and timely process of energy efficiency institution building seems imperative, especially in developing countries; there is evidence that the existence of such separate institutions has for instance helped Indonesia, South Korea and Thailand make greater headway in the scope and coverage of energy efficiency policies and programmes (Byrne et al., 1991).

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

2. 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 - \$22/1C (i.e. savings).

3. 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 (1) (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).

4. 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).

5. For a more detailed discussion on top-down versus bottom-up modelling, reference is made to chapter 8 and 9.

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

7. 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.

8. 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). Obviously, the use of an aggregate figure for fossil fuels (which is mostly coal reserves) should not obscure the fact that the corresponding time span for the individual fossil fuels differs widely. The ratio of proven Reserves to annual Production (R/P) is estimated at about 55 years for natural gas, at about 45 years for oil, and at about 235 years for coal.
9. 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.)
10. This is, because type of transport and combustion technologies are roughly the same for natural gas and hydrogen (H₂).
11. Adopting a 100-year time horizon.
12. 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.
13. $BEP = A / ((MER \times GWP) + A)$, 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.
14. See e.g. Jackson (1991) for an analysis of cost-effectiveness in the UK, explicitly incorporating CH₄-leakage.
15. In this respect, electricity and hydrogen appear as rather ideal intermittent energy carriers from a technological point of view.
16. See e.g. IPCC (1991), Johansson et al. (1993), WEC Commission (1993) or WEC (1994). With respect to the classification of renewables as commonly used, it should be noted that classifying geothermal as a renewable resource is technically not correct as the Earth's core will slowly but surely cool down.
17. 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.
18. 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.
19. 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).
20. 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 *situa*. It should be realized, that this significantly hampers a direct comparison. However, a greater sense of detail was avoided for the purpose of clarity.
21. 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.
22. For an extensive discussion on the nuclear option, see WG IIa, Second Assessment Report.
23. Only relatively minor fossil fuel inputs are used that support the overall functioning of the breed reactor.
24. Recovery of carbon at power plants has the advantage of removing carbon from energy before it is distributed to highly dispersed end-users.
25. As the use of coal and natural gas is predominant in power plants, virtually no technologies are based on oil.
26. In an ICGCC coal is converted prior to combustion. After some intermediate steps, CO₂ and H₂ are obtained. The former can be extracted by absorption at a 98% rate and the latter can either be used directly in the power plant to generate electricity, or as a carbon-lean fuel to be distributed to end-user sectors, like households, industry or transport. Modifying a conventional gas or coal fired boiler comes to changing the oxidant from air into pure oxygen. The gas turbine of an IGCC or a STEG can be modified by changing the combustion medium into a O₂/CO₂ medium.
27. Cost information suggests absorption and oxyfuel combustion to be most attractive. It appears that absorption is cheaper for conventional coal-derived flue gases than for natural gas flue gases. An ICGCC is promising, though it is not clear yet whether it will replace proven conventional pulverised coal-fired installations.
28. In enhanced oil recovery, part of the injected CO₂ reenters the atmosphere, and in food packaging CO₂ is released within days or weeks. Obviously, insofar as CO₂ is released into the atmosphere, these applications, though perhaps commercially interesting, are of no significant long-term interest from an abatement point of view.
29. 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.

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

31. 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.

32. Grubler et al., 1993, p. 499; see also Houghton, 1990.

33. 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.

34. For a detailed assessment of: the subclasses of forestry measures; the potential quantity of carbon that could be conserved and sequestered by forestry measures; the effects of climatic and demographic changes on the potential amount of carbon conservation and sequestration; and the new research directions needed to improve the assessment and development of practical forestry strategies, see also IPCC, Second Assessment Report, WGII, Chapter III.F. Establishment and Management of Forests for Mitigation of CO₂ Emissions.

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

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

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

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

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

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

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

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

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ESTIMATING THE COSTS OF MITIGATING GREENHOUSE GASES

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0. Introduction

Although most of the available literature on the costs of GHG mitigation has been written in the period since 1988, interest in this issue began more than a decade earlier with Nordhaus (1977; 1979) whose contribution was followed by around a dozen pioneering studies. The picture has evolved since then, but it retains two features from this earlier period:

- First, the focus is on CO₂ emissions and the other GHGs are either ignored or treated separately in an ad hoc manner. This is not only due to the importance of CO₂ emissions relative to those of other GHGs, but also to the existence of a strong tradition in long-term energy modeling and energy forecasting, which made possible analysis of the CO₂ emissions associated with energy production and use. Because of the long lead-times required for planning of energy supply systems, and the instability of energy markets (oils shocks, influence of geopolitical considerations, etc.), energy analysts had by the mid-1970s started to develop long-term energy demand and supply models. These models could be used to analyze the CO₂ emissions associated with the energy system simply by adding emission coefficients to the models. Such a modeling capability was not available with respect to other GHGs.
- Second, the structure of the debate was determined very early by the wide range of numerical results about the potential for, and costs of, mitigation: some studies argued that mitigation policies were likely to entail very substantial costs (Nordhaus, 1977; 1979; Manne, 1984), others that the costs would be relatively small (Edmonds and Reilly (1983), and still others that these costs might in fact be negative and bring an overall benefit (Lovins, et al, 1981).¹

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

The resultant controversies about the overall costs of GHG mitigation 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.²

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,³ as well as the more general problems of errors in economic forecasting even over short time horizons (Ascher, 1978; 1990). Part, however, stems from misunderstandings about what economic and energy models are able to capture and about how to use their results. There is a gap between the answers expected by policy makers and the type of information economic models can supply. As discussed below, the lessons of modelling analysis are rather complex and cannot easily be translated into clearcut policies.

Another difficulty stems from the fact that, in the first phase, many agencies have employed models that were not initially designed to shed light on the cost of emissions reductions. Examples would be models with energy sectors so aggregated that it was impossible to

describe a substitution between fossil and non fossil energies, or the use of short term models to simulate medium term impacts. Some of these models are no longer in use; others have evolved through several versions, further complicating the picture. The result of such factors is that part of the apparent diversity of results is simply due to the development of research itself.

These circumstances have created an opportunity for misusing models and their results in public debates. To help avoid either uncritical acceptance or total distrust of current analyses of mitigation costs, this chapter will present a discussion of the critical determinants likely to influence the overall cost of climate policies and of the main methodologies employed to account for them. The purpose is not to have a detailed comparative analysis of the models, but to concentrate on the possible sources of misunderstanding and misinterpretations of the results presented in Chapter 9 so as to facilitate the discussion of their policy implications. We will examine successively:

- the various concepts of costs used in the literature (section 8.1);
- the relationships between economic cost assessments and assumptions about development patterns and technical change which (explicitly or implicitly) underlie any economic scenario used to assess mitigation costs (section 8.2),
- the main methodological approaches for costing assessments, the key assumptions likely to determine the numerical results, and the lessons derived from modelling debates in the energy field and in the forestry sector (section 8.3).

We will not in this chapter discuss methodological issues having to do with integrating cost analyses with analyses of the benefits of mitigation. Discussion of estimates of benefits (i.e. of the costs of climate change) are contained in Chapter 6; while a discussion of issues related to the integration of cost and benefits are discussed in Chapter 10 on integrated assessment. The purpose of this chapter is to provide a basis for a better understanding of the mitigation cost estimates summarized in Chapter 9. These cost estimates need to be compared with the estimates of the benefits of mitigation (i.e. the damages or costs of not reducing net emissions) summarized in Chapter 6 in order to provide the basis for an integrated assessment of the merits of climate control policies (Chapter 10). But the research agenda for the new generation of integrated models will have to address the methodological issues discussed in this chapter.

1. Costs: definitions and determinants:

1.1 How Is Cost Measured?

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

1.2 Taxonomy of Mitigation Cost Concepts

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

First, we have to recall here a classic distinction in economic among marginal costs (e.g. the incremental cost of removing an additional ton of carbon), total costs (the sum of all marginal costs), and average costs (total cost divided by the quantity removed). Confusion can easily result from neglecting these distinctions. For example, the marginal cost of reducing emissions by an additional tonne may be very high in a given scenario while the total and average cost of the relevant emissions reduction policy may be very low or even negative.

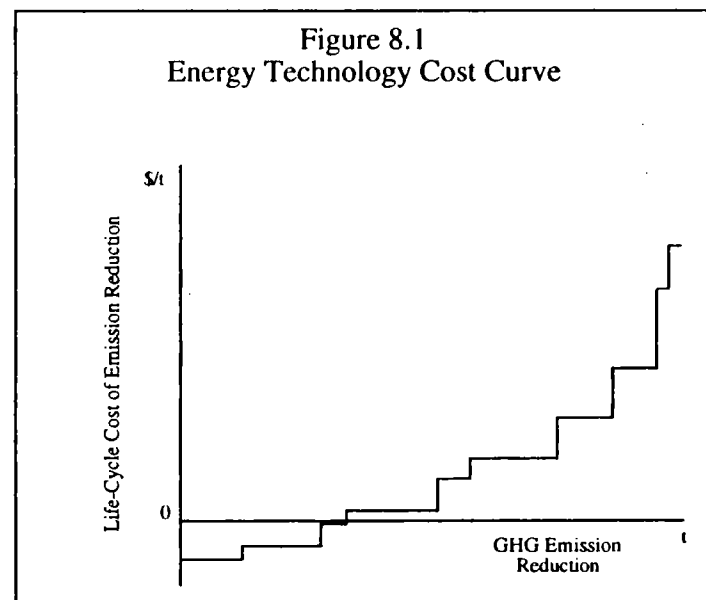
Before comparing any results, attention must be given to the way reduction targets are set because this affects their meaning. Some models calculate reduction from a benchmark date in the recent past; this is the case for most of the US studies in the energy field and for the studies carried out in the other OECD countries on how to stabilize GHGs emissions over the next decade. Others (usually in developing countries studies and very often in long term studies in Europe) set the target in terms of a percentage reduction from an emission level at a given future date. Given expected growth in baseline emissions in the future, a given percentage reduction from a base year typically implies much more total reduction than the same percentage reduction from the future baseline scenario.

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

1. the **direct costs of specific technical measures** to reduce emissions, for example the cost of switching from coal to gas in electric production, of improving the thermal efficiency of existing homes, or of planting trees in reforestation programs. Costs are normally reported in present value terms and can represent the life-cycle cost of the technique used or of the project (the up front cost of the measures considered plus annual energy and operating costs, all reduced to a net present value or levelized costs). These costs depend upon both technico-economic data and a given interest rate and can be used to construct technology cost curves of the kind described in Figure 8.1. They can be calculated in the absence of any global scenario but, as such, they do not provide an economically meaningful cost assessment unless they are fed into coherent technical and economic frameworks. They are the only source of information available for mitigation measures in sectors for which no comprehensive sectoral model has been so far developed.

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

Figure 8.1
Energy Technology Cost Curve



transportation or agriculture models, exist but that they have not yet been used so extensively for analysis of GHG mitigation.

3. **macroeconomic costs** measure the impact of a given strategy on the level of the gross domestic product (GDP) and its components (household consumption, investment, etc.). This aggregate index measures the monetary value added of goods and services produced in single year and provides an index of the scale of human activities that pass through markets plus, by convention, the imputed value of some nonmarket activities (such as the value of services provided by public administration). At this level of cost analysis one tries to account for the interrelationships between a

specific sector and the overall economy. This requires the use of either pure macroeconomic models or modelling frameworks coupling sectoral models and macroeconomic models in order to capture the changes throughout an economy caused by policies in a given sector (what is commonly labelled the general equilibrium effects which are to be distinguished from the partial equilibrium (sectoral) effects).

4. welfare costs GDP variations do not provide direct measures of human welfare. There are many reasons for this. First a climate policy may change the composition, but not the size, of GDP in the direction of higher investments and lower consumption. These changes are invisible to an analysis looking only at the level of GDP. Second, human welfare does not increase linearly with consumption, so consumption changes do not necessarily indicate commensurate changes in welfare. Third, changes in the level of GDP do not account for the relationship between distribution of income and overall welfare. Finally, spending money on disaster relief or environmental rehabilitation enhances economic growth without increasing welfare. The result of these factors is that even GDP does not include all costs of interest, and even general equilibrium models that attempt to measure welfare costs do not include all costs that matter.

The four types of costs outlined here represent increasing levels of generality as one moves from direct financial costs to welfare costs. However, the different levels of cost cannot be aggregated or correlated in any systematic way. For example, ranking efficient technologies in terms of their individual price on the marketplace (direct costs) does not usually reveal the way these technologies will be actually adopted and combined in an economically consistent productive system; for example, a given energy efficiency improvement may not be rationally selected if this improvement occurs in a period of time where the electric supply is in excess. Similarly, a sectoral optimization of a very capital intensive sector may not give results consistent with some form of overall macroeconomic optimum; for example, the amount of money spent in optimized energy supply or transportation systems may prevent investment in other sectors such as education and health. On the other hand, aggregate macroeconomic analysis of costs may not capture important changes to the extent that these changes remain below the level of "noise" of analysis and are not captured by historical variation in the aggregate variables. This typically occurs with respect to the agricultural sector, for example, which represents a small part of overall GDP but often plays a decisive role in the social and spatial equilibrium of a society.

Despite these technical difficulties, progress has been made in incorporating successively broader concepts of costs in GHG mitigation studies, and in accounting for the possibility of significant technological and behavioural change. Two more general problems, however, remain.

The first lies in the fact that, in a number of developing countries and Central and Eastern European countries, the level of government intervention or market distortion (which exists also in OECD countries but not to the same degree) may interfere drastically in the absolute and relative prices of goods and services. This results in distortions between observed market prices of technologies and their "shadow prices" assessed "at factor costs" which would reflect the actual balance between human capabilities, technical potentials, natural resources scarcity and final needs within a given economy. To use market prices is relevant for assessing the likelihood of the adoption of some technical alternatives for a given institutional context⁴; but, if these costs are interpreted as capturing the overall social costs of a given measure they conceal some intrinsic costs of goods and services and can be very misleading.

More empirically and theoretically difficult is passing from GDP costs to welfare costs. In most empirical models welfare cost measures are calculated as the income required to leave a typical household no worse off after a tax than before. In models devoted to analysing the short-term

impact of taxation policies, welfare costs are calculated on the basis of the so-called "Harberger triangle" which demonstrates that welfare losses grow at a higher rate than increases in taxes. These results, however, are not complete measures of welfare costs. In the first place, they generally do not account for the dynamic effects of important policy measures on technology and consumer preferences. In the second place, they depend on market product calculations and do not account for the goods and services produced by non-market and informal economies. Finally, the measure is not unique in an economy with a diversity of household types.

In fact much work remains to be done in attempting to incorporate broader conceptions of human welfare (such as those that are suggested in the United Nations Development Program's Human Development Index) and most of the models reported hereafter ignore such factors. The consequence is that the cost figures provided by current economic modelling studies must be strictly interpreted as estimates of losses (or gains) in the value of new final goods and services foregone as a consequence of the policy, not as estimates of impacts on overall welfare.

Of course, the different kinds of cost estimates discussed here are of great value; the point is simply that before drawing policy-relevant conclusions from even the most general analyses of macroeconomic costs it is important also to examine other indicators (e.g. unemployment, distribution of income, security and political stability).

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

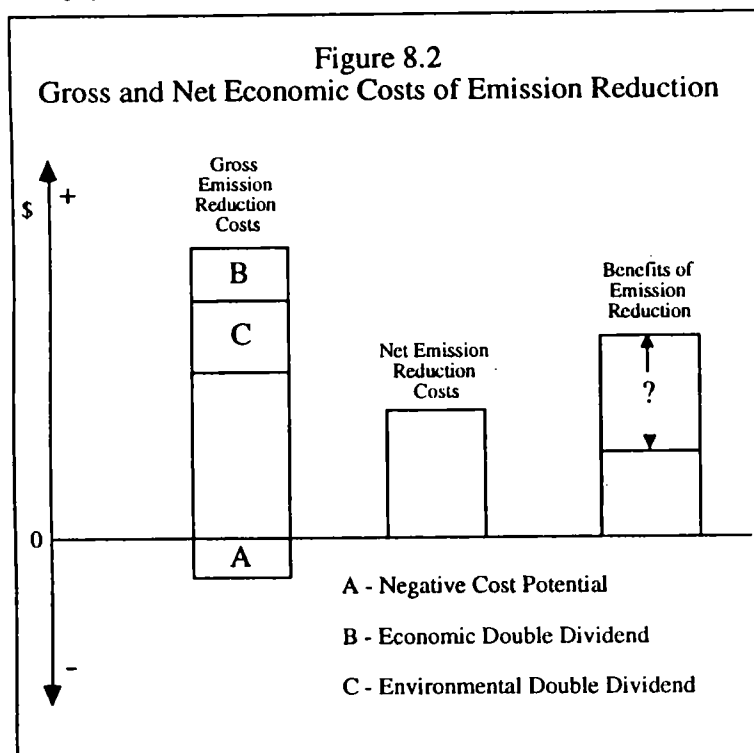
In assessing the costs of mitigation, it is first important to make a distinction between what economists call the gross costs and the net costs of mitigation strategies. The two are different to the extent that there are possible positive side-effects of mitigation strategies that would offset some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

- the **negative cost potential**, namely mitigation caused by technologies whose costs are lower than the technologies currently in use. As discussed further in section 3 below, this issue is controversial since it implies that there are cost-effective mitigation strategies which are not now in use and which will not be adopted in the absence of new policies. Such measures would have a negative net cost, and obviously lower the gross cost of GHG mitigation for a given target.
- an **economic double dividend**, such as the possible positive effects on growth or employment of the recycling of carbon tax revenues or of the technological externalities (i.e. side-effects) associated with fostering research and development programs;
- an **environmental double dividend**, namely the synergy between GHG mitigation strategies and the mitigation of other environmental nuisances such as local air pollution, urban congestion or land degradation, such that GHG mitigation also contributes to reducing these other problems.

The existence of such positive side-effects within a suite of mitigation measures would result in lowering the gross cost of these measures. To the extent that such positive side-effects may totally offset the gross costs of a specific emission strategy, then they represent what has been called a "no regrets potential": measures that are worth undertaking whether or not there are climate-related reasons for doing so⁵. 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 mitigation policy, what matters is the net costs of mitigation strategies, that is gross costs minus any positive side-effects.

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 mitigation policies (or costs of climate change) which are discussed in Chapter 6 above. Instead, these positive side-effects represent items which lower the total cost of mitigation policies and it is the resulting net cost figure (gross cost minus positive side-effects) which is to be compared with the benefits of mitigation policies (whether these benefits are accounted for in terms of explicit monetary values or purely normative mitigation targets). Figure 8.2 aims at clarifying these differences between gross costs and net costs.⁶

Many current economic models account for the first and/or the second category of positive side-effects; very few account for positive environmental externalities.⁷ This is mainly due to practical reasons and one can expect quick improvement in this direction in the near future. In the meantime, it is useful to remember that the studies discussed in this chapter do not include this category of secondary benefit.



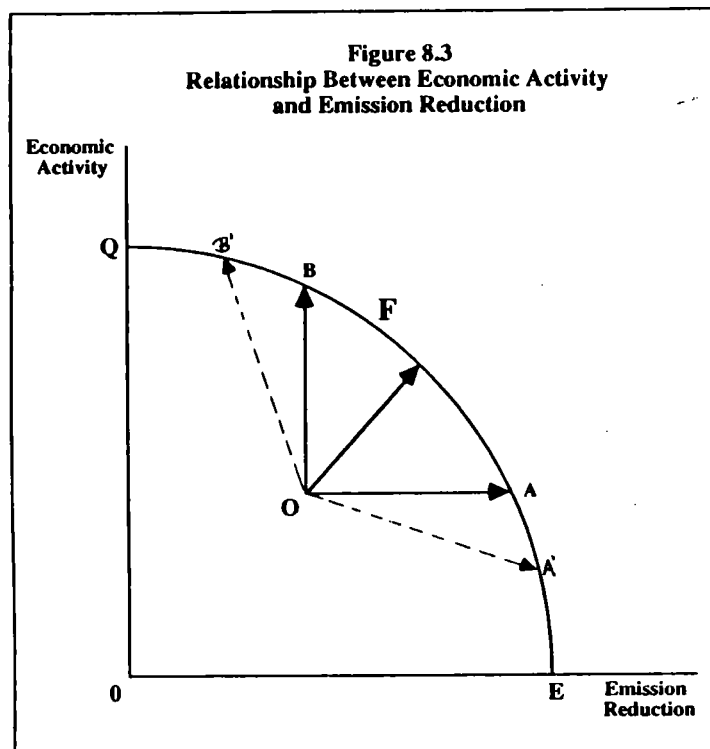
1.3 Key Factors Affecting the Magnitude of Costs: Costs as a Function of Baselines and Policy Strategies:

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

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

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

The discussion of "no regrets" potential has triggered a sensitive policy debate which can be summarized rather simply, though rather abstractly, in graphical form. (See Figure 8.3). To begin, we represent the whole economy as producing two sets of goods and services: (i) a composite good Q, namely an aggregate of all existing goods and services, and (ii) a given level of environmental quality E, represented in this case by a certain amount of emissions reductions. Given such an assumption, then it is possible to construct a curve $F(Q, E)$, called a theoretical production frontier by economists, which represents the trade-off between economic activity (Q) and emission reduction (E). For a given economy at a given time, each point on this curve shows the maximum size of the economy for each level of emission reduction; put another way, it shows the maximum emission reduction for each level of economic activity. If the economy is at a size and level of emission reduction that is below and to the left of this curve (e.g. point O in Figure 8.3), 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 to move somewhere in between, increasing both economic activity and emissions reduction.



From the point of view of cost analysis, a key consideration is what is assumed about the location of the reference or baseline scenario with respect to this curve. If the baseline scenario assumes the economy to be located somewhere on the theoretical production frontier (curve F), it is clear that there is a direct and unavoidable trade-off between economic activity and the level of emissions. In effect, all increases in emission reduction (moving down the surface of the curve to the right) will decrease economic activity (i.e. increase costs). That is, there is no "no regrets" potential: moving up to the left on the curve will increase economic activity but also increase emissions. In such a context, an appropriate policy mix can minimize the net cost of lower emissions but can never offset it totally.⁶ Conversely, in a baseline scenario which describes an economy below the production frontier represented by curve F, no-regret

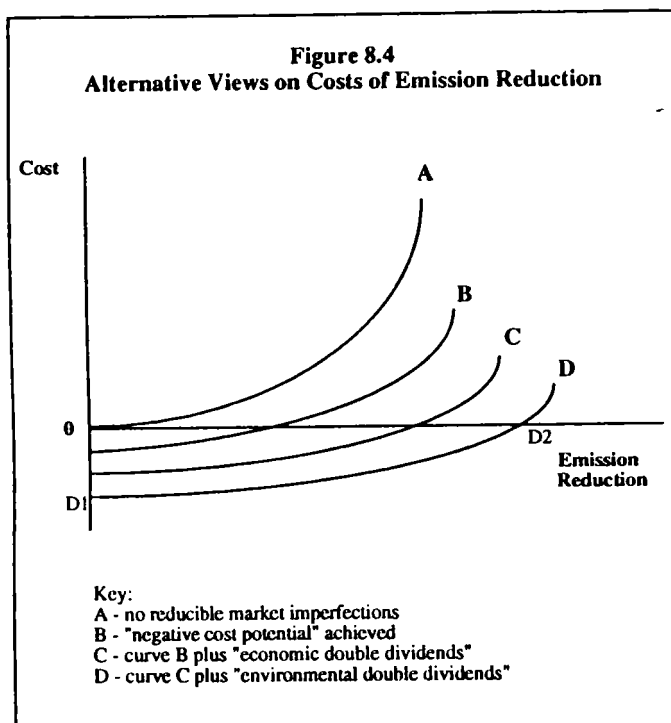
strategies are possible, by moving from O to any point between A and B on curve F. Under these conditions, emissions can be reduced without reducing the size of the economy (i.e. without increasing overall costs) and, possibly can enhance economic activity.⁹

The critical question is then whether the reference or baseline scenario to which mitigation scenarios are compared is on this frontier or not. Assuming "no regrets" potential exists implicitly suggest that any baseline scenario is below the frontier and that appropriate policies would move the economy up towards that frontier. The counterargument is that, if such a potential had existed, it would already have been adopted by the marketplace at least as long as there are no institutional failures preventing market forces from operating. This line of reasoning leads many analysts to assume that any cost-effective emissions reduction is already embodied in any baseline scenario and to locate their baseline scenario on the frontier. In this sense the economic debate is as much about the location and characteristics of the baseline scenarios as it is about the nature and costs of specific mitigation measures.¹⁰

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

In other words, the existence of market and institutional failures that give rise to a "no regrets" potential is a necessary but not sufficient condition of the development of strategies to realize that potential. The latter depends on the existence of significant political desire to realize the potential. In practice, in many fields of public policy-making, countries will consider climate policies in a multi-objective decision-making framework, whereby GHG mitigation policies are likely to be a by-product or joint product of policies developed in part for other reasons. Few costing studies address these complexities.

Figure 8.4 illustrates different views about the relation between cost and emission reduction in the case of a carbon tax. Each curve in Figure 8.4 shows how marginal costs would increase for higher levels of emission reduction, given different underlying assumptions about offsetting policies. Curve A assumes that there exist no reducible market imperfections; thus there are no negative cost potentials. The greater the level of emission reduction, the higher the costs. Curves B, C and D start below the x-axis: they all assume that there exist market failures in the energy, transportation or agricultural systems that can be corrected by emission reduction policies at negative cost. Curve B includes only the "negative cost potential" described in section 1.2.1 above; curve C includes also "economic double dividends" gained by using carbon tax revenues to replace highly distorting taxes elsewhere in the economy; curve D includes also the "environmental double dividend" represented by the other environmental benefits induced by GHG emission reduction. The overall potential for no regret policies is represented by the line OD₁. The area OD₁D₂ is the potential net benefit to society of implementing all of the "no regrets" measures. Some analysts have argued measures with a positive cost should be implemented to the point where the total net cost to society is zero, i.e. to a point D₁ > D₂ such that the area under curve D between D₁ and D₂ is equal to the area OD₁D₂.



1.3.2. Target setting: Level and Timing

The growth rate of CO₂ emissions is determined by the growth rate in GDP, the ratio between GDP and the required level of end-use services (energy, transport, food), and the level of GHG emission per unit of each of these services.¹¹

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

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

For given assumptions about technical progress the time profile of the abatement may be a key determinant of differences in cost estimates. In discussing these timing issues, a key distinction is between the transition period and the backstop period.

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

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

1.3.3 Policy Instruments

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

To date the focus of macroeconomic models has been on carbon or energy taxes, while the focus of new generations of sectoral technico-economic analysis has been on the impact of other types of incentive instruments. However, significant differences also exist within these broad categories of models. For example, critical differences in the outcome of different macroeconomic models come from the way the revenues of a carbon tax are recycled in an economy. In the earlier models, many simulations were made assuming no recycling which amounts to treating a carbon tax as an external shock such as an oil shock, and places an upper bound to the macroeconomic costs. In later analyses, most of the models represented recycling in the form of a lump-sum process, namely without modifying the rest of fiscal structure; this makes the comparison easier but does not describe the recycling techniques which have the highest probabilities of being implemented. In a third step, models tried to exemplify other ways of recycling a tax by changing the level of payroll taxes, income taxes, corporate taxes or simply by reducing public deficits. This methodological development complicates comparisons because the outcome depends on the ways the existing distortions of fiscal structures (or subsidies) are accounted for in the baseline; but this is more meaningful from a policy-making viewpoint. These differences among different macroeconomic modelling analyses are a major determinant of differences in the existing macroeconomic studies.

1.3.4. International Dimensions of Climate Policies:

The last parameter determining the cost figures provided by the model is the nature of the assumptions made about the international context of climate policy.

On the one hand, unilateral reduction of GHGs may negatively affect the competitiveness of national industries and create a "leakage" of GHG emissions from one country to another. This "leakage" occurs if mitigation 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 mitigation policies gain a comparative advantage due to lower costs, thus increasing their output and thereby their emissions relative to countries with mitigation policies.

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

2. Patterns of Development and Technological Change

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

2.1. Links Between Development Patterns, Technical Change and Mitigation Costs

2.1.1 The Importance of the Socio-Economic Assumptions Underlying Scenarios

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

It is well known that countries with rather similar development levels may have very different energy consumption per capita ratio, or very different transportation requirements. Some of these disparities are obviously due to natural and geographical characteristics (temperature, population density, etc.), but many of them stem from differences between the development patterns of these countries. Comparative studies aiming at explaining these differences (Martin, 1992; Darmstadter, et al, 1977) suggest the importance of five considerations that will influence the amount of GHG emissions, given a certain overall rate of economic growth:

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

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

- *the geographical distribution* of activities, which encompasses the distribution of human settlements in a given territory, climate impacts on energy demand and the nature of urban form within a given settlement. The impact of this parameter is threefold: first on the evolution of land uses, second on mobility needs and transportation requirements, and third on the energy used for heating and cooling;

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

9 - *trade patterns*: it is generally argued in the economic literature that removing tariff
10 and non-tariff trade barriers enhances overall economic efficiencies. But, because historical
11 experience demonstrates that some form of protectionism was necessary to many countries at
12 the early stages of industrialisation, and because of the transition problems for removing these
13 barriers (risks of social and economic disruptions), free trade will be implemented only
14 gradually after the Uruguay Round. In the meantime, the world is apparently moving towards
15 the creation of regional trading blocks (European Union, NAFTA, Mercosul). The future of
16 these arrangements is very hard to predict and will alter significantly the access to the best
17 available technologies, the capacity of developing countries to generate high enough internal
18 capital accumulation to finance infrastructures and education, the location of industrial activities,
19 and future land uses (because of the impact on agricultural markets).

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

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

42 More fundamentally, the dynamics of long-term technological development cannot be fully
43 captured by changes in the capital output ratio (the aggregate amount of economic capital used
44 per unit of output) and by the impact of the rate of investment on overall productivity. These
45 parameters are of course important but the outcome in terms of GHG emissions will also
46 depend upon dynamic linkages between technology, consumption patterns (mainly as regard to
47 energy requirements), transportation and urban infrastructure, urban planning or rural-urban
48 distribution of population. We will come back later to the attempts of existing models to take
49 these parameters into account but the lack of knowledge available about their dynamic linkages
50 and about their interactions with economic policies and economic signals over the long run
51 must be underlined at this stage, together with the intrinsic difficulty of predicting innovations

1 and transformations of lifestyles over the long run. While many fields of social science address
2 these issues, such information is not typically available in a form easy to process in a numerical
3 model.

4 In principle, alternative configurations of the factors determining development patterns could be
5 formally combined to give internally consistent scenarios characterized by various physical and
6 technical characteristics and economic equilibria for a given rate of economic growth. But this
7 does not mean that all of these possible scenarios are viable and that it is possible to achieve a
8 transition towards these long term pictures without entailing high social and economic costs.
9 What matters here is that these underlying technological and consumption pattern factors are
10 critical not only for the definition of the baseline scenarios but also for the assessment of actual
11 mitigation costs for a given mitigation policy or objective.

12 As explained earlier, the mitigation costs attached to each possible baseline scenario depends
13 not only on the absolute level of the required mitigation and on the array of available
14 technologies (energy efficiency, fuel switching, biomass planting, modal choices in transport)
15 but also on the timing of this mitigation (Grubb, et al. 1994; Hourcade and Chapuis, 1993;
16 Manne and Richels, 1992). In this connection, three groups of partly related issues become
17 very important:

18 - *the flexibility (conversely inertia) of consumption patterns* underlying the
19 activity of GHG-emitting sectors such as energy, transport or cement. This flexibility
20 parameter determines the speed of adaptation to a given economic or non economic signal and
21 encompasses two aspects. The first one is the rate of renewal of existing end-use equipment,
22 which is likely to be an important factor in the case of buildings, which have longer lifetimes
23 than most capital stock. A more critical inflexibility stems from the systemic linkages between
24 consumption patterns, technology and the spatial distribution of activities. To take an extreme
25 illustration, it would be far more costly to move away from oil-based automobile fuels in big
26 conurbations where urban structure makes the use of cars almost compulsory than in, say, a
27 European town of about 40 000 inhabitants where it would be easier to satisfy a significant
28 proportion of intra-urban personal transportation with electric buses and bicycles. The second
29 aspect is the length of time required for turnover of the energy supply system. In this
30 connection, the flexibility of policy response is associated with the size and lead times
31 associated with new energy supply technologies.

32 - *behavioral characteristics* which determine technical change and the evolution of
33 life styles; this point will be elaborated further as regard to technical adoption mechanisms. As
34 regard to consumption patterns, the roots of inertia are not only technical; anthropology and
35 social psychology demonstrate how far they are embedded in cultures, habits and, more
36 generally, how individual consumption behaviors are shaped by social determinants hard to
37 change overnight (Robinson, 1991).

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

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

A special case for inertia in development patterns occurs when such inertia creates irreversible processes of technological change. To a large extent such irreversibilities emerge out of the factors traditionally discussed in the literature on technical innovation: learning curves, economies of scale, increasing informational returns, positive network externalities, barriers to entry, etc. Irreversibility occurs when these factors combine such that a particular trajectory of technological change and development is created, which effectively makes impossible alternative choices that were available earlier. This gives rise to a time dependence of technical choices and the occurrence of "lock-in" effects (Arthur, 1988). 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 R, D and D risks will be incurred simultaneously on electric cars, 2l/100 km gasoline engines and 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 systems (combined rail-road versus road dominant) and will certainly have gone beyond a bifurcation point (Hourcade, 1992). A similar choice is to be faced in the near future in many of large developing countries with far more dramatic consequences, as decisions are made how to expand road, rail and air networks to respond to large increases in the demand for personal mobility and freight transport.

2.1.2 Current and Future Socio-Economic Development Patterns

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

(i) Material and energy content of development in industrialized countries

An important determinant of GHG emissions in any economy is the raw material intensity of that economy: the amount of matter and energy used per unit of economic activity. Broadly speaking, for any given level of economic activity, the lower the raw material intensity, the lower the GHG emissions. Over the past several decades, the raw material intensity of industrialized countries has dropped significantly (Bernardini and Galli, 1993; Williams, 1987). 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 (IAEE, 1993).

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 services (Chen, 1994);
- the effects of telecommunications on travel and transportation energy use (Selvanathan and Selvanathan, 1994);
- 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 mitigation costs per unit of economic activity (e.g. dollars per unit GDP) will depend on both the mix and level of such intensities and will necessary vary among economies with different structures.

(ii) Links among energy, transport and urban planning

Transportation energy use accounts for a significant proportion of GHG emissions¹³ and its growth rate is typically higher than for other categories of energy demand. More critically it is the only form of energy use not drastically decoupled from economic growth after the oil shocks. This does not demonstrate that prices effects are nonexistent in this sector but that they interact with other structural determinants. In the U.S., for example, energy efficiency gains in private automobiles over the 1970s and early 1980s were almost exactly offset by increases in distances driven per vehicle, so that total energy use remained flat (Schipper and Howarth, 1990). In the transport sector, the size and type of GHG emissions are 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 (Newman and Kenworthy, 1989). Important factors 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; and
- 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 (Ross, 1989). 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 mitigation. 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 (Grübler et al, 1993). In the metropolitan area of Sao Paulo, for instance, most of the increase in atmospheric pollution has been attributed to increased congestion, as indicated by a reduction in the average vehicle speed from 28 kilometers per hour during the eighties to 20-24 km/h in 1993 (CETESB, 1994).

Clearly, quite different configurations of these factors can be envisaged and transportation is typically a field in which bifurcations towards contrasted paths may occur in any region of the world and these alternatives would have major impacts on mitigation options and costs. As

suggested earlier, the costs of transportation sector mitigation for a population that is dependent 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 and a high uncertainty stems from the long run impact of short term decisions (or non-decisions).

(iii) Land use and human settlements

This issue concerns all the regions of the world but its quantitative impact is more impressive in developing countries. 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 these countries. Deforestation in most developing countries is a complex phenomenon mainly caused by the expansion of the road network, logging and cattle raising activities, agricultural production and population growth fostered by rural-rural migrations due in some cases to the absence of guaranteed access to land (agrarian reform) in other regions.

These examples show that mitigation 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 mitigation strategies feasible.

In this field it is even more important than elsewhere to look at the "GHG mitigation component" of more general development strategies instead of considering GHG mitigation measures on their own. Mitigation 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.

(iv) Development patterns in developing countries

The importance of development pattern assumptions for the assessment of mitigation 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 countries and how that structure might evolve given such global transformations. A crucial question regards the developing countries' share of the world production of highly energy- and pollution-intensive goods, such as steel and aluminum. For example, as the recent shift of heavy industries from the North towards developing countries begins to slow, economic output may increasingly come from services and other less energy intensive activities.

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

Finally, the spatial distribution of the population and economic activities is still not settled in most developing countries, offering the possibility of adopting urban/regional planning and industrial policies directed towards rural development and a stronger role for small and medium cities, thus reducing the extent of rural exodus and the degree of demographic concentration in large cities.¹⁴ But, given current heavy trends towards huge conurbations, it will be difficult to shift them over the next century; we are faced here with a large degree of socio-economic inertia that can be overcome only gradually through steady long term policies. For example more decentralized development patterns than typical of industrialized countries could facilitate tapping the large amount of natural resources available in developing countries through the use of modern technology (biotechnology, solar energy, wind and small scale hydro power). In the same ways it could change the needs for transportation.

These examples show that developing countries might be in position to adopt anticipative strategies directed to avoid in the long-term some of the problems faced today by industrial societies. For example, in industrialized countries, energy demand/GDP elasticities first increased with successive stages of industrialization (with an acceleration during the fifties and sixties), but have sharply decreased since then, due to a number of different factors: relative growth of services in the share of GDP, technical progress induced by higher oil prices and energy conservation efforts, etc. (Martin, 1988; Darmstadter, et al, 1977). 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") (Berrah, 1983).

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

very often the lack of appropriate institutions to use the indigenous technical and economic capabilities of these countries.

This means that switching to very different development patterns than customarily assumed will depend upon the removing of these barriers, the setting up of an appropriate context by national public policies, and the evolution of international economic relationships. Development theory has not yet provided the analytical tools needed to enable modellers to discriminate among such different development patterns.

2.2 Modeling Development Paths and Mitigation Costs

It is clear from the preceding discussion both that underlying socio-economic conditions will have an important effect on future GHG emissions and the costs of mitigation, and also that there exists great uncertainty about how those conditions may evolve over the next century. The extent of these uncertainties is such as to cast some doubt on the ability of models to predict long-term development patterns. On the other hand, it has become more and more important to have a scientific understanding of the implication of possible long trends. It is in the context of this tension between uncertainty and the need to act that we have to assess the meaning and lessons of modelling analyses.

2.2.1 Prediction and Simulation: The Need for Multiple Baselines

In coming to grips with the uncertainty of long-term projections, it is important to recognize that that uncertainty goes beyond the uncertainty that is associated with any given emissions forecast or scenario. The point is not 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 underlying socio-economic development paths that would give rise to different emissions scenarios and costs of mitigation. 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 the set of long-term development paths. Such bifurcations can be triggered by short-term decisions and actions that are not predictable.

The logical implication of this is the necessity to use multiple scenarios in order to account for uncertainties with regard to development patterns and the possibility of what economists call "multiple equilibria" in the long term. At time "t", there are several possible market equilibria at "t+n" (i.e. several states of the world characterized by different technical contents), and these are not easily predictable from current trends. From a pure analytical perspective it is possible to resort to some subjective or logical probability distribution in order to narrow these uncertainties among different scenarios and provide some kind of average scenario. But this could be misleading for decision making. The point is that these alternative base cases represent quite different, and internally consistent, patterns of development. Many of the uncertainties about such scenarios are due to the long term consequences of short term decisions or behaviours, and to the collective expectations regarding time "t+n" prevailing at time "t". In turn, these decisions, behaviours and expectations are part of a particular sequence of events, and cannot simply be combined with the components of other such sequences to produce an "average" or "most likely" sequence.

These concerns about the predictive value of models and the existence of possible multiple economic equilibria and their logical implications for policy-making are not new in various fields of socio-economic modelling. The origin of these concerns lies in the recognition of the

limits of empirical forecasting methods that appeared by the end of the 1960s. This led to the development of approaches which tend to emphasize the unpredictability of alternative futures, the degree to which they are subject to partial choice, and the need for analysis of multiple alternatives.¹⁵ In the energy field, approaches based on the concept of multiple scenarios were pioneered by Shell International Petroleum Company in the early 1970s (Wack, 1985a, 1985b), and have been adopted in various forms in the electric utility industry in North America (Southern California Edison, 1988; Northwest Power Planning Council, 1991). 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 (FRN, 1987; Stockholm Environment Institute, 1997; Robinson and , 1997).

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* (Meadows, et al. 1972)¹⁶, the publication of which stimulated a extensive debate about alternative development paths. This debate was fueled by the publication of a number of subsequent studies (Mesarovic, 1974), including the Leonticff report launched to illustrate the International Development Strategy adopted by the United Nations in 1974 (Tinbergen, 1976). 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 (Amilcar, et al. 1976).

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 (Ford Foundation, 1974), Amory Lovins' provocative "soft energy path" analysis (Lovins, 1977) helped to launch many exploratory works in North America (Craig, et al. 1978; Sant, 1979; CONAES, 1980; Stobaugh and Yergin, 1979; Ross and Williams, 1981) and in many European countries (Johansson and Steen, 1977; Leach, 1979; Norgard, 1979; Krause, 1981; Messenger, 1981; Olivier, et al 1982) about the possibility of avoiding possible physical limits and nuclear risks. These studies were based upon what came to be called "bottom-up" methods of analysis and produced energy system projections that were significantly at odds with the "top-down" analyses prepared by governments, the energy industry and energy economists¹⁷ relying on extrapolatory approaches. In the early 1980s, the publication of the results of the IASA energy study (Hafele, 1981) sparked a vigorous debate about both modelling methods and alternative energy futures (Kecpin and Wynn, 1987; Thompson, 1984). 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 Development (1987), and the subsequent UN Conference on Environment and Development in 1992.¹⁸ Throughout this period, a major bone of contention has been how best to analyze alternative patterns of development and technological change that represent significant departures from past trends.

These debates are not restricted to applied analyses. They have been raised in many fields of social science theory concerning such issues as the plurality of economic equilibria generated by different sets of expectations (such as the works about the so-called "sunspot theory" (Azariadis and Guesnerie (1986)); self-fulfilling or the self-defeating prophecies (Henshell, 1977); "common-knowledge" and "conventions" (Lewis, 1969); the coordination game (Schelling, 1960) or, more generally the outcome of repeated games in game theory (Fudenberg and Tirole, 1991); and chaotic behaviour and surprises. The general point is that there is a rich history of approaches to modelling that emphasize the importance of

incorporating alternative development paths and multiple base cases. As yet such approaches have made only a modest impact on GHG costing studies.

2.2.2 Economic Modeling and Development Trends: Some Limits

There is perhaps an unavoidable gap between advanced thinking in social science theory, and the empirical tools available, given computational constraints, data availability and the priorities adopted by research funding institutions. Nevertheless, over the past two decades the state-of-the-art of long-term policy-oriented energy system modeling has evolved very rapidly, due in large part to significant progress in energy-economy modeling. This progress has been driven by questions raised by the oil shocks of the 1970s, perceived risks of resource exhaustion, the nuclear debate, and climate change issues.

Progress has also been made in modelling other sectors such as transportation or agriculture. However, less attention has been paid in this work to the linkage between sectoral analysis and a more comprehensive economic framework than in energy sector analyses, where policy-makers have been very interested in the macroeconomic imbalances caused by oil imports and price increases (external debt, inflation, and unemployment). Moreover, the initial focus on energy-related GHG emissions has meant less attention has been paid to the GHG emissions of other sectors. As a result, the state-of-the-art of modelling in the energy field serves as a useful indicator of the difficulties of representing alternative development paths in current models.

Macroeconomic econometrically driven "top-down" models, initially build for the purpose of economic policy analysis, usually contained rather aggregate sectoral demand functions (one or two energy services, one composite food product, for example); they consequently capture future development and technological trends in the econometric relationships among standard econometric indicators. Using them in long term analyses amounts to extrapolating current trends in the relationships among key variables, on the assumption that historical changes in these relationships capture the essence of likely future responses to changes in input variables such as the future price of energy, food or wages. Such analysis provides very useful "counterfactual" information on, say, the aggregate impact of a carbon tax relative to some assumed base case, but they do not pretend to have a predictive value on the very long term or as regards to, say, bifurcations in the transportation sector.

"Bottom-up" models have historically been designed for the specific needs of a given sector (e.g. energy, transportation, forestry), and in the energy field are sometimes linked to standard macroeconomic models. They give a disaggregated picture of demand and supply, and point out potential gains in efficiency from specific technologies or the potential for substitution to carbon free technics. Such models rely on rather precise descriptions of end use and production technologies (e.g. appliance penetration and usage rates, building heat loss coefficients, tonne-kilometers of freight transportation), but typically do not contain much treatment of feedbacks between these parameters and underlying economic variables (for example feedbacks between energy efficiency savings and employment, or consumption behaviour for other goods and services). The lack of macroeconomic behavioural feedbacks means that such models are best suited for "what if" simulation analyses, rather than prediction.

Virtually all of the modeling analyses of GHG mitigation undertaken to date have used some form of these two approaches to energy/economy modeling or of coupled models. We will enter a more detailed discussion of the difference between these approaches in section 3 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 just been identified. Instead, the models have been used to analyze the effect of certain policies (typically tax policies in the case of top-down models, and the implementation of specific energy-using technologies in the case of bottom-up models), given implicit assumptions about development paths.

This suggests that existing mitigation cost studies are meaningful primarily 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 a mitigation strategy and the overall development pattern (bottom-up analyses).

2.3 Multiple Baselines, Uncertainty and Long-Term Mitigation Costs

The preceding discussion explains why there is a growing consensus among experts on the necessity to work with multiple baseline scenarios when long term horizons are under consideration. Such scenarios would represent different internally consistent sets of assumptions concerning the factors discussed above rather than simple variants of a base case generated by altering input parameters of a given model. The point is not to predict what long-term outcomes are most likely (an exercise at which few have been successful (Ascher, 1978, 1990)), 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.

The limitations of current methodologies heightens the need for making explicit what type of structural determinant is explicitly accounted for in each baseline scenario and what type is considered as fixed. There is need for more 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. However, 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 mitigation strategies.

Beyond these technical difficulties we would like to emphasize two major issues stemming from the existence of several baseline scenarios.

2.3.1 Multiple Baselines and the Non-Comparability of Cost Assessments

Given that contrasted underlying assumptions about development patterns can give rise to a number of quite different types and levels of GHG emissions, and of mitigation costs and potentials, a comparison between cost assessments theoretically requires an evaluation of baseline and mitigation scenario assumptions, including technology data.¹⁹ Such an evaluation should identify key determinants and assumptions behind the cost estimates in order to explain differences. Without a comprehensive and transparent documentation of the full set of scenario assumptions, any comparison of cost estimates coming from studies with very different baseline scenarios, will be misleading. For example, a mitigation scenario derived from a baseline scenario that incorporates substantial air quality improvements for reasons unrelated to climate change is likely give rise to GHG mitigation cost estimates per unit of reduction higher than a mitigation scenario derived from a baseline scenario without such improvements.²⁰ Similarly, mitigation 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 mitigation costs cannot be interpreted as being economically superior to other baselines.

Such lower cost estimates simply mean that the incremental costs of mitigation 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. Two historical examples help to illustrate this problem is far from being a simple intellectual fancy.

If the climate debate had emerged in 1973, just before the decision to launch the nuclear program in France, any assessment of mitigation 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 mitigation costs; and
- the second including a nuclear program and a resultant lower emission level; the mitigation requirements would have been lower, but paradoxically the costs of an incremental emission reduction of, say, 20% would be far higher.

Beyond the fact that assessing the relative costs of two totally different energy systems is technically difficult (for example in the non-nuclear case France would not have developed electrical heating to the degree it did), the critical point is that the nuclear choice would not have been made, in practice, purely for climate-related reasons and that in any negotiation the French administration would have tend to argue the contrary so that this program would have been considered as a specific contribution to a collective climate policy.

In the opposite direction, both the baseline and mitigation scenario are very different in the Brazilian case depending upon assumptions about the future of its biomass ethanol program. Even though, when it was first implemented in 1975, no environmental factors were taken into account for its justification, the existence of this program can be shown to lead to both a lower emissions baseline and lower mitigation costs. So far, many questions are still pending with regard to the overall costs and benefits of this program in terms of macroeconomic impacts, distributional effects, refining structure of oil or innovation, which makes it difficult to project the likely future of the program. And 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.

In both cases, the best analytical strategy is to recognize that different baselines are possible and that any mitigation cost estimates are only relevant at the margin of each baseline, not in absolute terms.

2.3.2. The Meaning of the Baseline

The function of baseline scenarios in cost studies is to provide a basis of comparison for calculation of mitigation costs. It is important to bear in mind that such baselines pose a somewhat artificial distinction between a notional "business as usual" case (i.e. what would happen if no mitigation policies were instituted) and a "policy intervention" case (what would happen if they were). Such a procedure is required to obtain a basis of comparison and thus an estimate of the costs of such intervention but, in principle, it does not imply anything about the likelihood or relative economic efficiency of the baseline compared to the intervention case.

A similar problem emerges with respect to the conventional distinction between adaptation to, and mitigation of, climate change. In the short term, the meaning of that distinction is clear: mitigation means reducing sources of emissions and/or increasing sinks (i.e. reducing the

causes of climate change), while adaptation means improving our capability to withstand changes in the global climate system (i.e. responding to the effects of climate change). In the longer term, however, the distinction between mitigation and adaptation begins to blur. Not only will measures adopted to serve one goal have significant consequences for the other (e.g. some energy efficiency measures adopted to reduce emissions may make energy systems more resilient to climate variability) but many policies adopted for other reasons will have both adaptive and mitigative effects (e.g. urban planning decisions).

Indeed, in the long term, both "mitigation" and "adaptation" measures are part of the long-term adaptive responses of societies to a whole host of conditions and perceived problems, only a small number of which have to do with climate change. From this point of view, the distinction between baseline and intervention scenarios is particularly artificial. Their importance lies in the difference between them, not in the plausibility or likelihood of either as a forecast.

3. Differences among Models and their Results

3.1 General Methodological Considerations

We have suggested that existing models do not generally address in an effective way questions of alternative paths of technological development. Yet even without the variation that consideration of such factors might be expected to induce, the range of results in GHG mitigation costing studies is very large. It is difficult to disentangle the various reasons for these disparities in modelling results, given (1) the diversity of tools used to calculate cost estimates, (2) the many and varied assumptions employed, and (3) the disparities in geographical coverages of different studies.

Historically the debate in the energy field has been framed by the distinction between "top-down" and "bottom-up" studies, a distinction that can be applied in other fields as well. Basically, top-down models analyze aggregated behaviours based on economic indices of prices and elasticities; these models began mainly as macro-economic models that try to capture the overall economic impact of a climate policy, that policy being usually in the form of a carbon tax because of the difficulty of assessing other types of policy instruments. Bottom-up models, on the other hand, rely on detailed analysis of technical potential, focusing on the integration of technology costs and performance data.

In fact, as suggested above, not all models fall neatly into one of these two categories and several "hybrid models" are now available in which analysts attempted to merge top-down and bottom-up model characteristics. As a result, differences in findings are increasingly the effect of differences in input assumptions rather than differences in model structure. However, the discussion in this text will maintain the dichotomy to the extent that this distinction remains meaningful for understanding some critical policy issues.

The top-down/bottom-up categorization has been portrayed as opposing the optimism of the "engineering paradigm" to the pessimism of the "economic paradigm" (Grubb, Edmonds et al 1993). From an engineering standpoint the evidence is that the best available technologies have not been adopted so far; this "efficiency gap" is the gap between the energy efficiency of equipment actually chosen by consumers and the energy efficiency of the technology that could theoretically minimize the costs entailed in providing a given amount of energy service. Bottom-up models are able to demonstrate the existence of such an "efficiency gap" and thus they suggest that, thanks to "negative cost measures", substantial emission reductions could be achieved with low taxes and low costs or even net savings.

In response, the professional reflex of many economists was to call attention to the reasons why consumers do not adopt technologies that appear to be optimal, and to suggest that accounting for these reasons together with the economic feedbacks of a given policy would reduce the magnitude of, or eliminate, the efficiency gap that is actually achievable. Top-down macroeconomic models concluded, at least in early analyses, that relatively large carbon taxes would be required to counter current emission trends, which would result in significant economic costs.

The methodological difficulties lying behind these differences are how to describe the processes of technology adoption, the decision making behavior of economic agents, the feedbacks between any public policy measures and the overall economy, and how markets and economic institutions actually operate over a given period of time. From this viewpoint the opposition between "top-down" and "bottom-up" methodologies does not fully represent the whole spectrum of critical issues. That is why, before discussing the lessons of the top-down and bottom-up debate, we will sketch the dimensions of a typology of existing models. Given

the prominence of energy/economy models in the field, we will concentrate upon them. However, many of the methodological issues are quite general and similar arguments could be applied to models of other sectors, such as forestry.

3.2. Critical dimensions of a typology of existing models

Various attempts have been made to categorize the large variety of models that have been used to analyse the costs of reducing GHGs emissions²¹. Instead of providing a new and necessarily arbitrary typology we will try here to provide a description of the main characteristics that differentiate these models, in order to make clear what each type of model describes, and what kind of policy question it can best address. In order to accomplish this, we will focus those characteristics which have to do with the purposes of the models (i.e. the questions they are meant to address), their structure (i.e. those assumptions that are embedded in the equation system) and the external assumptions (i.e. assumptions expressed in terms of inputs to the models). Because few if any individual models represent pure types within these categories, we have not referenced specific models. Instead the goal here is to provide a general framework to aid in interpretation of the specific modelling results presented in Chapter 9.

3.2.1 Diversity of models, diversity of purposes

Significant misinterpretations of the results of modelling studies can arise from overlooking the purpose of the analysis. The meaning of the numerical results of a model will differ depending upon whether a given scenario is used to predict (forecast) the future, to explore it, or as a tool for "backcasting" exercises.

Many models try to "predict" (forecast) the future and to provide an estimate of the most likely set of future events. This purpose imposes very strict methodological constraints on the modeler. He or she must produce 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 successfully, for an economic modeler, requires that it is possible to derive econometrically from current trends 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 short-term, econometrically driven macro-economic models adopt this approach; for the long-term (middle of the next century), the Jorgenson-Wilcoxon model is the only such model 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.

Because of the difficulty in extrapolating past trends over the long run, the purpose of some modellers is to "explore" the future and in so doing to provide counterintuitive assessments. This leads to a scenario analysis approach, 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 about economic behavior, physical resources endowments or technical progress together with assumptions on economic or population growth. 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" scenarios, 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 (Leggett, et al, 1992). It is shared by both bottom-up and top-down models²² 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 simulate predictively real world behavior in terms of technology adoption.

Finally, another possible purpose of 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 in so far as it 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 (Robinson, 1988, 1990). 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 belonging to this category. But it is also possible to use a backcasting methodology as a purely analytical tool by simply linking bottom-up analyses about the long-term evolution of technology and development patterns to a macro-economic framework (Hourcade, 1993), so as to be able to assess the economic consistency of different and competing views about the long run.²³

These three different purposes have implications for the types of models that are required, the analytical questions being asked, and the meaning of the results. As discussed in section 2.2.1 above, there has been a historical correlation between attempts to move away from predictive modelling approaches and the early development of bottom-up models; these models were in many cases built precisely in order to undertake simulation and backcasting analyses not possible with the current generation of top-down models (Baumgartner and Middelton, 1987; Robinson, 1982b). The greatest emphasis in current climate modelling efforts is on "exploratory" analyses, using a combination of top-down and bottom-up methods, but there continues also to be interest in "backcasting" analyses aimed at exploring quite different future scenarios than would otherwise be examined (FRN, 1987; Stockholm Environment Institute, 1997; Robinson and , 1997).

3.2.2 The Structure of Existing Models

A second basis for distinguishing among different models is the nature of the model itself (i.e. those assumptions that are embedded in the mathematical structure of the model). At a very general level, it is possible to characterize some of the main structural differences among existing energy and emissions models in terms of four main dimensions. This description abstracts from a number of more detailed distinctions among models but captures the points that differentiate the models in a way that helps to show the connection between model structure and policy questions (see the next section for a more detailed discussion in the context of the top-down/bottom-up modelling debate). These four dimensions, and some of the related policy questions, are sketched in Table 8.1 for energy/economy models. An equivalent typology could be applied to models focussing on other sectors (e.g. forestry).

Table 8.1
Key Structural Characteristics in Energy/Economy Models

Structural characteristics	Policy Issues
1. The degree to which behavioural relationships are endogenized in the model equations, or left to be supplied as exogenous assumptions	Models that endogenize behaviour are suited to predict actual outcomes; those that exogenize it are more suited to simulate the effects of changes in historical patterns
2. How detailed the description is of the non-energy sector components of the economy (investment, trade, consumption of non-energy goods and services, income-distribution, etc.).	Models that describe these sectors in more detail are more suitable for analysing the wider economic effects of energy policy measures)
3. How detailed the description is of energy end-uses	Models that describe these end-uses in more detail are more suitable for analysing the technological potential for energy efficiency
4. How detailed the description is of energy supply technologies	Models that describe these end-uses in more detail are more suitable for analysing the technological potential for fuel substitution and new supplies.

Each of the four structural characteristics shown in Table 8.1 represents a spectrum from more to less, and individual models can be located on that spectrum for each dimension. This means that individual models are more or less suited to answering particular policy questions, depending on where they are located on the spectrum for each dimension. Traditionally, top-down models represented one end of the spectrum on each of these dimensions, and bottom-up models the other, as illustrated on Table 8.2.

Table 8.2
Key Structural Distinctions Between Bottom-Up and Top-Down Models

Structural Dimension	Early Models		More Recent Models	
	Top-Down	Bottom-Up	Top-Down	Bottom-Up
1. Endogenization of Behaviour	HIGH	LOW	HIGH	(MORE)
2. Detail on Non-Energy Sectors	HIGH	LOW	HIGH	(MORE)
3. Detail on Energy End-Uses	LOW	HIGH	(MORE)	HIGH
4. Detail on Energy Supply Technologies	LOW	HIGH	(MORE)	HIGH
5. Predictive Orientation	HIGH	LOW	(LOWER)	(HIGHER)

It is clear from Table 8.2 that the early top-down and bottom-up models represented virtual mirror images of each other, with respect to the four characteristics shown on Table 8.1. Bottom-up models tended to describe the energy system in great detail, with little endogenization of behaviour, or description of other parts of the economy. Top-down models tended to have very little detail on the energy sector but explicit treatment of behaviour and larger economic relationships. As suggested in the previous section, this led to each type of model being most useful at answering somewhat different questions: with bottom-up models useful for looking at simulation of detailed technological substitution potentials ("exploration") and top-down models aimed at predicting wider economic effects ("prediction").

Table 8.2 also shows that this simple characterization of the differences between top-down and bottom-up approaches is increasingly misleading, as more recent versions of each approach have tended to move in the direction of greater detail in those dimensions that were relatively less developed in the past. This is possible because the four dimensions shown in Table 8.1 are independent of each other. Thus any particular model can be located at virtually any point on the spectrum represented by each dimension. It is this independence of these key structural characteristics that makes it so hard to classify the large population of existing models on any single spectrum, whether bottom-up to top-down, or any other. Instead we increasingly have a wide range of models, which, in terms of their structure, occupy different places on each of the four dimensions shown here. Thus, while the differences represented by these four dimensions remain important, no simple classification scheme is adequate.

Tables 8.1 and 8.2 describe the differences among different types of models in very general terms. Coming closer to the structure of actual models, we can distinguish several kinds of modelling procedures.

Among bottom-up models two approaches are usually distinguished, (1) spreadsheet models that resolve a simultaneous set of equations to describe the way a given set of technologies is (or could be) met throughout the economy; and (2) simulation or optimization models which simulate investment decisions endogenously. Each of these two approaches can be used in two different ways, prescriptive or descriptive.

A prescriptive model examines the effect of acquiring only the most efficient technologies available or of minimizing explicit costs for a given service at a system level (e.g. electric supply, urban transportation, land use). A descriptive model, in contrast, would try to estimate the technology mix that would result from actual decisions, based on factors such as more complex preferences (people preferring private cars even if the cost/km is higher than the railway transportation), intangible costs (differences in cost of acquisition of technologies), capital constraints and attitude to risk (via higher discount rates for some agents) or any kind of market barriers. Such analyses will typically tend to be less optimistic than prescriptive studies about mitigation unless appropriate policies are assumed to remove existing barriers to the adoption of the best available technologies. Considerable disagreement now exists in the literature about the potential for such policies.

Top-down models resort to two main methodologies: (i) neo-keynesian macroeconomic models, and (ii) computable general equilibrium models and models simulating very long term growth paths. Each of these approaches can be coupled to process energy models.

Neo-keynesian macroeconomic models are econometrically calibrated and their purpose is to trace the short and middle run dynamics of energy and the economy. Unemployment in the short run is allowed in response to shocks and disequilibrium in the economy and for structural unemployment due to an inadequate demand for labor. The fact that they assume a non perfect equilibrium economy explains why, as it will be seen in chapter 9, there is a gap between their findings in the case of no-recycling or lump-sum recycling of tax revenues (which show high costs) and their findings in the case of efficient recycling (some of which show an overall economic benefit from a carbon tax).

Computable general equilibrium models or optimal growth models (for the very long term) focus mainly on a long term analysis of the effect of climate policies in the period after adjustment of the economy to short-term effects. They rely on a resource allocation principle and a market clearing mechanism for all goods by equating prices with marginal costs. The dynamics of these models are produced by capital accumulation and/or by the exogenous growth of the factors of production and of productivity. Contrary to the neoknesian models they do not rely systematically on econometric relationships. They are instead frequently benchmarked on a given year in order to guarantee the consistency of the parameters. This allows for a greater flexibility for using information coming from other models (or expert judgments) about possible shifts in current trends (technological breakthroughs for example) that would not be picked up in econometric relationships but which would be dangerous to neglect when very long time periods are being examined.

3.2.3 The Role of Key Input Assumptions

A third factor important to consider in evaluating the meaning of the specific modelling studies is the nature and value of the assumptions that make up the external inputs to those models. Changes in the values of these assumptions will have a significant impact on the results of the study.

The distinction between input assumptions and assumption embedded in the structure of the models changes over time as models evolve, often incorporating more assumptions in the model structure as they develop. Moreover, input assumptions can be based upon implicit mental models of the way the world works which have not yet been formalized in explicit terms, and which may or may not be consistent with the formal model. For example, assumptions about the cost and availability of biomass energy supplies in the future imply

certain assumptions about future land use which may or may not be consistent with the rest of the analysis.

The assumptions listed in Table 8.3 represent assumptions that are important for any findings regarding costs of GHG mitigation.

Table 8.3

Key Input Assumptions in GHG Mitigation Costing Studies

Assumption	Meaning and Relevance
1. Population	Other things being equal, population growth increases GHG emissions.
2. Economic Growth	Increased economic growth increases energy-using activities, and also increases the turnover of energy-using equipment (e.g. allowing penetration of more efficient equipment).
3. Energy Demand	
a) Structural Change	Degree to which the structure of the economy changes. Since different sectors of the economy have different energy intensities, this will have a significant impact on overall energy use.
b) Technological Change	Energy intensity of energy-using equipment and processes. This "energy efficiency" variable influences overall energy demand.
4. Energy Supply	
a) Short-term Availability of Alternative Supplies	This determines the potential for fuel substitution.
b) Backstop Technology	The cost at which an infinite alternative supply of energy becomes available. This sets an upper bound on the cost of mitigation.
5. Price and Income Elasticities of Energy Demand	These elasticities measure the relative change in energy demand given relative changes in energy prices and in incomes. Higher elasticities cause larger changes in energy use.
6. Tax Recycling	Whether carbon tax revenues are used to reduce the distortionary effects of existing taxes. This has a large impact on the overall cost of carbon taxes.

3.3 The Top-Down versus Bottom-Up Modelling Controversy: Some Lessons from the Energy Field

As discussed earlier, many recent analyses incorporate features of both bottom-up and top-down models, so the distinction between these two approaches is becoming blurred. Despite this convergence, in Chapter 9 we have reported the results of costing studies separately for bottom-up and for top-down analyses, and we turn here to a discussion of the bottom-up/top-down controversy. There are several reasons for this. First, the prevalence of this modelling dichotomy in the energy field (most studies in other fields are bottom-up) means that the bulk of studies reviewed in Chapter 9 fall naturally into these two camps. Second, the differences between the results that emerged from these two approaches (the bottom-up models tended to suggest that the costs of GHG mitigation might not be high and top-down models tended to suggest the opposite), has led to a significant level of controversy organized around this distinction. Finally, the fundamental questions raised by the differences in approach between bottom-up and top-down models are important to understand in order that these results not be misinterpreted; they also raise important policy issues relevant beyond the energy field.

The terms "top" and "bottom", in the usual jargon of the economic modeler, are commonly linked to the distinction between aggregate models and disaggregated models. The top-down label is derived from the way in which the first developers of these models applied econometric techniques (i.e. statistical analysis of past trends) to historical data on consumption, prices, and incomes to estimate price and income elasticities for final demand goods and services such as energy, transportation, food, and industrial products. These aggregate models were criticized for not providing a complex enough description of the determinants underlying sectoral demand dynamics. Simulation-oriented technico-economic models were then developed in order to explore the potential for a possible decoupling between these energy demand and economic growth. This required "bottom-up" or disaggregated analysis of technical alternatives and demand for specific services.

In fact, many macro-economic models are also very detailed, but not in the same way as bottom-up models: they account for economic activities at a two-digit SIC level and can break down consumer demands into many household types. In many models the so-called aggregate demand functions of consumer expenditure are constructed by summing "individual demand functions", which allows for testing the income distribution effects of various types of climate change policies.

A second methodological distinction, partly correlated with but not identical to the aggregation level, is the degree to which behaviours are endogenized in the model equations (i.e. predicted by the model) and extrapolated over the long run. Because econometric relationships among aggregated variables are generally more reliable than among disaggregated variables, and the behavior of the model is more stable with such variables, a common practice used to achieve robust top down econometric models over longer time periods is to adopt higher levels of aggregation (between 2 to 10 goods and services). This means that, with a few notable exceptions, as longer time periods are under consideration, the aggregation gap between top-down and bottom-up models tends to increase.

Top-down models attempt to examine a broad equilibrium framework, meaning that they are interested in feedbacks between the energy system and other sectors of the economy, between all sectors of the economy and the macro-economic performance of the economy, between national energy markets and global energy markets, and, in some cases, between the national economy and the global economy. Given all of these feedbacks, early top-down models generally included little detail of the energy-consuming side of the economy, especially at a technology-specific level. In contrast, bottom-up models attempt to examine in detail the

technological options, especially on the energy-consuming side of the economy. This detailed representation of different energy end-uses and the technologies serving those end-uses, generally meant that larger feedbacks were ignored. In a sense, bottom-up models hold a magnifying glass up to the energy demand-side of the economy, and other connections and feedbacks tend to be obscured or lost from the picture.

Another way to look at the difference between these approaches is by returning to the first three types of costs of mitigation introduced in section 1.2. We can say that top-down models focus on financial flows across the whole economy and provide rather sophisticated analytical tools at this level, while sectoral models, which have tended also to be top-down but sometimes with fairly detailed representation of technology, focus on the market dynamics stemming from a given industrial structure but with little consideration devoted to overall feedbacks with the rest of the economy. Finally, bottom-up models focus on the technical margins of freedom likely to be evident at a micro-economic level and provide a detailed analysis of the technical and economic dimensions of specific policy options. Historically, this difference in focus has led to significant differences in results, as the larger economic feedback loops originally examined in top-down models (higher production costs, lower investments in no-energy sectors) tended to increase the macroeconomic costs of emissions reductions relative to bottom-up results. More recently, other feedbacks which tend to reduce overall costs (efficient tax recycling) have been examined in top-down analyses, while bottom-up methods have increasingly incorporated detailed examination of the behavioural dimensions of the policy options examined. The effect of these developments has been to narrow the range of difference in mitigation costs between these two approaches.

But, behind this difference in the level of aggregation, lie two different ways of representing technology. One side tries to capture technology in the engineering sense: a given technique (coke oven steel versus electric-arc steel, an incandescent light bulb versus a fluorescent light bulb) with a given technical performance at a given direct cost. On the other side, the term technology in macro-economic models, whatever the level of desegregation of the model, is represented by the share of the purchase of a given input in intermediate consumption (steel products to make cars for example) and by the allocation of the sales revenue among the cost of intermediary inputs, returns to labour, and returns to capital. These shares constitute the basic ingredients of the economic description of a technology in which, depending upon the choice of production function, the share elasticities represent the degree of substitutability among inputs.

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

Bearing in mind these differences in fundamental approach, it is clear that there is no a priori reason that the two modeling approaches must give different results. Top-down models account for the technological changes so valued by bottom-up analysis via two parameters: (1) the autonomous energy efficiency index (AEEI), and (2) the elasticity of substitution between the aggregate inputs to household and firms. AEEI is a function of time (a proxy for all the long-run reasons for equipment turnover) and suggests the rate at which the penetration of new

technologies may change the energy intensity of the economy. The elasticity of substitution is a function of relative prices of inputs, and allows measurement of the degree to which capital or labour can be substituted for energy (i.e. energy intensity can be reduced) as energy prices rise relative to these other inputs. The values of AEEI and elasticity of substitution can be adjusted to provide results that match those frequently suggested by bottom-up analysts. Recently, top-down modellers have proven to be more willing to abandon historically-derived parameter values in favor of other values, derived, for example, from detailed bottom-up analysis, both for AEEI and the elasticity of substitution (benchmarking). They have also worked to develop model forms that achieve greater disaggregation of energy end-use activities, if not a detailed representation of technologies. Thus a relatively high value for AEEI, say a 2% decline per year, and a relatively high value for the elasticity of substitution between fossil fuels and other factors of production (labour, capital), could lead to top-down simulation results in which the cost of carbon emission stabilization, and even a 15-30% reduction, were below or close to zero. This way of incorporating bottom-up information is relatively easy to achieve in the generation of top-down models that use "benchmarking" approaches to calibration; in the case of econometrically-calibrated models it requires the adoption of some *ad hoc* hypotheses and a departure from strict econometric consistency.

Conversely, some of the recent refinements to bottom-up modeling have tended to lead to relatively higher cost of greenhouse mitigation than earlier work. Recent bottom-up studies seek to be more descriptive of energy-using behaviors and include behavioural parameters of firms, households, and institutions estimated from responses to price signals and to energy efficiency programs, as well as administrative costs of policy programs. Once such field data are included, relatively higher costs of greenhouse mitigation may result than found in earlier work.

At the same time, technological input assumptions on energy efficiency and low-carbon supplies vary over a wide range within the body of past bottom-up work, reflecting, in part the availability of more advanced technologies and more detailed end-use data. In combination, these factors explain why a wide range of results is found in the bottom-up studies reported in the next chapter. Because a considerable range of findings also exists in past top-down work, a certain amount of overlap can be observed between the two methods.

Most of the results presented in the next chapter will show little of this potential for overlap in the results of either method. This is because efforts to use similar assumptions have only affected a few recent study efforts. Most of the top-down and bottom-up studies referred to in this report were conducted with distinct differences in their input assumptions about the role of consumer surplus and intangible costs.

An example of consumer surplus would be the extra satisfaction or value that a consumer derives from a particular automobile that may not be reflected in its capital or operating costs. Common examples of intangible costs are (1) the cost of becoming sufficiently informed about a new technology in order to consider it seriously as an option, (2) the perceived risks associated with capital or operating costs of a technology, (3) the various transaction costs associated with finding, ordering, shipping, installing, operating and maintaining a technology, (4) externally or internally-imposed restrictive investment criteria that differ from the social time preference of consumers and the opportunity cost of capital of firms. One or a combination of these intangible cost factors or consumers surplus could differ sufficiently between two goods so as to offset differences in tangible costs.

Top-down modellers, who tend to be economists, are generally reluctant to doubt the economic efficiency of firm and household consumption choices, while recognizing the classical imperfections in markets (oligopoly, natural monopoly, subsidies etc.) will tend to assume that if a technology does not penetrate the market to the extent that an bottom-up engineering/economic analysis (which focuses only on tangible costs) suggests that it could, it

is probably at least in part because the intangible cost and/or consumer surplus differences are at least large enough to make the investment unattractive. As a consequence of this general assumption, most economists are more likely to put their faith in values for AEEI and elasticity of substitution that have emerged from studies of the economy using statistical regression of historical aggregate data sets. Since the historical data is based on actual behaviour, behavioural parameters estimated from it may represent a synthesis of all tangible and intangible costs including differences in consumer surplus.

As with top-down modellers, it is hazardous to make sweeping generalizations on the bottom-up side. However, bottom-up analysts in the past were more likely to be engineers and physicists. Their detailed knowledge of thermodynamic potentials and the energy-using characteristics of new and emerging technologies has led them to be aware of the apparent economic potential for society to adopt new technologies more quickly than in the past, at rates that, in aggregate, would imply values for AEEI and elasticity of substitution far higher than the values emerging from the historical data relied on originally by top-down modellers. This issue is particularly important when faced by the very long timeframe required by the climate change issue.

In addition, bottom up modelers point out that econometrically derived relationships may incorporate market imperfections. While many top-down modelers assume that these imperfections are either negligible or very costly to correct, bottom-up modelers have noted the significant successes in fostering technological innovation and greater energy efficiency resulting from (1) government initiatives during the energy crises of the 1970s and (2) utility and government initiatives in the 1980s. They see these experiences as evidence that well-designed R&D and policy programs could significantly affect the evolution of the AEEI term and even the elasticity of substitution. In so far as institutional reforms could lower transaction costs and remove barriers to the adoption of technologies whose life cycle costs are advantageous, there would be room for "no regrets" improvements.

Given these assumptions, bottom-up modellers tend to argue that appropriate policy will cause energy efficient products to have lower transaction costs and risks than are generally assumed by firms and households, and perhaps even higher consumer surplus. From this perspective the market as currently configured simply isn't delivering levels of energy efficiency that would be economically advantageous, not just at the micro-level of direct financial costs but also at more aggregate and inclusive levels of cost. They suggest that significant potentials for emission reductions can be realized at net economic savings through a combination of mandatory energy efficiency standards, labeling and auditing programs, least-cost planning-oriented utility regulatory reforms, profit incentives for utility demand-side management programs, market-pull incentives provided through innovative utility or government procurement programs, and increased R&D and commercialization efforts for modular small-scale, modular technologies with fast gestation periods, notably energy efficiency improvements and renewables.

The differences in results between top-down and bottom-up modelling analyses are thus rooted in a complex interplay among differences in purpose, model structure, and input assumptions. The growing tendency for the development of hybrid modelling approaches means that differences of model structure are becoming a less important factor in many climate modelling studies, but the overall difference in perspective and thinking about energy markets represented by these two modelling approaches remains. Hybrid modelling approaches allow the exploration of the relative importance and implications of different input assumptions, and are likely to narrow the difference in results between bottom-up and top-down studies. They will not by themselves, however, resolve the underlying question of whether energy markets are efficient with respect to the delivery of energy efficiency gains or not. Moreover, it remains to be seen whether these new approaches will be equally fruitful in fulfilling the range of purposes discussed above in section 3.2.1. In particular, it seems clear that we need to improve

our ability to explore long-term development paths or configurations of technology that are very different than those typical of experience in past decades (i.e. the alternative future scenarios that are often the subject of backcasting analyses). Much work remains to be done to address these larger issues in a satisfactory way.

3.4 Beyond Energy: Carbon Sinks and Non-Energy GHG Emissions

The focus of the literature on the potential for controlling CO₂ from energy sources has developed in part because of the ready availability and adaptability of models that were designed to analyze energy markets. As regards to carbon sequestration and reductions in emissions of methane, nitrous oxide, halogenated substances and other GHGs, there were no ready made macroeconomic models that could be adapted to analyze the potential for these activities. This explains why the debates in these areas have not been structured around the bottom-up and top-down modelling approaches. Nevertheless controversies in these fields are in fact related to fundamental issues very similar to the ones underlying the bottom-up versus top-down division in the energy field; namely, the reasons for a wedge between the direct cost of technical alternatives from an engineering viewpoint and the overall costs of their adoption and implementation if transaction costs and economic general equilibrium effects are included in the accounting.

3.4.1. Carbon Sequestration Studies

The differences among the studies that give rise to the wedge between direct and social costs arise at each stage of a carbon sequestration cost analysis: (1) identification of forestry practices and available land within the study region; (2) analysis of the costs of implementing the practices on the available land; and (3) analysis of the expected accomplishments of the practices and valuation of those accomplishments.

As indicated by Table 8.4, there are a variety of forestry practices that may contribute to increasing the size of forest carbon sinks. Just as in the case of the best available technologies in the energy field, the appropriate forestry practice for carbon sequestration is, in theory, the one that provides promise as a cost-effective way to capture and store carbon (see, e.g., Parks and Hardie 1993). The analysis of "intangible" factor costs or of "double dividends" has been hampered by the fact that many studies have imposed constraints on the forestry practices or types of land that they consider. Constraints have included requirements that adopted forestry practices decrease soil erosion (Moulton and Richards 1990), meet local needs (Andrasko et al. 1991) or provide other environmental benefits such as habitat preservation. Ideally, these factors should be accounted for as beneficial secondary effects, which in many cases appear to be higher than for energy efficiency.

Significant dispersion of the cost assessments of sink studies can be traced back to disagreements on the assumptions and data related to the many factors that determine total costs: land costs, first treatment and maintenance costs, transaction costs, the valuation of wood product, and the discount rate applied to expenditures.

As regards to the land costs, studies of carbon sequestration costs in the United States have, for example, employed several methods to identify the social costs associated with conversion of land to forestlands: the use of land rental rates derived from surveys (Moulton and Richards 1990), the use of market prices adjusted for the elasticity of demand for agricultural land (Richards et al. 1993), the use of the estimated lost profits from removing the land from agriculture production (Parks and Hardie 1993), and the use of consumer surplus loss from increases in food prices due to the constriction of agricultural land availability (Adams et al. 1990). In the absence of extensive experience, estimating land costs has proven difficult because of the low reliability of data on the elasticities of demand for agricultural land. Also,

uncertainties about the future of government subsidies for agriculture raise questions about land costs. These subsidies tend to drive a wedge between the market prices and the social cost of land.

Table 8.4

Examples of Forestry Practices to Increase Carbon Sequestration

Afforestation of agricultural land
 Reforestation of harvested or burned timberland
 Preservation of forestland from conversion
 Adoption of agroforestry practices
 Establishment of short-rotation woody biomass plantations
 Lengthening forest rotation cycles
 Modification of forestry management practices to emphasize carbon storage
 Adoption of low impact harvesting methods to decrease carbon release

These accounting difficulties are obviously far more difficult in countries that do not have well established land markets, that have land tenure laws that do not allow permanent transfer of land at all, or where the government owns a significant portion of the land. Further, even where land markets do function, the lack of data about market activities often renders land cost estimates speculative at best.

The transaction costs associated with establishing forestry programs can be significant. Even in well-developed market economies, the costs of program administration can rise to as much as 15% of the total costs of land rental, establishment and maintenance (Richards et al. 1993). It is reasonable to expect that where land and labor markets are not as well developed or when a public administration is not well established, the costs of administration and information gathering might rise to a much higher level, even surpassing the financial outlays. In the context of developing countries where the pressure on land comes from agricultural purposes or from wood exports, these transaction costs should, theoretically, encompass policies required to slacken this pressure. This could narrow the range of feasible low cost carbon sequestration opportunities.

While some carbon sink cost studies have assumed that carbon sequestration project lands would be taken out of agricultural or timber production permanently (Nordhaus 1991; Richards et al. 1993), most have allowed for some kind of derivative benefit in the form of forestry products such as pulpwood, timber, firewood, and biomass energy. This raises two additional issues. First, harvesting of forestry products suggests the need to modify the flows of carbon associated with the project to reflect the removal of carbon from the site. This in turn raises the question of the rate of release of the carbon back to the atmosphere after harvest. Second, in a cost-effectiveness study, the costs of the project should be reduced to reflect the non-carbon benefits of the wood products.

As the three examples used in Box 1.2 to illustrate the discussion of summary statistics imply, harvesting can have a significant impact on the carbon benefits of a project. Further, the measure of that impact depends very much on the choice of summary statistics. At the same

time, the economic benefits of timber harvest can be significant. Studies that do not quantify either of these two effects will overstate both the costs of carbon sink projects and the carbon benefits. While the effect or carbon costs of ignoring timber harvest is indeterminate, it is likely that inclusion of forestry products in the analysis would generally lower unit cost. Studies that include the effects of harvest on carbon flows but do not incorporate the economic benefits of harvest will almost certainly overstate the unit costs of carbon sequestration. At the extreme, some forestry practices may pay for themselves in the form of forestry products and the carbon benefits are a costless bonus (often referred to as "no regrets" strategies).²⁴ For example, Xu (1994) suggests that there may be negative costs associated with some carbon sequestration practices in China. Conversely, those studies that only consider the benefits of forestry products but do not adjust the carbon flows to reflect increased releases of carbon back to the atmosphere will understate the costs of carbon sequestration.

It is apparent that, as with energy efficiency, there are opportunities in the carbon sink area to achieve "double dividends". These become evident under an analysis that provides full accounting for the wood product benefits of projects as well as for the less tangible benefits such as habitat and watershed preservation, improved local self reliance, and soil erosion control. However, full accounting must also include those factors that tend to increase social costs relative to financial costs, such as the effect of removing non-marginal quantities of land from agricultural production, transaction costs associated with establishing new land use patterns, administrative costs of implementing a large-scale carbon sequestration program, and decreases in carbon benefits associated with timber harvest. Perhaps the most important factor, one commonly ignored by carbon sink cost studies, is the potential for "leakage" of the carbon sequestration gains due to changes that owners of existing forests make if they feel that the value of their forests are threatened by the carbon sequestration program itself.

3.4.2 Non-Energy Greenhouse Gas Emissions

[TO FOLLOW]

4. Conclusions

• It is important to be clear what types of costs (direct, sectoral, macroeconomic, welfare) are included in the analysis. What matters from the point of view of policy are the net costs, not the total costs of emissions reduction (i.e. the total costs minus any positive side-effects of mitigation).

• It is the insights generated by modelling analyses (e.g. the areas of greatest potential for cost-effective emissions reduction, the directional effect of tax recycling on emissions reduction costs), not the specific numerical results of any one analysis, that matter.

• The size of the costs of mitigation depends critically upon assumptions about the efficiency of the baseline scenario used in the analysis. The higher the underlying economic growth in the baseline scenario, the greater the costs of mitigation. The more emissions reduction built into the baseline, the higher the costs of further reduction.

• Whether a "no regrets" potential for emissions reduction exists depends on whether the economy under consideration is on or below its theoretical production frontier. The existence of a "no regrets" potential implies that (i) significant market failures exist (the society is below the frontier) which give rise to increased GHG emissions, and (ii) that policies can be designed and implemented that correct those market failures.

• There exists a range of quite different socio-economic and technological development paths that would give rise to quite different emissions scenarios and costs of mitigation. Existing energy and emissions models do not address these underlying factors in a very effective way. Future analysis should make use of multiple baseline scenarios to help capture the differences in these factors.

• Infrastructure decisions are critical because they can allow or restrict future options, and different infrastructure decisions can lead to very different cost outcomes. This issue is of particular importance to developing countries, where major infrastructure decisions will be made over the next 25 years.

• Mitigation costing analyses reveal the costs of mitigation relative to a given baseline. The results of different studies cannot easily be compared to each other unless differences in baselines are taken into account. Neither the baseline nor the intervention scenarios should be interpreted as representing likely future conditions.

• There is growing integration of bottom-up and top-down analyses of the costs of energy-related GHG mitigation. This convergence means that differences in results are increasingly driven by differences in input assumptions rather than differences in model structure. Nevertheless, differences in structure remain important as different types of models are best suited to answer different kinds of questions. Substantial disagreement still exists, over the existence and size of a significant "no regrets" potential for GHG emissions reduction.

Notes

¹ For a discussion of the wide range of views on future energy demand in the early 1980s, see Caputo (1984) and Thompson (1977).

² For discussion of the sometimes vexed relationship between energy modellers and energy policy-makers, see Robinson (1992).

³ See, for example, the various national case studies in Baumgartner and Midttun (1987).

⁴ Early works in this area is summarized in Little and Mirrlees (1974) or Squire and Van der Tak (1975) (for a more recent methodological surveys see Gruninger (1982)). A good illustration of the interest of making a distinction between market prices and factor costs is given in the debates around the biomass ethanol program in Brazil where the cost of ethanol is far lower if one utilize some form of social costs (Nastari, 1991).

⁵ 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. But whatever positive side-effects are included, the "no regrets" concept should not be taken 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. A better term might be "worth doing anyway" measures.

⁶ See also the discussion in Chapter 7.

⁷ See section 6.7 of Chapter 6 for a discussion of some estimates of the magnitude of the environmental double dividend.

⁸ For a more general presentation of the different meanings of concepts such as "no regrets" and "double dividend", see Goulder (1994).

⁹ Of course it would also be possible to move from O to a point above and to the left of point B (increasing economic growth and also increasing emissions); this means that the economic surplus gained thanks to the removal of inefficiencies (i.e. moving from O to curve F) will be devoted to improving environmental quality only if there is a collective preference and political will to do so. It could also be possible to move to a point below and to the right of A (reducing both emissions and economic activity) if the surplus is devoted to very high investments with a low return and a very low efficiency in terms of environmental quality improvement. This could occur in the case of misallocation of efforts for a given level of concern for environmental quality.

¹⁰ The same debate surrounds the analysis of fiscal reforms linked to a carbon (or energy) tax. Some analysts consider that it is more legitimate to separate the gains from reducing existing fiscal distortions from the incremental impact of a carbon tax. Others consider that both such effects should be accredited to the carbon tax, since reducing fiscal distortions is associated with, and made more politically palatable by, the imposition of the carbon tax. This latter position, which can reduce or more than offset the costs of the carbon tax, is the position taken in most of the empirical modelling work to date; the former assumption is more typical of more theoretical analyses.

¹¹ This is a logical identity and does not imply the independence of these three terms.

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

¹³ In 1989, the range for Europe and North America was 20-35% (World Resources Institute, 1993).

¹⁴ Alternatively, countries might adopt strategies encouraging the development of very energy-efficient urban design.

¹⁵ For discussion and examples of such approaches see Jantsch, E. (1967); Harman, W. (1976); Gault, et al. (1987); Gal and Fric (1987); Gilmet and Lacetadius (1987); Godet, (1986); and Robinson, (1988).

¹⁶ Meadows, D., et al. (1972) *The Limits to Growth*. London

¹⁷ See the country case studies in Baumgartner and Midttun (1987). See also Caputo (1984). For a discussion of the bases of disagreement, see Robinson (1982a).

¹⁸ For examples of more recent bottom-up work, see Goldemberg et al. (1988) and Johansson et al. (1993).

¹⁹ In Chapter 9 we provide the findings of some attempts to provide such comparisons.

²⁰ 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.

²¹ For a recent example, which characterizes individual bottom-up and top-down models, see Grubb et al. (1993).

²² For example, Environmental Protection Agency (1990); Edmonds, et al. (1986); Manne and Schramm (1993); and Johansson et al. (1993).

Notes (cont.)

²³ For a discussion of the implications of backcasting approaches, see Gault, et al. (1987) and Robinson (1991b).

²⁴ As a result, many top-down modellers assume that the baseline scenario describes a world without important market imperfections (or at least without imperfections that would not be very costly to correct). However this interpretation of the meaning of the baseline is not the only one possible: a given econometrically-derived relationship may instead be viewed as incorporating market imperfections. In such a case there would be room for "no regrets" improvements through, for example institutional reforms removing barriers to technical adoption and lowering transaction costs. As yet, however, the coupling between econometric models and bottom-up behavioural models is in its infancy.

²⁵ Of course, as in the case of energy-related emissions, the assertion that there exist opportunities to enhance sinks at a negative cost raises the obvious question of why these activities are not already being undertaken if their costs truly are negative.

*(that must be negative)
to mitigate with effect
properly)*

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A REVIEW OF MITIGATION COST STUDIES

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1 Summary

2
3 • Estimates of the cost of GHG emission reduction are sensitive to assumptions about
4 appropriate model structure, demographic and economic growth, the cost and availability of
5 energy demand-side and supply-side options, the desired level and timing of abatement, and
6 the choice of policy instruments. Different assumptions have led to a wide range of
7 emission reduction cost estimates.

8
9 • Despite significant differences in views, there is agreement that some energy
10 efficiency (perhaps 10-30% of current consumption, depending on baseline assumptions and
11 the implementation time frame) can be realized at negative to slightly positive costs. The
12 existence of such a "no regrets" potential depends upon the existence of substantial market
13 or institutional imperfections that prevent cost-effective emission reduction measures from
14 occurring. The key question is whether such imperfections can be removed cost-effectively
15 by policy measures.

16
17 • Energy-related emissions can be reduced through both demand-side (energy
18 efficiency) and supply-side (alternative sources of supply) options. In the short term,
19 demand side options are cheapest in most countries.

20
21 • Estimates of the costs of stabilizing CO₂ emissions vary widely as a result of
22 differences both in the baseline scenarios used (e.g. how much energy efficiency or what
23 rate of economic growth is contained in the baseline scenario), and in the calculated costs
24 of various policy measures.

25
26 • There has been much more analysis to date of emission reduction potentials and
27 costs for industrialized countries than for other parts of the world. Moreover, many existing
28 models are not well suited to study economies in transition or developing country
29 economies. Much more work is needed to develop and apply models outside of developed
30 countries.

31
32 • The overall cost of abatement programs will ultimately be determined by the rate of
33 capital replacement, the discount rate, and the effect of R&D. Appropriate long-run signals
34 to encourage R&D will reduce long-run costs. The implementation of any "no regrets"
35 potential will increase the time available to learn about climate risks and to bring new
36 technologies to enter the market-place.

37
38 • Infrastructure decisions are critical because they can enhance or restrict the number
39 and type of future options, and different infrastructure decisions can lead to very different
40 cost outcomes. This issue is of particular importance to developing countries, where major
41 infrastructure decisions will be made in the near term.

42
43 • If the climate issue is formulated in terms of stabilizing atmospheric concentrations,
44 the choice of emissions time path is critical in determining the overall price-tag. It is
45 important to identify those paths that minimize the costs of achieving a particular

1 concentrations target.

2
3 • The overall impact of a carbon tax will depend not only on the size of the tax, but
4 also on the uses to which the revenues are put. If carbon tax revenues are used to reduce
5 more distortionary taxes, overall emission reduction costs will be reduced. Inefficient tax
6 recycling could, however, increase costs.

7
8 • There is need for both detailed (bottom-up) analysis of technological options and
9 also more aggregate (top-down) analysis of economic effects. Whereas historically these
10 two approaches have been associated with very different cost estimates, this need not be the
11 case. Indeed widely differing methods can produce quite similar results when calibrated to
12 the same set of input assumptions.

13
14 • Given differences in marginal emission reduction costs among countries,
15 international cooperation can significantly reduce the global price-tag for emissions
16 reduction. Economic efficiency would be enhanced by carrying out emissions reduction
17 where it is cheapest to do so.

18
19 • Estimates of the costs of stabilizing CO2 emissions at 1990 levels in *OECD*
20 *countries* vary widely. Many bottom-up studies suggest that the costs of achieving this
21 target over the next few decades may be negligible. Given rising baseline emissions over
22 the longer term, however, many top-down studies suggest that the annual costs of
23 stabilizing emissions may ultimately exceed
24 1-2% of GDP.

25
26 • The costs of stabilizing emissions for *economies in transition* may be small relative
27 to OECD countries. The potential for cost-effective reductions in energy use is apt to be
28 considerable but the realizable potential will depend upon what economic and technological
29 development path is chosen. A critical issue is the future of structural changes in these
30 countries that are apt to change drastically the level of baseline emissions and the emission
31 reduction costs

32
33 • Analyses suggest that there may be substantial low-cost emission reduction
34 opportunities for *developing countries*. However, these are likely to be insufficient to offset
35 rapidly increasing emissions baselines, associated with, for example, increased economic
36 growth. In the absence of a highly favorable allocation of carbon emission rights, the likely
37 magnitude of emissions reduction will be particularly costly for developing countries.

1 9.0 Introduction

2
3 A variety of options can be adopted in response to the prospect of increasing concentrations
4 of greenhouse gases in the earth's atmosphere. These include 1) options that eliminate or
5 reduce greenhouse gas emissions; 2) options that offset emissions, for example, through the
6 enhancement of sinks; and 3) options that help human and ecological systems adjust or
7 adapt to new climate conditions and events. The first and second types of interventions take
8 effect prior to climate change and are intended to slow its pace. As such, they are referred
9 to as "mitigation" measures. The third category of intervention takes place after warming
10 occurs and falls under the classification of "adaptation". This chapter reviews existing
11 studies on the economic costs of mitigating greenhouse gas emissions.

12
13 A caveat is in order. Sensible greenhouse policy should involve careful consideration of the
14 costs of mitigation and adaptation options together with what these options may buy in
15 terms of reduced environmental impacts. **This chapter focuses exclusively on mitigation**
16 **costs. The benefits from adopting such options are discussed in Chapter 6.**

17 9.1 Review of existing studies of the costs of reducing CO2 emissions

18
19 In recent years, there have been numerous studies of the costs of reducing CO2 emissions.
20 Unfortunately, estimates have spanned such a wide range that they have been of limited
21 value to policy making. Figure 9.1.1 from Grubb et al. (1993) is illustrative of the current
22 lack of consensus about the costs of reducing CO2 emissions. It summarizes recent
23 projections of the costs of reducing US CO2 emissions. Whereas some studies place losses
24 at several percent of GDP, others question whether there will be any losses at all. An
25 essential first step in narrowing the range of disagreement is to determine why estimates
26 differ so widely.

27
28 There are many possible explanations for the disagreement -- choice of methodologies,
29 underlying assumptions, emission scenarios, policy instruments, reporting year, etc. In
30 chapter 8, we explored some of these reasons, paying particular attention to the modeling
31 of technological change. In this chapter, we provide a more systematic examination of the
32 published literature on the costs of reducing CO2 emissions. In doing so, we will show
33 that, despite widely varying and often contradictory findings, the impressive accumulation
34 of modeling results provides a number of useful insights for climate policy making.

35
36 The review is organized by region, with results presented successively for 1) the US, 2)
37 other OECD countries, 3) the transitional economies of Eastern Europe and the former
38 Soviet Union, 4) developing countries and 5) the globe as a whole. For each region, we
39 first present results from top-down studies, then from bottom-up studies. In the last section,
40 we attempt to draw some general conclusions based upon our interpretation of these
41 studies.

42

43

9.1.1 Studies of the Costs of Reducing CO₂ Emissions in the US

9.1.1.1 A Review of Top-down Studies

There have been several attempts in the US to systematically compare the results of modeling analyses of GHG emission reduction costs. 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 9.1.1.1.1.

The EMF exercise provides the most comprehensive application of top-down methodologies to date and gives a wealth of useful information for policy making. The harmonization of key exogenous inputs makes it possible to verify to what extent the disagreements were due to differences in methodologies, and to understand better the economic meaning of these differences. Although the focus was primarily on the US, many of the insights are applicable to developed countries in general. It is instructive to examine its results in some detail.

9.1.1.1.1 Key assumptions

In selecting parameters for standardization, the EMF study focused on what were felt to be most influential determinants of emission reduction costs. These included: GDP, population, the fossil-fuel resource base, and the cost and availability of long-term supply options.

Given its importance as a determinant of future carbon emissions¹, the GDP growth rate was a key parameter for harmonization across models. 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).

To facilitate model comparisons, 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.

9.1.1.1.2 Emission scenarios

Table 9.1.1.1.2.1 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 9.1.1.1.2.1 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 9.1.1.1.2.2 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.

9.1.1.1.3 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 a given emission target.

Table 9.1.1.1.3.1 compares model results for the stabilization and 20 percent reduction scenarios. Estimates range from \$20 to \$150 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 and left to the choice of the modelers. Not surprisingly, 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 9.1.1.1.3.1 represent averages of the model results. Note that the size of the required tax doubles as the limit is tightened to 20% below 1990 levels. And nearly doubles again for a 50% reduction. This suggests that the economic efforts to be devoted are nonlinear with respect to the level of controls in any given year. That is, incremental reductions are apt to cost more as the absolute level of allowable emissions is reduced.

Figure 9.1.1.1.3.1 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.

9.1.1.1.4 GDP losses

Table 9.1.1.1.3.1 shows a marked variation in GDP losses across models. Stabilizing emissions at their 1990 levels is estimated to reduce GDP by .2 to .7 percent in the year 2010 -- roughly a \$20 billion to \$70 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 replace other tax payments by individuals and corporations without affecting marginal tax rates or total tax revenues. 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. The assumption of lump sum recycling avoids confusing the economic impacts of carbon taxes with costs or benefits attributable to potential uses of the revenues.

Figure 9.1.1.1.4.1 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.

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.

9.1.1.1.5 The nature of the GDP losses

Figure 9.1.1.1.5.1 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. (Note that the top-down models, on average, project sizable reductions in energy intensity -- even in the absence of explicit measures to reduce emissions.)

In the stabilization case (the right-most bar in Figure 9.1.1.5.1), the carbon taxes induce sufficient investment in supply-side substitutes and conservation to eliminate growth in carbon emissions. That is, carbon emissions and GDP are virtually decoupled. Note that this is done without significantly reducing the growth of the economy. Whereas the losses may be considered large in absolute terms, they are relatively small when measured in terms of a reduction in the GDP growth rate.

9.1.1.1.6 The relationship between timing, emission reduction costs and R&D

The EMF study also addressed the issue of the timing of the carbon constraint. An important question is whether the costs of CO₂ emission reduction will increase or decrease if emission reductions are deferred to the future. This is a complex issue. 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 could raise costs, all else being equal. But all else is not equal.

There are three reasons why deferring emission reductions may reduce costs (Leary and Scheraga, 1994). 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 emissions 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.

To bound the potential benefits from successful R&D, 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 (IERM, 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. This implies 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.

9.1.1.1.7 The issue of revenue recycling

The overall impact of a carbon tax will depend not only on the size of the tax but also on the uses to which the revenues are put. In the standard EMF scenarios, it was assumed that tax revenues will be redistributed in a neutral manner (i.e., without affecting the marginal tax rates). There are, of course, numerous ways in which tax revenues can be used. These include: reducing budget deficits; reducing marginal rates of income, payroll, corporate or other taxes; granting tax incentives to preferred activities; or increasing the level of government expenditures. The costs of the tax will vary widely depending on how the revenues are recycled.

Table 9.1.1.1.7.1 from Shackleton et al. (1992) 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 would increase the GDP

costs of the tax over the neutral case (see Nordhaus, 1994).

9.1.1.2 A Review of Bottom-up Studies

Bottom-up research in the U.S. and Canada has tended to suggest, as elsewhere in the world, that significant decreases in CO₂ emissions are possible without great cost to the economy. In this sense, their results differ from those of most top-down research, the latter suggesting substantial economic costs to CO₂ emission abatement. The methodology discussions in Chapter 8 reviewed some of the key reasons for these differences. As was noted, the bottom-up studies hold up a magnifying glass to the services required of energy and the technologies providing these services. Then, they apply engineering-economic analysis to assess the cost-effectiveness of using alternative technologies to satisfy these same energy services, these alternative technologies consuming less energy and, to the extent such energy is carbon-based, producing less CO₂ emissions.

Reductions in CO₂ emissions is a non-monetized benefit of these alternative technologies, which is not accounted for in estimating cost-effectiveness. These technologies may have other non-monetized benefits and costs, and these too are not accounted for. For example, their adoption by energy consumers may entail substantial transaction costs and additional risks: indeed, this is a common argument of those who suggest that bottom-up approaches will tend to under-estimate the full costs of CO₂ emissions reductions.

Because they examine technologies in such detail, the fine resolution of bottom-up approaches renders them difficult to connect with broader level models that simulate the macro-economic interactions of the economy. As a consequence, bottom-up models are rarely tested for the feedback effects on the economy resulting from GHG emission reduction policies; generally, alternative technologies are assumed to penetrate over a certain time period with no feedback effects on the structure of the economy or level of overall economic activity. However, more recent modelling efforts have attempted to overcome, at least in part, these shortcomings.

9.1.1.2.1 Variations in Bottom-up Methodologies

While bottom-up models have tended to provide lower abatement cost results than top-down models, there has nonetheless been considerable variation among bottom-up modelling efforts and results. This variation is explained in part by differing assumptions about the baseline or reference scenario and differing exogenous assumptions about future technology efficiencies and costs, but also by differing bottom-up methodological approaches to and assumptions about consumer behaviour with respect to technology acquisition.

In the latter case, one might refer to three general bottom-up approaches to estimating technology-acquisition.

- One bottom-up approach is to establish efficiency indices for each energy end-use and then develop scenarios for the evolution of these indices as a function of assumptions about efficient technology penetration. This involves no explicit modelling of individual technologies; instead, the indices are simply the weighted average outcome of gross assumptions about discrete technology choices.

- A second bottom-up approach is to assume 100% penetration of the most efficient (or least carbon-intensive) technology for each energy end-use at some time in the future, and then to compare the emissions and costs of this scenario with a reference scenario. While technologies are modelled explicitly, in this case, the simplistic assumption about equipment acquisition behaviour allows for a fairly simple model. As with the first approach, the model is essentially a spreadsheet of technology shares and efficiencies linked to specific energy end-uses.

- A third bottom-up approach is to input technology cost and efficiency data into a simulation model, and then simulate the market share of technologies over time as a function of changing energy end-use demands, technology costs and efficiencies and, perhaps, explicit behavioural parameters related to factors such as time preference, risk and non-cost preferences. Like the second approach, this involves an explicit treatment of technologies. However, this approach requires a technology choice algorithm and various behavioural parameters in order to simulate technology acquisition behaviour.

Most bottom-up analysis has applied the first two approaches, although there is an increasing effort directed toward the third approach. In this latter case, the potential for convergence with top-down modelling is clearly demonstrated because behavioural parameters can be found that will replicate the results of some top-down models.

9.1.1.2.2 Key Assumptions and Results

In this section we survey some of the key assumptions and results in the U.S. and Canada. Unfortunately, there has not yet been an effort to undertake a harmonized comparative exercise of U.S. bottom-up models, as has been the case with U.S. top-down models. However, a survey of the approaches at least allows for some tentative observations.

An overview of the main assumptions and results of the major U.S. bottom-up studies is provided in Tables 9.1.1.2.2.1 and 9.1.1.2.2.2. Most studies test the sensitivity of their results to changes in GDP growth rates. Energy prices are generally assumed exogenously, although some studies have attempted to incorporate the feedback effects of efficiency measures on energy prices. RIGES, for example, assumes low cost fossil energy in 2030 as a consequence of successful implementation of energy efficiency. In contrast, Carsmith et al. (1990) assume high rates of near-term energy prices increases.

In spite of these opportunities for significant differences, the cost estimates are generally rather close. Most cost estimates for a 20% reduction in U.S. CO₂ emissions by the year 2010, for example, range between -0.6 and +0.5% of GDP (see Table 9.1.1). As noted in

1 section 9.1.2.1, this difference is explained at least in part by the type of bottom-up
2 modelling approach. The RIGES study assumes 100% penetration of markets by all
3 technologies shown to be cost-effective in an engineering / economic analysis. In contrast,
4 Carsmith et al. constrained their model to link all market penetration of efficient
5 technologies to consumer behaviour parameters (expressed as price elasticities) and policy
6 constraints (expressed as efficiency standards). This latter approach did not lead to 100%
7 market penetration by efficient technologies.

8
9 Bottom-up studies for Canada were compiled and reviewed by Robinson et al. (1993) in the
10 study, Canadian Options for Greenhouse Gas Emissions Reduction (COGGER). Estimates
11 of cost-effective CO₂ emission reduction potential by 2010, relative to a reference (or
12 baseline) scenario ranged from 20% to 40%, with a median of about 23%. Relative to
13 1988 or 1990, many studies showed savings in energy use or emissions between 10% and
14 30%, with a median of about 16%.

15 16 17 9.1.2 Studies of the Costs of Reducing CO₂ emissions in Other OECD Countries

18
19 Much of the early work on the costs of CO₂ emission reduction was US based and, as a
20 result, tended to be US focused. More recently, there has been a flurry of analytical activity
21 elsewhere in the OECD, mainly in Western Europe. In general, these country-specific
22 studies have had relatively shorter time horizons than in the US, focusing on the costs of
23 stabilizing emissions in 2000 or a 20 percent reduction by 2005 (the "Toronto target").

24 25 9.1.2.1 A Review of Top-down Studies

26
27 Top-down studies of non-US OECD countries have been of two types: those focusing on
28 an entire region or a subset of countries and those focusing on individual nations. In this
29 section, we review the results of both. As with the US, the types of policies tested have
30 been limited for the most part to taxes on CO₂ and energy, under alternative domestic
31 fiscal recycling schemes.

32 33 9.1.2.1.1 Regional Studies

34
35 One notable attempt at a systematic model comparison of non-US OECD models was
36 conducted by the OECD in the early 1990s (Dean and Hoeller, 1992). The exercise was
37 patterned after the parallel study being undertaken by the Energy Modeling Forum. The two
38 studies used many of the same models and shared a common set of input assumptions. For
39 purposes of the model comparison, the OECD was divided into two regions: the US and
40 "other OECD countries."

41
42 The OECD analysis encompassed both the transition and backstop phases. This long-term
43 perspective is useful when examining issues related to the timing of the transition away
44 from fossil fuels and the potential role of technical innovation in lowering overall costs of

1 reducing emissions.

2
3 The OECD study examined a range of emission reduction scenarios. Among the more
4 interesting is one in which emissions are permanently held to 1990 levels. Figure
5 9.1.2.1.1.1 compares annual GDP losses for three models: ERM, GREEN and MR. The
6 models are fairly consistent in their projections of losses in 2010 -- between .3 and .5
7 percent of GDP. The convergence is due in part to the standardization of key input
8 parameters. But it is also important to note the aggregation effect. Combining all non-US
9 OECD countries into a single region masks important intercountry differences. As we will
10 see in the next section, the variance around the mean is likely to be large.

11
12 The models are in less agreement as we move beyond 2010. The differences can be traced
13 to several uncontrolled parameters. MR, for example, employs a lower rate of autonomous
14 energy efficiency improvements than ERM and GREEN. As a result, its baseline emissions
15 path is somewhat higher. More carbon must be removed from the energy system to
16 maintain emissions at 1990 levels. Hence annual abatement costs are apt to be higher.

17
18 Assumptions about the rate at which backstop technologies can enter the energy system
19 also tend to be important. GREEN, for example, assumes a more rapid introduction rate
20 than the other models. Hence its marginal cost of emissions abatement is lower for each ton
21 of carbon removed. This coupled with the lower baseline, easily explains the ranking of
22 cost estimates among the three models.

23
24 Figure 9.1.2.1.2 shows the taxes that would be required to stabilize emissions at 1990
25 levels. The results from ERM, Global 2100 and GREEN are consistent with the above
26 discussion. In addition, the OECD report included results from the IEA model. This
27 econometric model is relatively pessimistic about the prospects for energy conservation and
28 fuel switching. Hence, high energy prices are needed to bring down emissions.

29 9.1.2.1.2 National Studies

30
31
32 Figure 9.1.2.1.2.1 reports the results of a number of non-US OECD national studies.
33 Annual GDP losses are plotted as a function of emissions abatement, where reductions are
34 measured relative to the model's baseline or business as usual emissions path. Note the
35 story is quite similar to that for the US. The costs of emissions abatement tend to be
36 positive, but there is considerable variation in the magnitude of the losses.

37
38 Some of the differences are to be expected, particularly when they are intercountry in
39 nature. Nations differ widely in indigenous resources, supply infrastructure and energy-use
40 patterns. Those with plentiful natural gas supplies, large existing investments in carbon-free
41 alternatives, and/or low energy use per unit of economic activity should see less growth in
42 carbon emissions. Hence, less carbon will have to be removed from the energy system to
43 meet a specific target.

44
45 Intercountry differences, however, do not explain the wide variety of results for an

1 individual country. Here, as in the case of the US, we must turn to the models and their
2 underlying assumptions. Unfortunately, sorting out the reasons for the disagreement is more
3 difficult. Unlike the EMF exercise, these studies were conducted independently. There was
4 no opportunity to standardize key inputs. Nevertheless, based on the discussions of the
5 previous sections, it is possible to identify several probable causes for the lack of
6 consensus.

7
8 The national studies encompass the period in which we are apt to be most constrained on
9 the supply-side, i.e., the next ten to fifteen years. During this time, the amount of fuel
10 switching capability will be mostly restricted to switching among fossil fuels.
11 Consequently, much of the burden for the emission reductions will fall on the demand-side
12 of the energy sector.

13
14 The potential for end-use improvements remains one of the more controversial issues in the
15 greenhouse debate. The wide range of opinion is reflected in the models. Those which are
16 optimistic about the prospects for price and non-price induced conservation show relatively
17 low abatement costs. Conversely, the more pessimistic models tend to report considerably
18 higher losses.

19
20 Assumptions relating to what is going on in other countries are also important. In the
21 absence of an explicit model of global world trade², the common practice is to adopt one
22 of two hypotheses: 1) unilateral initiatives -- which places an upper bound on trade losses,
23 or 2) initiatives coordinated at a OECD or European Community level -- which places a
24 lower bound to trade losses. The impact of a tax at the national level will also vary
25 depending upon industrial composition (particularly, the existence of large energy intensive
26 industries) and a country's dependence on international trade.

27
28 How a model handles preexisting energy taxes is also important. Many countries rely on
29 energy taxes as a major source of revenue. If a country already has high energy taxes, it
30 will require a larger carbon tax to achieve a given percentage increase in retail energy price
31 levels. This means that the deadweight losses are apt to be higher. Unfortunately, models
32 differ widely in their treatment of preexisting taxes -- adding yet another reason why results
33 are apt to differ. (This was not an issue in our review of US analyses since US energy
34 taxes are much lower than those elsewhere in the OECD. They are more like user fees,
35 barely covering the costs of highway construction and maintenance.)

36
37 Still another reason why estimates of GDP losses differ so widely relates to the revenue
38 recycling issue. The national models embrace an even wider variation of recycling options
39 than those reported for the US. Indeed, some modelers assume that the tax revenues are
40 removed entirely from the economy, likening an imposition of a carbon tax to the oil
41 import price shocks of the 1970s. As one would expect, this leads to much higher GDP
42 losses than would be the case if the revenues were used to stimulate investments or
43 consumption elsewhere in the economy. In the next section, we look at the issue of revenue
44 recycling in some detail.

45

9.1.2.1.3. The effects of revenue recycling on GDP and employment

It has recently been advocated that independent of their intrinsic environmental merits, carbon or energy taxes could be used to reduce non-wage labor costs and consequently, increase employment in Europe. Many European countries finance not only their public administration but also their health system, social security system and teaching system by raising funds from taxes levied directly or indirectly on wages. This way of meeting these financial requirement raises total labor costs and causes structural unemployment.

In some countries, taxes on labor represent nearly half of total hourly labor costs. 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. There is considerable evidence to suggest that this tax wedge, in combination with existing legal or contractual minimum wage arrangements, entails particularly detrimental employment effects for low- or unskilled labor. 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.

Table 9.1.2.1.3.1 compares the results from several studies which suggest that GDP losses of an energy tax could be at least partially offset through effective revenue recycling that reduces particularly burdensome taxes. Where the agreement breaks down is in whether recycling through appropriate cuts in other taxes can actually increase employment. This type of recycling can be compared either with a lump-sum recycling or with the baseline scenario. The first comparison aims at isolating the gains from corrections of fiscal distortions from the specific dividend yielded by the carbon/energy tax; the second comparison assesses the overall result of the reform and assumes implicitly that the greenhouse concern facilitates its acceptance. Some studies suggest that the negative impact on employment and growth is only slightly reduced 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. Because of the short to medium term focus, the majority of studies for Europe have been carried out using neo-keynesian models. However, some studies have employed general equilibrium models to examine the period between 2000-2005: Glomsrod, 1990 (Norway), Proost et al., 1991 (Belgium), Bergman, 1991 (Sweden) and Conrad, 1993 (Germany). In these studies, carbon taxes were used to maintain a given level of CO₂ emissions assuming a lump-sum recycling. The results are not surprising. The loss in GDP is relatively low for reductions of up to 10% to 20% from the baseline (below 0.2% of the GDP) but rises dramatically as the target is further tightened. This is because these studies are pessimistic about the necessary tax level required to achieve a 25-30% reduction from baseline in 2000-2005 (e.g., 380 \$/t in Belgium, 100 \$/t in Norway, 195 \$/t in Sweden. GDP reductions of the order 2.5% are found in some studies. It is important to note that such studies, however, typically ignore the effects of correcting distortions in the existing tax system.

Neo-Keynesian models embed more rigidities and 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. In both types of models, other factors may also be responsible for increased employment. For example, energy taxes may cause labor to be substituted for energy and technical progress to be biased to save energy and use labor.

Many studies have been carried out at a national level and it is impossible to analyze them in detail. Beyond the specifics of national context, what makes comparison difficult is the variety of the ways models handle preexisting energy and non energy taxes and of the ways a carbon or energy tax is levied. Some useful insights can be nevertheless derived. For example, a study by Erasme placed originally the costs of a carbon and energy tax in France at 1.5 percent of GDP in 2000, assuming lump sum recycling of tax revenues (Beaumaïs (1992)). In a subsequent study, applying a complex mix of recycling measures (decreased payroll taxes, incentives to energy efficiency) the same team calculated GDP gains (.5 to .93 percent) from an identical tax (Godard and Beaumaïs (1994)).

In the English context, Barker (1994) and Barker, Baylis and Bryder (1994) point out that results differ according to the product on which the excise tax is levied: a road duty escalator in the UK is shown to reduce inflation (when the revenues are recycled via reductions in employment taxes) and raise employment.

Difficulties in comparative analysis are reduced when the same measure is analyzed. This was the case for studies of the EC proposal for a combined carbon and energy tax (EC Commission, 1992). The proposal called for levying new taxes on most major sources of energy 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.

Several studies have attempted to quantify the macro economic impacts of the EC proposal. Table 9.1.2.1.3.1 reports results from Hermes, Quest, DRI and Hermes-Link. It compares a case without tax recycling with different recycling schemes. In all cases, lump sum recycling entails net costs. The payroll tax cut is demonstrated to be more efficient than a personal income tax cut in the European context. Interestingly, recent Hermes-Link (Bureau du Plan-Erasme, 1993) and Quest (European Economy, 1994) simulation results arrive at a net positive impact. The employment effects tend to be particularly favorable when the energy taxes are simultaneously introduced by several countries and when the compensatory reduction in social security contributions is targeted to the low-skilled.

A more detailed picture of effects on GDP, private consumption, employment and inflation is given in Table 9.1.2.1.3.2 which reports results based on the HERMES and DRI models for six countries. Note that in the case of HERMES, the carbon/energy tax would result into a net positive effect on employment for all the countries and a slight increase in GDP

for four of them. In the case of the DRI model, the results are less optimistic and do not conclude that a double dividend will offset totally the costs of a carbon tax; this is due in part to a different recycling scheme and in part to differences in model structure.

9.1.2.1.4 The effectiveness of energy and carbon taxes

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. However, the EC proposal represents a departure from this pure case by not only aiming to limit CO₂ emissions, but also other objectives like, notably, energy efficiency in general. 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.

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 9.1.2.1.4.1 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.

These analyses could be criticized from a bottom-up perspective because of their reliance on econometric assumptions and because they neglect the role of accompanying measures apt to accelerate the adoption of energy efficient equipment. Moreover, such stylized model simulations neglect important institutional characteristics of the European energy market (for example, natural gas prices are effectively linked to mineral oil prices as there is no gas to gas competition; or, the decision to build nuclear power stations being significantly influenced by political choices), and therefore tend to overstate the likely actual difference between carbon and energy taxes.

The analyses, however, provide important insight about the impact of other environmental concerns on CO₂ abatement and illuminate the importance of the trade-off. This loss in terms of CO₂ reduction seems more important in Germany (between 35% to 49%) and in UK (32.5% for Hermes-Midas) than in France (20%) where the shift of electric supply towards nuclear energy has been completed during the two past decades.

9.1.2.2 A Review of Bottom-up Studies

This section summarises and compares the results of major co-ordinated 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 (sometimes also called the CRASH programme),

- three of the UNEP Costing studies (1994b) (Denmark, France, Netherlands),
- the recent IPSEP study (1993) covering five countries
- the ETSAP study (Kram, 1993)
- the Swedish study of 1989, Johansson and Bodlund (1989).

9.1.2.2.1 Methodology of the Studies

The COHERENCE study adopted a uniform modelling methodology, the EFOM linear optimisation model developed by the research programme of the European Community. In the UNEP studies, a common methodological framework was applied across countries comprising uniform assumptions on technology input data, time horizons and cost definitions. The Netherlands study used the MARKAL linear optimisation model, whereas the French study relied on a bottom-up simulation framework combined with a static general equilibrium model. The Danish study used an integrated energy system simulation model.

The IPSEP studies defined a common methodological framework and uniform assumptions like the UNEP studies. The customised scenario modelling in the IPSEP project involved a combination of detailed assessment of potential, cost and behaviour related to energy end-use demand and supply options. The participating countries were U.K., The Netherlands, Italy, West Germany and France.

The ETSAP project was a comparable assessment for nine countries using the MARKAL model with consistent cost and technology assumptions. The participating countries were Belgium, Italy, the Netherlands, Norway, Sweden, Switzerland together with the non-European countries (USA, Japan and the provinces of Ontario and Quebec in Canada).

The study by Johansson and Bodlund did not use any formalised modelling framework but focused on the assessment of technologies and their emission reduction potential.

An overview of the methodologies and models is given in Tables 9.2.5 and 9.2.6.

9.1.2.2.2 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 analyse 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 reductions costs.

The study results are highly dependent on the assumptions on energy efficiency measures included in the baseline scenario. The COHERENCE and the ETSAP projects assumed that

all profitable efficiency measures were included in the baseline, which meant that all emission reduction options by definition have positive costs in these analysis.

In the UNEP studies, Denmark, The Netherlands and France followed different principles for baseline definition. Denmark defined its baseline to include the persistence of some major inefficiencies implying that a large potential for no-regret emission reduction options was found. The French study accounted for transaction costs for adopting more efficient technologies and the Dutch study assumed the baseline to be efficient.

The IPSEP and Johansson and Bodlund studies included major inefficiencies in their baselines and found consequently a significant potential for no-regrets.

9.1.2.2.3 The Results

Despite differences in baseline definition, all the studies demonstrate the existence of an economic potential for the reduction of CO₂ emissions at negative or low costs. At the same time, the results demonstrate that the basic assumptions have an important bearing on the existence and possible implementation of no-regret options. This can have a significant effect on the total, average and marginal costs of reductions.

The main results of the European COHERENCE study are shown in Figures 9.1.2.2.3.1 and 9.1.2.2.3.2 and in Table 9.1.2.2.3.1. 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 negligible costs associated with 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.

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). Some of this variation can certainly be explained by intercountry variations in industrial structure, capital stock constraints and different national energy systems. However the national baseline projections and cost assessments still show larger differences than would be expected from "real" differences in energy systems and economic development patterns.

One of the main explanations behind the widely varying national cost assessments is the heterogeneity of the national technology data used in the analysis. 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. It seems for example surprising that France with the present technology mix (large installed nuclear capacity) in the energy system arrives at an abatement cost very similar to Britain and Germany, while Italy arrives at a lower cost. This is in contrast to the fact that the scope for manoeuvre in the power sector is much higher in the latter three countries due to the dominance of conventional power production than in France.

The Coherence study also assessed the potential for negative cost energy efficiency improvements for the countries. This was done by the construction of a MURE scenario which embedded this the end use savings measures. It was estimated that the implementation of these negative cost options would lead to 6% decrease in CO₂ emissions in 2010 from 1988 level for Germany, stabilisation in Denmark and increases of 52% and 82% for Greece and Portugal respectively.

The COHERENCE study was a pioneering study in development of the methodology of comparative cost assessment between countries and gained as such important methodological lessons on the requirements for uniformity in national scenario and technology assumptions. This has induced CEC to organise a homogenous new data collection on efficient energy technologies.

Differences in assessed reduction potential and costs are also seen in the UNEP studies for Denmark, The Netherlands and France. These differences are consistent with "real" variations between the countries in carbon content of energy systems and baseline definitions. Denmark and to a lesser degree The Netherlands have high emission reduction potentials as a consequence of a carbon-intensive power production systems. In the French country study, certain more costly transportation sector measures are included because reductions in electricity supply are limited and end-use demand options are assumed to have positive costs.

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 9.1.2.2.3.2.

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 9.1.2.2.3.3.

The French study estimated a tax rate for emission reductions in a macroeconomic model. In one scenario variant, it was assumed that carbon taxes would be combined with complementary measures in the energy sector such as information, efficiency standards, research and development, grants and with measures in other sectors. The tax was estimated to be \$187.5 per tonne CO₂ for a 12.5% reduction in 2005, \$75 per tonne of CO₂ for a 25% reduction in 2030 and \$1425 per tonne of CO₂ for a 50% reduction in 2030. The lower tax rates in 2030 compared with 2005 are due to assumptions on technical progress.

Despite the fact that the UNEP country studies followed a common methodological framework (UNEP 1994) the results still show differences as 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 compared directly between the countries.

Still a different approach to country differences is taken in the IPSEP study. Though the analysis started from the baseline data and demand growth projections unique to each of the five countries, emphasis was placed on the aggregate carbon reduction potentials and costs in the five-country region. This reflects current plans for a common internal market within the European Community, including a homogenization of the policy frameworks for the energy sector.

The costs and potentials for conventional fossil supplies, nuclear power, demand-side efficiency, cogeneration, and renewables potentials were developed in several substudies. The costs of efficiency resources include estimates of administrative costs developed from a review of market transformation policies (standards, financial incentives to consumers, financial incentives to manufacturers of efficiency equipment, and utility regulatory reforms) in Europe and the US. High/low sensitivity ranges are modeled not only for fuel prices, but also for technology and administrative program costs. In the behavioural module of the analysis, assumptions about implementation rates are validated on the basis of empirical investigations of consumer responses to market transformation policies (standards, financial incentives to consumers, financial incentives to manufacturers of efficiency equipment, and utility regulatory reforms). The effectiveness of these policies is expressed in terms of the fraction of the resource potentials assumed to be mobilized by 2020. Scenario results are then given for 25%, 50%, 75%, and 100% effectiveness.

Figure 9.1.2.2.3.3 shows results for the least cost (1a) and minimum risk (1b) cases for the five countries combined, based on four permutations of cost assumptions. Because of feedback effects, and combination of low fuel prices and low technology costs is considered most plausible. For this combination, emissions drop by 40 percent relative to 1985 in the least cost case, and energy service costs drop by 23 percent relative to the CEC reference case. In the minimum risk case, the same combination of cost assumptions results in emissions dropping by 60 percent while costs decline 20 percent.

The country-to-country variations of the IPSEP study are smaller than in other studies. The large "no regrets" efficiency potentials found in all five countries make the differences on the supply side relatively less important.

Although the Swedish exercise of 1989 included a detailed assessment of end-use demand options similarly to the IPSEP study higher abatement cost was estimated. This is a consequence of very low Swedish CO₂ emissions today because of the present use of hydro power and nuclear power. In the future these two supply sources will be supplemented and substituted respectively by fossil fuels due to other environmental

regulations than the aim to reduce CO₂ emissions.

The results of the ETSAP study are illustrated in figure 9.1.2.2.3.4 showing the marginal costs in the year 2020 of successive carbon emission reductions from the 1990 level. There are wide variations among the countries. Norway, Sweden and Switzerland - which now emit the least CO₂ per capita - would be among those measuring the highest cost to achieve a specific further reduction in CO₂ emissions. The Netherlands with the assumed availability of CO₂ removal and storage options, appears able to make the greatest reductions at the least cost.

9.1.2.2.3.1 Time Dependence of Abatement Costs

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 Dutch UNEP studies simply because more technologies are available.

9.1.2.2.4 The Dependence of the Results on Input - Assumptions and Modelling Approach

Though the choice of models in bottom-up analysis may have some effect on the calculated carbon reduction costs, these results cannot explain the large differences in findings between the CEC, UNEP, IPSEP and ETSAP studies. Differences appear to be explained mainly by two factors: the assumptions in some studies that the reference case is already more or less economically efficient, and the use of limited number of possible efficiency improvements.

More systematic research on the importance of technology assumptions for the results of bottom-up studies would be useful. Optimisation models may encourage the use of more aggregate data on end-use demand estimated on historical data and in some cases this may imply a more pessimistic assessment of the savings potential. However studies have also shown that when identical data on efficiency potentials are used, optimisation and simulation results appear to converge. Also, optimisation models are being continuously refined. A large contribution is currently being made to provide a range of standardised algorithms for modelling alternative policy programs.

Overall, the divergent results suggest the need for further empirical research on how end-use market efficiency could improve the implementation of end-use options. Also,

1 comparative bottom-up modelling exercises should be done in which identical national data
 2 sets for efficiency potential and costs are combined with standardised assumptions about
 3 implemented fractions in the reference case. Such an exercise has already been done for
 4 Denmark. It was shown that uniform input assumptions in the EFOM model for Denmark
 5 and the Danish UNEP study produced very similar results (Morthorst 1992).

6
 7 The French IMACLIM-NEXUS study shows the sensitivity of the results to the
 8 assumptions on the industrial and socio-economic content of the reference scenario. A
 9 second reference scenario considers that urban transportation problems will become so
 10 important that, independent of CO₂ policy, there will be radical change in urban planning
 11 and inter-mode substitution. New urban policies could determine, between now and 2030, a
 12 change of fuel consumption growth just as significant as a huge taxation of 280 \$/t,
 13 compared to the first reference scenario.

14 9.1.3 Studies of the Costs of Reducing CO₂ Emissions in Transitional Economies

15
 16 The term *economies in transition* is often applied to the countries of the former Soviet
 17 Union, and Eastern Europe. The implication is that market reforms are underway. The stage
 18 of the transition varies dramatically, however by country, and there is no certainty about
 19 the type of economic institutions likely to emerge at the end of this process and the type of
 20 development pattern which will ultimately win out.

21
 22 Modeling emission reduction costs for the formerly planned economies is particularly
 23 challenging. The region has a long history of highly subsidized energy prices, and other
 24 inefficiencies in the structure of incentives. Models which assume the existence of market
 25 mechanisms will miss many of the important features of these economies. Applying
 26 equilibrium models to planned economies assumes that planned economies mimic the
 27 behavior of market economies. This assumption is impossible to accept empirically,
 28 particularly with regard to energy use.

29
 30 The problem is further complicated by the fact that the transition process per se generates a
 31 state of crisis. The Russian GDP, for example, declined by 18.5 percent in 1992. Economic
 32 activity in 1993 was lower than in 1985 (Bashmakov, 1994). Standard econometric
 33 techniques derived from historical records cannot be consequently applied without caution.
 34 Until these economies achieve a more stable footing, predictions of future growth will be
 35 tenuous, at best.

1 9.1.3.1 A Review of Top-down Studies

2
 3 The problems of adapting top-down models for use in transitional economies explains the
 4 dearth of applications for this region of the world --particularly when compared to the
 5 growing body of analysis being amassed on developed economies. The few studies that do
 6 exist were conducted by Western economists, using models that are best suited for
 7 application within the OECD. This is not to imply that the studies are without merit.
 8 Indeed, as we will see shortly, they have yielded some useful insights about the costs of
 9 emissions reduction. Nevertheless, as we move beyond the OECD, we need to be
 10 increasingly circumspect in the interpretation of results.

11
 12 A key issue in extending top-down models to emerging economies is the treatment of
 13 energy subsidies. Many of the early studies showed relatively high emission reduction
 14 costs. See for, example, Dean and Hoeller (1992). Critics claim that the high numbers
 15 reflect "the difficulties top-down studies have with economies undergoing restructure
 16 (Grubb et al., 1993)." They argue that the high costs are due, in large part, to a failure to
 17 adequately capture the demand-side impacts of subsidy removal.

18
 19 There is some validity to this criticism. The removal of subsidies will result in costless
 20 conservation in addition to that induced by the AEEI factor. The early studies may have
 21 indeed underestimated the potential for demand-side savings. (It is important to note,
 22 however that the criticism applies more to the choice of input assumptions than to the
 23 models themselves. The models are not inherently limited to scenarios in which markets
 24 clear.)

25
 26 The importance of existing market distortions is underscored in a modeling experiment by
 27 Manne and Schrattenholzer (1993) using the Global 2100 model. They examined the
 28 sensitivity of emission reduction costs for emerging economies to the presumed size of the
 29 subsidy. They found that the removal of artificial barriers which insulate domestic
 30 consumers from international price movements may well lead to a drop in carbon emissions
 31 over the next several decades.

32
 33 The same result was confirmed in a subsequent study by Manne and Oliveira-Martins
 34 (1994). They used the GREEN and 12RT models to estimate the taxes required to stabilize
 35 emissions at 1990 levels. Importantly, price reforms and the removal of energy subsidies
 36 were included in the "baseline" scenario. This enabled the modelers to separate the impacts
 37 of restructuring from those of a carbon constraint.

38
 39 For purposes of the analysis, the transition economies were divided into two regions: the
 40 countries of the former Soviet Union (FSU) and the Eastern European countries in
 41 transition (EET). Figure 9.1.3.1.1 displays the carbon taxes required to achieve stabilization
 42 in each region. The former Soviet Union and Eastern Europe countries have zero taxes
 43 before 2010. This is because the stabilization constraint is non-binding. With price reforms
 44 and the removal of energy subsidies, there is a decline in emissions relative to 1990 levels.
 45 For the GREEN model, the emissions constraint begins to bite shortly after 2010. For

1 12RT, emissions remain below the 1990 level until 2040.

2
3 Despite the intrinsic difficulties of applying top-down models to the countries of this
4 region, the implications of these analyses are important. The costs of stabilizing emissions
5 may be relatively small for economies in transition. Market failures have undoubtedly
6 limited investment in energy efficiency. The potential for cost-effective reductions in
7 energy use is apt to be considerable. The key is a successful transition towards a new
8 institutional context in which, under whatever form, prices actually reflect the full cost of
9 energy.

12 9.1.3.2 A Review of Bottom-up Studies

13
14 This section summarises selected studies of the potential and cost of carbon emissions
15 reduction strategies in the post-planned economies. Bottom-up methods offer some
16 advantages for dealing with transitional economies in that they focus on the physical stock
17 of equipment and apply scenarios for its evolution, with less concern for anticipating
18 macro-economic equilibrium conditions. However, just as top-down models are constrained
19 by lack of reliable data for these economies, the data on current equipment end-use energy
20 efficiencies is severely limited.

22 9.1.3.2.1 Summary of Studies

23
24 A comparison of emissions reduction cost studies reveals striking differences with the
25 results of some top-down models (see Table 9.1.3.2.1.1). On the bottom-up side, a number
26 of studies have been completed by Eastern European and Russian experts since the
27 revolutions of 1989. Some of this work was conducted using the EPA End-Use Energy
28 Model, while others applied indigenous country-specific models. The EPA model projected
29 future energy demand to the year 2030 in five year increments, giving results for the major
30 fuel types and future aggregate industrial energy intensity. The model estimates energy
31 demand on the basis of economic growth, structural change, price response and technical
32 energy-efficiency improvements not attributed to price response. Like Makarov et al.
33 (1991), most of the bottom-up studies incorporated economic restructuring as a driving
34 force for determining the energy content of economic growth.

35
36 A relationship can be seen between the magnitude of the emissions reductions and costs in
37 the above scenarios, but this factor cannot explain the significant variation in cost estimates
38 across the scenarios. And while the discount rate varied among the studies, there seems to
39 be little correlation between this variation and variations in cost estimates. Indeed, the one
40 major difference in cost estimates in the studies reviewed appears to be that of
41 methodology, specifically the choice of top-down versus bottom-up models (see Figures
42 9.1.3.2.1.1 and 9.1.3.2.1.2 and Table 9.1.3.2.1.1). This result is not surprising given the
43 special nature of planned and post-planned economies.

1 9.1.3.2.2 Evaluation of cost estimates

2
3 The most energy-intensive economies in the world are the planned or post-planned
4 economies (Chandler et al. 1990). However, a short digression on the meaning and
5 importance of energy intensity in the formerly-planned economies may be in order. Energy
6 intensity (energy consumed per unit of economic output) is an important, if controversial,
7 indicator of future emissions. This value is difficult to measure accurately because GNP is
8 difficult to quantify in comparable units. Also, differences in economic structures may be
9 significant.

10
11 If energy intensity is interpreted simply as a surrogate for energy efficiency, then the
12 measure can be misleading. However, a vast literature has verified that the planned
13 economies use energy inefficiently both because they use technology that is not optimised
14 and because the structures of their economies - that is, the remarkable reliance on heavy
15 industry - is not economically justified (Kornai 1990). Yet, most models of future energy
16 use in this region imply both continued high energy intensity and high economic growth.
17 The results are sometimes startling when one realises that they indicate that the formerly
18 planned economies would be twice as energy intensive in the year 2050 as Japan is today.
19 This outcome may be unlikely given the constraints of international competition.

22 9.1.4 Studies of the Costs of Reducing CO₂ Emissions in Developing Countries

23
24 Climate analysts have long recognized that GHG emissions and consequent climate change
25 are a global phenomenon and need global responses. Yet in most global abatement studies,
26 the analysis for developing nations is usually piggy-backed on the developed country
27 studies. The fact that the developed nations at present account for nearly two-thirds of
28 GHG emissions has continued to overshadow the results of the very same models which
29 show that within two or three decades the GHG emissions from the developing nations will
30 surpass those from the present developed nations. GHG abatement studies for developing
31 countries are therefore not many. The relatively few that do exist are based on
32 methodologies designed for use in developed nations. These models tend to treat the
33 dynamics of developing nations as a caricature of industrialized economies.

36 9.1.4.1 A Review of Top-down Studies

37
38 This is particularly so, in the case of top-down models where the dynamics of each
39 geographical regions tend to mirror the market based economics of the western world. The
40 models are market driven and assume the existence of future markets, perfect information,
41 competitive economic dynamics on the demand and supply side, and optimizing behavior of
42 producers, consumers and the government. These assumptions are often found to be invalid
43 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.

9.1.4.1.1 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 9.1.4.1.1.1 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.

9.1.4.1.2 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.

9.1.4.1.3 The impacts of carbon taxes on non-commercial energy consumption

But, even if this conclusion relies non contestable price mechanisms, it should be balanced by the consideration of the role of informal economy who could offset part of the expected gain. That was pointed out, among others by researchers from the OPEC Secretariat who used a macroeconomic model to investigate the impacts of OECD type carbon taxes on developing countries (Walker and Birol, 1992), and explicitly considered the impact of income and price levels on consumption of Non Commercial Energies.

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.

9.1.4.2 A Review of Bottom-up Studies

Most bottom-up studies of developing countries focus at the national level and typically cover scenario periods from 1988/90 to 2020/30. This contrasts with top-down studies which tend to treat developing countries in groups, with the exception of China. Some of the main studies are listed in Table 9.1.4.2.1.

Emission reduction targets in developing country bottom-up studies typically formulate reduction targets as percentage changes from a baseline (or reference) case, reflecting reference economic development and energy requirements (UNEP 1994a), or related to a high emission case for the energy sector (Sathaye and Goldman 1991). This contrasts with most of the studies carried out for developed countries, where emission reductions targets generally are calculated for each scenario in terms of stabilisation or abatement from a given benchmark date.

Two major multi-country studies have been conducted by the Lawrence Berkeley Laboratory (LBL) and by the UNEP Collaborating Centre on Energy and Environment (UCCEE). These two research centres facilitate comparative analysis in a similar way to the studies carried out by the Energy Modelling Forum in the USA. The results and methodological framework of the UNEP and LBL multi-country studies are reviewed in this section along with similar country studies for China, West Africa and South East Asia.

Only some of the studies have estimated the costs of achieving emission reduction: the UNEP studies (UNEP, 1994a), the LBL study for India (Mongia, 1991), and the ADB study for China (Asian Development Bank, 1993). The UNEP studies, for example, 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 (UNEP 1994L).

9.1.4.2.1 Main Assumptions and Findings: Trends and Margins of Freedom for Curbing GHG Emissions

Growth rates of GDP, primary energy consumption and CO₂ emissions are shown in Table 9.1.4.2.1.1 for the reference and emission reduction scenarios of the country studies. The annual economic growth rates range from 3.0% up to 8.0%, with most projections below 5.0%.

A variation is seen between economic growth rate forecasts in different studies for the same country. Generally the growth rates of the UNEP studies are higher than for the LBL studies. This is understandable given the uncertainties surrounding such long term forecasts.

The elasticities of primary energy to GDP, CO₂ emissions to primary energy and CO₂ emissions to GDP are shown in Table 9.1.4.2.1.2 for the reference or baseline scenarios. Many of the countries have a primary energy/GDP elasticity between 0.6 and 0.8, implying that a 1% increase in GDP leads to a .6% increase in energy consumption. This value, which is low if one considers current trends with developing countries, is explained in part by structural changes and technical efficiency improvements expected in these countries over the long run. However, the CO₂/GDP elasticity is close to unity for most of the country studies as a consequence of high expected CO₂/energy elasticities. This latter elasticity reflects development processes in which traditional local biomass and also hydropower resources are expected in future to have a decreasing share of primary energy consumption while commercial fossil fuels are expected to play a larger role. A remarkably high CO₂/energy elasticity is projected in the UNEP Brazil study and in the studies by

Davidson for Ghana, Nigeria and Sierra Leone, where biomass is substantially replaced by fossil fuels in the reference scenario.

The combination of different assumptions on GDP, primary energy and energy supply in the baseline case results in large variations in projected CO₂ emissions. Emission projections range from a six to eight-fold increase for Thailand and Brazil to a two to three-fold increase for other developing countries in the UNEP study. In the LBL study, the projection is for a six-fold increase for India, a five-fold increase for Indonesia and a two to three-fold increase for China, Argentina, Brazil, Mexico and Venezuela in the LBL study. The emission projections of the UNEP and LBL studies are illustrated in Figure 9.1.4.2.1.1 - 9.1.4.2.1.4.

We later discuss the implications of such a wide range of results. Despite these discrepancies, however, the studies converge in suggesting a steep increase in CO₂ emissions from developing countries over the next decades. A second important convergence relates to the estimate of a significant potential for reducing the CO₂ content of economic growth in these countries.

In the UNEP study, the emission reduction scenario for all countries, with the exception of Thailand and Brazil, shows a 40-50% emission reduction from the reference scenario by 2020/30. However, this still implies up to a doubling of emissions, relative to the present, for these countries. For Thailand and Brazil, a 30% and 50% reduction from the reference scenario respectively, still leads to a six-fold and three-fold emissions increase from the present.

In contrast, in the low emission scenarios of the LBL study, emissions are projected to increase by only about 50% from present levels in Brazil and Argentina after a 54% and 25% reductions respectively from the reference scenarios. China, Mexico and Venezuela are projected to have emission increases between a doubling and tripling of today's level after 20% to 30% reductions from the baseline scenario. India and Indonesia are projected to have a persistent high emission level amounting to a four to five-fold increase from the present after small reductions of 13% and 18% from baseline respectively.

While these potentials for CO₂ emission reduction in developing countries are insufficient to offset the overall tendency toward increased CO₂ emissions, they are large enough to contradict the notion that, given current low levels of energy consumption in these countries, there is little utility in efforts to control their emissions.

A similar conclusion can be drawn from a study by the Asian Energy Institute. Bangladesh, Brazil, China, India, the Islamic Republic of Iran, Japan, South Korea and Thailand were included in the study. The study assessed the potential for emission reduction in these countries through energy efficiency improvements and a shift toward supply technologies with lower carbon intensity.

9.1.4.2.2 Emission Reduction Costs

The UNEP country studies include an estimation of costs for emission reductions between 12.5% and 25% from the baseline scenario in the short-term (2005/10) and between 25% and 50% 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 9.1.4.2.2.1 and 9.1.4.2.2.2 show the cost curves for a number of participating countries for both the short-term and long-term target years.

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 from baseline of up to 10% to 15%. 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 higher cost options were included in the analysis. Those that were included tend to be expensive supply-side options, implying a steep increase in marginal costs.

The long-term marginal cost curves shown in Figure 9.1.4.2.1.2 show many similarities for the developing countries. Venezuela may be regarded as an exception with a completely positive cost curve. This is the result of the methodological decision to include most "no regret" options in the baseline.

As with 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 for most countries.

Table 9.1.4.2.2.1 shows marginal, average and total emission reduction costs for the short and long term reduction targets. In the long-term, the average emission reduction costs for reductions from baseline of between 25% and 50% range between -\$5 and +\$37 per tonne of CO₂. Total emission reduction costs are negative for Egypt and Senegal.

The study of India (Mongia et al. 1991) estimated emission reduction costs for two emission reduction scenarios. One assumes a least cost supply system requiring foreign capital and resources. Another emission reduction scenario assumes a more expensive supply system with greater reliance on domestic renewable energy sources. The first emission reduction case estimates average emission reduction costs in 2025 to be -\$9.5 per tonne of CO₂ for a 45% reduction from baseline. The second case, based on domestic resources, is significantly more costly for achieving the same level of emission reduction.

9.1.4.2.3 The Special Case of China

Because of the expected magnitude of its future CO₂ emissions, China warrants separate treatment. The Asian Development Bank has, in collaboration with the Chinese government, conducted a comprehensive technology assessment study for the period 1990 to 2050 (ADB 1993). The economic growth rate for the baseline scenario over this period is assumed to be 6.0%, primary energy growth 3.1% and the CO₂ emission growth rate 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 combined with large 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, as well as some hydro power.

It is assumed that 3.6% annual efficiency gains in power production can be achieved until 2000, decreasing to 1.8% for the rest of the period to 2050. These high savings are related to the current low power production efficiency of 30% combined with the high expected investment level in new efficient electricity generation technologies.

9.1.4.2.4 Comparing Numerical Results: Critical Assumptions About Technical Options

The country studies have estimated emission reduction potential as a function of technical options, either related to individual technologies or to comprehensive packages of technologies. The costs and emission reduction potential of technical options have been assessed using energy system models that evaluate end-use efficiency improvements, fuel substitution and new supply technologies in an integrated way. This analysis has been conducted with different degrees of sophistication depending on the individual country and the particular study.

As an example, a summary of the main technical emission reduction options in the UNEP country studies is presented in Table 9.1.4.2.4.1. The national options are listed in aggregated form and thus represent classes of options rather than individual technologies. The cost curve may be considered in three segments, representing negative/low-cost options, intermediate-cost options and high-cost options. One general similarity among country studies is that the least expensive part of the cost curve contains energy end-use savings in households and/or industry. Another is that electricity supply options first appear in the intermediate cost part of the reduction potential cost curves.

On the supply side, most of the studies focused on 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 include any further reduction after the exhaustion of these options.

9.1.4.2.5 Comparability of the National Studies

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 efficiency improvements, energy supply efficiency improvements and the 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 is also likely to be cheaper than currently estimated.

The individual country studies are difficult to compare quantitatively because of differences in methodological approach and in scenario assumptions on economic growth, energy requirements and emission reduction costs. An important difference is to be found in the baseline scenario assumptions used in the different studies.

In the UNEP studies, the national research teams took official macroeconomic forecasts as the starting point for energy demand projections. In contrast, the LBL studies used a broader level international perspective to estimate an economic structure and income distribution which could be achieved in a developing country within a given time horizon. Thus, for example, it could be assumed that a country like Brazil would approach an economic structure and income distribution comparable to that of Spain in a given time frame.

The advantage of using national macroeconomic projections is that they reflect national views on development. However, national forecasts may be only partially consistent and realistic, while international economic studies may be of help in establishing a consistent data set across countries. Studies made on a common, well documented background can also be easier to compare than studies which use different national forecasts.

The degree of optimism of experts from different countries with regard to the penetration of energy efficiency or of carbon free energy supply options may differ dramatically. This can lead to different critical assumptions in the baseline as well as in the emission reduction scenarios. One approach is to assume that all possible efficiency improvements are implemented as part of the baseline scenario, implying that only positive-cost options remains. If the existing energy system - as in many developing countries at present - is relatively inefficient, the above mentioned approach implicitly assumes large investment programs to be carried out to implement the "efficient options" in parallel to any emission reduction effort. If instead it is assumed that major inefficiencies persist in the energy system in the baseline scenario, there will be an interrelationship between emission reduction measures and the general effort to overcome barriers for efficiency improvements in the energy system. In the UNEP study, for example, where country research teams were free to make judgments, the team for Venezuela assumed that all profitable efficiency improvements would be implemented in the reference scenario, while the teams for Brazil

and Thailand assumed a relatively inefficient reference scenario.

Another difference in reference scenarios between countries relates to difficult assumptions about structural change in the economy, about fuel supply and about the overall level of development. The striking difference between the UNEP and LBL in the case of Brazil is an enlightening example of the consequence of these differing assumptions. Part of the difference between the two studies for Brazil can be explained by different assumptions on the GDP growth rate, but another key difference is a consequence of the low fuel price increase projected in the UNEP study during a period long enough to make the existing alcohol fuels program unprofitable. Consequently, the reference case assumes replacement of present biomass use, including ethanol, with fossil fuels. The LBL studies, in contrast, defined reference energy scenarios as a continuation of historical trends, implying that the alcohol fuels program would be sustained in Brazil. 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.

9.1.4.2.6 Conclusion

The bottom-up CO₂ emission reduction costing studies carried out for the energy sector for developing countries exhibit, despite differences in methodological approach, some common empirical results:

- The 30-40 years reference scenario projections show a tendency to decreasing energy/GDP intensity, but increasing CO₂/energy intensity.
- The potential for a 30-40% emission reduction from baseline over a 40 year time frame has been estimated. However, even after such reduction, emissions will on average be two or three times more than present levels because of economic growth.
- The emission reduction potential includes low/negative-cost options relating to end-use and conventional supply technologies in the short to medium term. In the 30-40 years time frame, the UNEP country studies have estimated average emission reduction costs to be below \$37/tonne of CO₂.

9.1.5 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 abatement costs. 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 abatement supply curve.

Of course, all of the caveats expressed above about the limitations of country-specific or region-specific models should be borne in mind when evaluating the results of global studies. In addition, the global analyses confront aggregation issues which further complicate the interpretation of results. Not surprisingly, most of the global studies employ top-down methodologies. Nevertheless, there have been several bottom-up studies which illustrate the overall technical potential for curbing down greenhouse emissions at a world level.

9.1.5.1 A Review of Top-down Studies: the importance of international cooperation

Several of the models used for regional analyses provide the capability for analyzing emission abatement 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 9.1.5.1.1 summarizes the results of recent studies using these models. Not surprisingly, there is considerable disagreement concerning the costs of emission abatement. Consistent with the regional studies, the top-down global analyses indicate that emission abatement will involve positive costs, but the size of the model based cost estimates 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 abatement at the regional and global level.

9.1.5.1.1 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 rates required to achieve specific emission abatement targets and the resulting 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 emission stabilization scenario.

For emissions stabilization, it was assumed that global emissions would be permanently held at 1990 levels. The global 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 at 1990 levels without the opportunity of shifting emission abatement from high to low marginal abatement 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 9.1.5.1.1.1 compares output losses entailed by stabilizing emissions in the year 2020. It also shows the reduction in the average 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 the reasons for the differences in abatement cost estimates, the discussion of the preceding sections points to several possible causes.

The higher the baseline emission level, the more stringently carbon emissions have to be curtailed to achieve a given target, and hence the higher the overall abatement costs. The global baseline, however, is not the sole determinant of global abatement costs: The GREEN baseline projects the highest emissions for the year 2020, hence it requires the largest annual reductions to stabilize emissions at their 1990 level. Yet this does not lead to the highest cost estimates. This is because GREEN is the most optimistic of the four models concerning the speed 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 emission stabilization. Even so, estimated costs (in terms of resulting output losses) are higher than those projected by CRTM. This is because ERM does not include backstop technologies, resulting in higher marginal costs of emission abatement.

In a separate experiment, it was determined that ERM and MR project essentially the same

1 baseline emissions when employing identical rates of autonomous energy efficiency
2 improvements. However, for the OECD study, MR adopted an average annual rate of 0.5
3 percent, whereas ERM assumed that non-price induced efficiency improvements occur at
4 twice this rate. Standardization for this key parameter brings results of these two models
5 with respect to their projections of GDP losses from emissions abatement much closer
6 together.

7
8 The OECD Model Comparison Project suggests that the principal reason why model based
9 studies differ with respect to estimates of both baseline emissions and abatement costs is
10 alternative views about the future characteristics of the energy system embodied in the
11 models. In an attempt to place greater reliance on expert knowledge in this area, Manne
12 and Richels (1994) polled a group of individuals on their beliefs about key parameters to
13 which abatement costs are particularly sensitive.

14
15 For each parameter, expert beliefs were encoded in the form of probability distributions
16 which were in turn combined to form a group probability distribution. Using the poll
17 responses to describe the uncertainty surrounding critical parameters, a probability
18 distribution was then constructed for the costs of stabilizing global CO₂ emissions at 1990
19 levels, using the MR model.

20
21 Figure 9.1.5.1.1.2 presents the results of this analysis. The spread of the distribution is quite
22 broad, ranging from .2 to 6.8 percent of gross world product (GWP). The median (that is,
23 the fiftieth percentile) is located at approximately 1.0 percent of GWP. The distribution is
24 also quite skewed. Because of the long right-hand tail, the mean value lies to the right of
25 the median, at approximately 1.5 percent of GWP.

26 27 9.1.5.1.2 The costs of meeting alternative emission targets

28
29 In addition to the emission stabilization scenario, the OECD project examined three
30 alternative scenarios in which the growth rate of emissions in each region is reduced below
31 that of the corresponding baseline by 1, 2 and 3 percentage points, respectively. Figure
32 9.1.5.1.2.1 plots global GDP losses as a function of worldwide emissions. Although there
33 are significant variations in cost estimates across models, the results yield some important
34 insights.

35
36 First, notice that the costs of stabilizing emissions at 1990 levels (approximately 6 billion
37 tons) are lower in 2000 than in later years. The increase in emissions over the present
38 decade is relatively small and there are ample quantities of low-cost substitutes (e.g.,
39 natural gas and demand-side management) to achieve the objective.

40
41 This situation does not persist as we move out in time. Although technical progress may
42 eventually lower the marginal cost of emission abatement, more and more carbon must be
43 removed from the energy system in order to maintain a particular target. As a result, annual
44 losses are apt to increase.

45

1 As one would expect, output losses and macro-economic impacts in general rise with the
2 stringency of the abatement target, but it is important to note the non-linear nature of the
3 loss function. Successive emission reductions are increasingly expensive. As cheaper
4 options to reduce emissions are used up, it becomes increasingly difficult to substitute for,
5 or to economize on, fossil fuels.

6
7 For the models which incorporate backstop technologies, the marginal cost of emissions
8 abatement will eventually level off. This accounts for the linear nature of the total cost
9 curves for CRTM and MR in the year 2100. ERM, on the other hand, excludes backstop
10 technologies. Hence costs continue to rise non-linearly as a function of emissions reduction.

11 12 9.1.5.1.3 The potential gains from international cooperation

13
14 Emission reduction actions affect global emissions and atmospheric concentrations equally,
15 irrespective of the geographical and sectoral origin of the emissions. The least-cost global
16 abatement strategy requires reducing emissions where it is cheapest to do so. If the costs of
17 reducing emissions by a ton were constant and the same in all regions, the location of
18 emission reduction would have no effect on global costs. To the extent that marginal costs
19 vary among regions, there are opportunities for efficiency gains through international
20 cooperation.

21
22 These opportunities may be exploited through a system of international trade in carbon
23 emission rights or a global carbon tax. Emission rights trading would allow for a more
24 efficient allocation of emission reductions across regions by letting countries trade to the
25 point where the marginal cost of emission reduction is the same in all places and activities.
26 A global carbon tax would also result in the marginal cost of emission reduction being
27 equal for all countries.

28
29 Figure 9.1.5.1.3.1 shows the carbon taxes that would be required, on a region-by-region
30 basis, to achieve a given level of emission reduction (OECD, 1994). Although these
31 "emission reduction cost curves" are from a single study, virtually all analysts agree that
32 the marginal costs of emission reduction are apt to vary widely among regions. Efficiency
33 gains can be reaped from shifting abatement from high to low marginal cost regions. If the
34 resulting cost savings are shared between participating regions, all can be made better off.

35
36 The potential gains from international cooperation can be demonstrated by comparing the
37 total costs of achieving a global emissions target, alternatively with and without trade in
38 carbon emission rights. Table 9.1.5.1.3.1 reports the results of such an experiment. From
39 the viewpoint of economic efficiency, trade in emission rights is clearly worthwhile. A
40 reduction strategy in which each region reduces its emissions by the same percentage will
41 not be globally cost effective.

42
43
44
45

9.1.5.1.4 Allocation of emission rights

The establishment of international trade in carbon emission rights requires a decision on the allocation of emission rights among nations, which in turn has major implications for the international distribution of wealth. The decision on how emission rights are distributed among regions does not affect global abatement costs significantly⁴, but it will have a major impact on the distribution of net gains and losses and hence on the perceived equity of the agreement. This is a political rather than an economic issue, as there is no unique or objective definition of fairness (see chapter 3).

Edmonds et al. (1993) studied a variety of schemes for allocating emission rights. At one end of the spectrum they considered a "grandfathered" emissions principle in which future emission rights are allocated on the basis of the share in global emissions at the time of joining a global abatement agreement. At the other end of the spectrum, they examined an "equal per capita emissions" principle where emission rights are allocated on the basis of regions' shares in adult population.

Figures 9.1.5.1.4.1 and 9.1.5.1.4.2 are based on a scenario in which global emissions are permanently held at 1990 levels, representing results obtained by grandfathering emission rights, and granting quotas on the basis of equal per capita emissions, respectively. The allocation of emission rights differs markedly under these two extreme quota allocation schemes.⁵ OECD countries hold on to approximately fifty percent of the emissions rights when the status quo is maintained under a grandfathering scheme, while under the equal per capita emissions scheme, their share drops to about twenty percent.

The implications for regional net costs incurred are as expected: The OECD is much better off with the status quo. Indeed, the OECD region would be a seller of emission rights, and the resulting wealth transfers would be sufficient to reduce the region's GDP losses from abatement to negligible level. Under such a scenario, the economic burden on developing countries would be substantial.

An equal per capita quota allocation scheme would substantially shift the distribution of net benefits and losses: The OECD countries would incur significant net income losses, and the region labeled ROW (rest of world) would be a winner. Under either scheme, China incurs substantial net income losses, except for the very early years: Unless it can greatly increase its energy efficiency, China's rapidly rising demand for energy far outstrips its allocation of emission rights, even under an equal per capita quota allocation rule.

In a third scenario, also based on emission stabilization, Edmonds et al. explore what they refer to as a "no harm to developing nations" principle. Here developing nations receive sufficient emission rights to cover their own emissions and to generate sufficient revenue from excess quota sales to cover the economic cost of participating in the agreement. This leaves developing countries no worse off (in terms of total production plus income transfers) than had they not participated in the agreement. The results under such a quota allocation rule in terms of regional wealth transfers and net income changes are shown in

Figure 9.1.5.1.4.3.⁶

9.1.5.1.5 Carbon "leakage"

Some proposals for limiting CO₂ emissions call for high-income countries to take the lead in reducing emissions. When abatement actions are limited to a subset of regions, it is important to consider so-called carbon "leakage" effects, which represent the impacts of the emission policies of abating regions upon the emission levels of non-abating regions.

Leakage can occur through a number of channels, including

- a) the re-location of the production of energy intensive products to non-abating regions,
- b) energy market effects, including increased energy consumption in non-abating regions, and inter-fuel substitution between fuels of differing carbon contents, due to the (differential) decline in fossil fuel prices in response to reduced demand in abating regions,
- c) changes in regional incomes (and thus energy demand) due to terms of trade changes.

Such leakage effects can be positive or negative (i.e., reducing carbon emissions in non-participating regions). Negative carbon leakage occurs for example in the case of a reduction in the incomes of energy exporting regions when major oil consuming regions abate carbon emissions.

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 unilaterally 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) estimated even higher leakage rates. They find that for some industries (e.g., fertilizer production), unilateral abatement 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

1 case in which the OECD acts unilaterally to reduce emission by 20 percent below 1990
2 levels and finds that 25 percent of the OECD region's reductions could be offset indirectly
3 through changes in international trade patterns.

4
5 The reasons why results differ so widely are not entirely clear. Manne and Oliveira-Martins
6 (1994) have attempted a systematic model comparison of results from I2RT and GREEN.
7 They find that much of the differences in leakage rates reported by the two models can be
8 explained by different assumptions concerning the response of trade flows to changes in
9 comparative advantage and competitiveness entailed by a regional carbon tax. Other key
10 determinants of the extent of carbon leakage are the size and composition of the region
11 undertaking unilateral abatement action, the supply elasticities of different fossil fuels, and
12 the elasticity of substitution between energy and primary inputs of labor and capital in the
13 production process in participating and non-participating regions. The model comparison,
14 needs to be extended to include other models, particularly those which show extremely high
15 rates of leakage before firm conclusions concerning the leakage effects of unilateral
16 abatement actions can be drawn.

17 9.1.5.1.6 The costs of stabilizing atmospheric CO₂ concentrations

18
19
20 The United Nations Framework Convention on Climate Change has as its ultimate
21 objective the "stabilization of greenhouse gas concentrations in the atmosphere at a level
22 that would prevent dangerous anthropogenic interference with the climate system." The
23 question of what constitutes an appropriate concentrations level is likely to remain the
24 subject of intense discussion for sometime. But there is little disagreement over a
25 subsequent clause in the Convention -- that "policies and measures to deal with climate
26 change should be cost-effective so as to ensure global benefits at the lowest possible cost."

27
28 The issue of cost-effectiveness was addressed in a study by Richels and Edmonds (1994).
29 A particular concentrations target can be achieved in a variety of ways. Some will be more
30 costly than others. The authors attempted to identify emission paths that minimize the costs
31 of achieving alternative concentrations levels. They used a reduced form carbon cycle
32 model to construct alternative emission paths. Global abatement costs were calculated using
33 the Global 2100 and Edmonds-Reilly models.

34
35 The analysis suggests that the emissions time-path may be as important as the
36 concentrations level itself in determining the costs of emissions abatement. Time is needed
37 both for an economical turn over the existing capital stock and to develop and deploy low-
38 cost carbon-free alternatives.⁷ The most cost-effective emission time-paths are those which
39 provide the greatest flexibility in managing the transition away from fossil fuels. Shifting
40 emission reductions into the outer years can reduce costs substantially while preserving
41 both the concentrations target and the date at which the target is achieved.

42
43 As an example, the authors calculated the economic costs associated with two alternative
44 scenarios for limiting atmospheric CO₂ concentrations to 500 ppmv in the year 2100 (see
45 Figure 9.1.5.1.6.1). One involved stabilizing global emissions at 1990 levels through the

1 end of the next century. The second provided for some increase in emissions during the
2 early years when the costs of emissions abatement are highest, followed by sharp
3 reductions in the later years when it is cheapest to do so. For this example, shifting
4 emission reductions into the outer years reduced costs by as much as 50 percent.

5
6 The fact that deferring reductions may lead to lower costs should not be interpreted as
7 supporting a "wait and see" or "do nothing" strategy. Part of the savings stems from not
8 having to turn over the existing carbon intensive capital stock prematurely. If we are to
9 depart from the business as usual path, however, it is important that the new capital stock
10 be less carbon intensive. This means that energy sector decision makers must commit to a
11 less carbon intensive infrastructure when making new investments. Secondly, new supply
12 options typically take many years to enter into the marketplace. To have sufficient
13 quantities of low-cost substitutes in the future will require a sustained commitment to
14 R&D today.

15 9.1.5.2 A review of bottom-up studies: the critical role of innovation

16
17
18 Several bottom-up studies have been carried out with the aim of providing a normative
19 view of the very long term future. Following the work of Lovins in the seventies and early
20 eighties, the study by Goldemberg et al⁸ played a key role in emphasizing the differences
21 between the developed and developing countries⁹.

22
23 A typical global bottom-up analysis has been carried out for Greenpeace International by
24 the Stockholm Environment Institute, Boston (1993) for the period 1985-2100. The
25 scenario "fossil-free energy future" (FFES) has the following objectives and constraints:

- 26 - meeting ambitious global CO₂ emission reductions targets;
- 27 - phasing-out nuclear power by the year 2100;
- 28 - considering alternative scenarios for infrastructure, population and GDP with the aim
- 29 of achieving a greater degree of economic equity between different regions of the world.

30
31 For comparison, two reference scenarios were used as a high and low projection case for
32 CO₂ emissions, namely the IPCC 1991 scenario as the high alternative and an average of
33 the US EPA's Rapidly and Slowly Changing World cases as the low alternative (IPCC
34 1990; Lashof and Tirpak, 1990). The range of these reference scenarios is shown in figure
35 9.1.5.2.1. The main results of the FFES scenario are shown in table 9.1.5.2.1 together with
36 the IPCC91 and the EPA scenarios. CO₂ emissions decrease to zero in the FFES scenario
37 by 2100, compared with 22.6 (Pg C) in IPCC 91 and 17.7 (PgC) in EPA.

38
39
40 The total primary energy consumption is relatively similar in the FFES and the EPA policy
41 scenario. The FFES and EPA policy scenarios differ significantly, however, in their
42 assumptions on the energy supply system structure. The EPA policy scenario assumes a
43 share of renewables of 77% in total primary energy consumption, while the FFES assumes
44 100% renewables in 2100. Furthermore the EPA policy scenario assumes a higher share of
45

1 biomass, amounting to 58% of primary energy consumption in 2100, compared with only
2 18% in the FFES. The FFES instead expects solar/wind resources to cover as much as 79%
3 of primary energy consumption in 2100 compared with only 9% in the EPA policy
4 scenario.

5
6 The high expectations for the contribution of solar/wind in the FFES links to an assumption
7 of a breakthrough in solar photovoltaic electricity production costs during 2010-2030. In
8 the same way, a breakthrough is expected for electricity production costs for wind power
9 providing an opportunity for areas with poorer wind resources. Finally, the development of
10 advanced storage facilities enable intermittent solar and wind resources to follow a greater
11 part of electric system load. All these assumptions about technical progress explain why the
12 FFES concludes that the costs of implementing the scenario are small compared with the
13 baseline.

14
15 Similar results are produced by the Low Emissions Supply System (LESS) scenarios of the
16 IPCC WG II Second Assessment Report (Figure 9.1.5.2.2). These scenarios provide
17 estimates of the potential for GHG emission abatement with data developed from the
18 detailed technology assessments in the WG IIa assessment process. The energy supply
19 systems were constructed from work by both bottom-up (Lashof and Tirpak 1990;
20 Johansson et al. 1993) and top-down modellers (Edmonds, 1994). In the bottom-up variant,
21 the starting point is energy demand projections by world regions for 2025, 2050, 2075 and
22 2100 developed by the Response Strategies Working Group (RSWG, 1990) as part of the
23 IPCC 1990 Assessment Report. A high economic growth version of this scenario
24 demonstrated the importance of technology assumptions in the LESS analysis. Global GDP
25 grows 8-fold by 2050 relatively to 1985 and 28-fold by 2100 with primary energy
26 consumption growing from 323 EJ in 1985 to 559 EJ in 2050 and 664 EJ in 2100.
27 Biomass, mostly for fuels used directly, plays a major role. It accounts for 31% of primary
28 energy in 2025 rising to 50% in 2100 in one version of the scenario.

29
30 As a comparison with the LESS bottom-up analysis, a top-down analysis was carried out
31 (Edmonds et al. 1994) incorporating performance and cost parameters for some of the key
32 energy technologies used in the construction of the base case. The following six technology
33 cases were modeled:

- 34
35 1. A reference scenario which is very similar to IPCC 1992a; the exogenous end-use
36 energy intensity improvement rate is 0.5% by 2005, rising to 1.0% by 2035 and
37 reaching 1.5% by the year 2065;
- 38 2. Like case 1 but emphasis on energy-efficient power generation from fossil fuels
39 (efficiency reaches 66% by 2095);
- 40 3. Like case 1 but hydrogen, solar and wind power become more competitive;
- 41 4. Like case 3 but compressed hydrogen is used instead of liquefied hydrogen;
- 42 5. Like case 4 but biomass prices are more competitive;
- 43 6. Like case 5 but the autonomous rate of energy efficiency improvements increases to
44 2.0% per year in 2050.
- 45

1 The results of the scenario analysis are shown in figure 9.1.5.2.3 showing global annual
2 fossil fuel CO₂ emissions and energy production and use.

3
4 Cases 5 and 6 show that if the assumed technological characteristics are realized,
5 significant reductions in CO₂ emissions could be achieved without economic penalty as the
6 technologies embodied in the low emissions scenario become competitive under market
7 conditions with traditional fossil fuel technologies.

8
9 These results support the suggestion that the disagreement in the numerical outcomes of the
10 models, in the very long run, is less due to the modelling structure than to the exogenous
11 hypotheses. From a decision making point of view, however, the most sensitive issue which
12 remains to be addressed is the plausibility of this long-term transition if one accounts for
13 all the general equilibrium effects (for example the implications of shifting agricultural
14 activities to fuels production) and for all the transaction costs involved in the transition.

17 9.2 Studies of the Costs of Carbon Sequestration

18
19 Section 8.3.3.1 discussed the difficulties inherent in developing and comparing estimates of
20 carbon sequestration costs. Those difficulties notwithstanding, this section attempts to
21 summarize, compare, and critique the results of regional and global carbon sequestration
22 studies reviewed earlier.

23
24 Many factors affect studies' estimates of carbon sequestration costs and potential, including
25 assumptions, methods and data used with respect to land area, land costs, treatment costs,
26 discount rates, carbon capture rates and patterns, ecosystem components included in the
27 analysis, and the treatment of forest products. The data and assumptions employed by
28 various studies are summarized in Tables 9.2.1 to 9.2.8.

29
30 As an illustration of the variation in data employed by sequestration studies, consider the
31 estimates of land availability by region and practice listed in Table 9.2.1. For the tropics,
32 Grainger (1988) has estimated that 621 x 10⁶ hectares of land may be suitable for
33 establishing forest plantations. Dixon, Winjum and Krankina (1991) appear to be in
34 relatively close agreement with Grainger (1988), estimating that there are 551 hectares
35 suitable for forest plantations in Latin America, Africa and Asia. In contrast, for the same
36 three regions, Houghton et al. (1993) arrive at an estimate of less than half as much -- 251
37 x 10⁶ hectares. The more optimistic figures are lent support by the studies of Ravindranath
38 and Somashekhar (1994) and Xu (1994), which, taken together, suggest that there are more
39 than 150 x 10⁶ hectares suitable for forestry plantations in India and China. The estimates
40 for tropical agroforestry show similar disagreement. Dixon, Winjum and Krankina (1991)
41 estimate that there are 835 x 10⁶ hectares suitable for agroforestry, while Houghton et al.
42 (1993) suggest that 1895 x 10⁶ hectares are available.

43
44 The range of estimates of land availability for the temperate areas is only slightly narrower.
45 Adams et al. (1990), Moulton and Richards (1990) and Richards et al. (1993) suggest that

1 there may be 100×10^6 to 115×10^6 hectares of marginal agricultural land suitable for
 2 afforestation in the United States alone. However, Dixon, Winjum and Krankina (1991)
 3 identify only 42×10^6 hectares in all of North America as suitable for forest plantations.
 4 Parks and Hardie (1993) consider only 10.4×10^6 hectares in the United States for their
 5 analysis, though the land area constraint in their study is determined by an assumed
 6 programmatic budget and not by land availability.

7
 8 Studies have also shown a wide range of estimates of land costs. As discussed in Chapter
 9 8, this factor has proved particularly difficult because of the many non-market
 10 considerations associated with the social cost of converting between land uses. Because of
 11 the difficulty of determining the appropriate figures, some studies simply have not included
 12 land costs as an element of the cost analysis (e.g., Dixon, Schroeder and Winjum, 1991).
 13 Others have apparently assumed that the use of land is costless because it is either public
 14 land (New York State, 1991) or because the wood products will eventually pay for the land
 15 (van Kooten et al., 1992; Xu, 1994). As might be expected, those that have included land
 16 costs have arrived at a wide range of estimates for that variable. Table 9.2.2 provides a
 17 summary of the land cost data employed in the various studies. Note that several of the
 18 studies that provide estimates of land availability do not include cost figures.

19
 20 Initial treatment costs (see Table 9.2.3) are generally expressed as a capital outlay, while
 21 the maintenance costs, if included, are expressed as annual costs. Land costs may be
 22 expressed as either annual costs (rent) or capital costs. The cost analysis is facilitated by
 23 summarizing these costs as either a net present value equivalent or an equivalent annual
 24 cost. The key factor for this operation is the discount rate applied to these costs. Table
 25 9.2.4 summarizes the discount rates used by various sequestration cost studies.

26
 27 The importance of the choice of discount rate depends critically upon the specific structure
 28 of the analysis. For example, Moulton and Richards (1990) defined the cost per tonne of
 29 carbon as a ratio of land rent plus annualized establishment costs to average annual carbon
 30 capture. Since establishment costs are such a small part of the total costs in that analysis,
 31 the difference between applying a 4 percent and 10 percent discount rate was minor.
 32 However, in Richards et al. (1993), which used land purchase costs and time-dependent
 33 carbon yield curves, raising the discount rate from 3 to 7 percent nearly doubled the unit
 34 cost of carbon sequestration.

35
 36 One of the most significant differences among studies is how they have addressed the
 37 irregular flows of carbon inherent in carbon sequestration and the differences in patterns
 38 among activities. For example, as illustrated by Figure 9.2.1, planting loblolly pine on
 39 agricultural land in the Southeast Region of the United States leads to carbon uptake rates
 40 that peak during the second decade after planting and taper off during the next four
 41 decades. In contrast, the carbon uptake rates associated with planting ponderosa pine in the
 42 Mountain States do not peak until the sixth decade after planting. Other carbon
 43 sequestration activities have similar variations in their flows over time.

44
 45 Carbon sequestration studies have dealt with carbon flows in one of several ways. Some,

1 such as Adams et al. (1990) and Moulton and Richards (1990), have used average carbon
 2 yields, expressed in tonnes per acre per year over the first forty years after tree stand
 3 establishment. Others have used yield curves such as those illustrated in Figure 9.2.1 to
 4 describe expected carbon flows on a year by year basis (Nordhaus, 1991; Richards et al.,
 5 1993). A third approach, introduced by Schroeder (1992), expresses program effects on
 6 carbon in terms of storage rather than flows. The method, called mean carbon storage
 7 (MCS), assumes that once a practice is implemented, the forest system is sustained in the
 8 same use over time.

9
 10 Thus the carbon changes are expressed in terms of the change in the amount of carbon
 11 storage on site, averaged over one full rotation. This is expressed as

$$MCS = \frac{\sum_{i=1}^n C_i}{n}$$

13
 14
 15 where C_i is the standing carbon (tonnes) in year i , and n is the rotation length. Finally, the
 16 standing carbon method, a variation on the MCS method, expresses accomplishments in
 17 terms of the carbon standing at the end of the analysis period, say 50 years. This is the
 18 method apparently used by Ravindranath and Somashekhar (1994). Table 9.2.5 provides a
 19 summary of the methods employed by sequestration cost studies.

20
 21 Carbon flows into forests can also be reversed by harvest. Those studies that have
 22 concentrated on plantation establishment have dealt with this issue in one of three ways
 23 (Table 9.2.6). The group of studies that employ the MCS assume that all carbon is released
 24 upon harvest, but that the forestry practices are repeated in continuous rotations (Dixon,
 25 Schroeder, and Winjum, 1991; Dixon, Winjum and Krankina, 1991; Dixon et al., 1994).
 26 Hence, the concept of carbon release is built into the analysis. Another group of studies
 27 assumes that the land planted to trees is permanently withdrawn from other uses, including
 28 harvest of wood products, so that there is no release of carbon (e.g., Nordhaus, 1991;
 29 Richards et al., 1993). This assumption must be reflected in the calculation of land costs.
 30 Finally, some studies simply do not address the release of carbon upon harvest, implicitly
 31 assuming that either the forest area will not be harvested, or that harvest will occur so far
 32 in the future as not to be a concern (e.g., Moulton and Richards, 1990).

33
 34 Several components of a forest ecosystem store carbon, including tree trunks, branches,
 35 leaves and coarse and fine roots; soils; litter; and understory. Studies have varied
 36 significantly with respect to how they address these various components. Some have
 37 included all components in their carbon accounting (e.g., Moulton and Richards, 1990).
 38 Others have limited their analysis to above ground carbon (Dixon et al., 1991). Table 9.2.7
 39 provides a summary of which carbon components are included in each of the studies
 40 reviewed.

41
 42 Chapter 8 provided a discussion and example calculations of the various summary statistics

used in carbon sequestration cost studies to capture the concept of "dollars per tonne of carbon sequestration." Van Kooten et al. (1992) demonstrate the importance of the choice of summary statistic in their analysis of the cost-effectiveness of carbon sequestration in Canada. Their analysis of costs employs the flow summation method, while an appendix provides calculations using the levelization approach. The costs in the latter case rise by a factor of 5 to 10 relative to the former case. Table 9.2.8 provides a summary of the approaches employed by the carbon sequestration cost studies.

9.2.1 Costs of Carbon Sequestration

Table 9.2.1.1 summarizes the estimates of unit costs of carbon sequestration provided by the studies reviewed here. The table indicates that the studies fall into four general categories. One group concentrates on the potential of North America to sequester carbon (Adams et al., 1990; Moulton and Richards, 1990; New York State, 1990; Van Kooten et al., 1990; Parks and Hardie, 1993; Richards et al., 1993). This group predominantly uses a cost levelization/discounting approach. The one exception is van Kooten et al. (1992), and they complement their flow summation approach by providing cost levelization results in their appendix. The second group considers the carbon sequestration potential of major ecological regions of the world using average storage method (Dixon, Schroeder, and Winjum, 1991; Dixon, Winjum and Krankina, 1991; and Dixon et al., 1994). The third group is comprised of studies of the global potential and cost of carbon sequestration (Sedjo and Solomon, 1989; Nordhaus, 1991). Sedjo and Solomon (1989) do not provide unit cost calculations of carbon sequestration, while Nordhaus applies a discounting method. The fourth group, a set of recent studies, examines the potential for carbon sequestration in individual developing countries (Masera et al., 1994; Ravindranath and Somashekhar, 1994; Xu, 1994). These studies use either the average storage method or the flow summation method.

Among the group of studies that concentrate on North America the estimates of carbon costs fall in a relatively narrow range. After accounting for the differences attributable to cost analysis methods, Moulton and Richards (1990) provide the lowest cost range (\$9 per tonne to \$41 per tonne of carbon captured). These estimates were subsequently revised to reflect refined (lower) carbon yield estimates, the elasticity of demand for agricultural land, administrative costs and failure rates (Richards et al., 1993). The analysis by Adams et al. (1991), which is based on a method of imputing land values through consumer welfare loss derived within a mathematical programming model of the agricultural sector, tends to confirm the revised results. Both studies suggest that the marginal cost of carbon sequestration would range from 9 to about 65 \$/ton of carbon captured (levelized cost basis). The New York State (1991) study is in close agreement with the previous two studies.

Parks and Hardie (1993) present a very different picture. They suggest a similar lower range on costs but a very rapid increase that approaches \$500 per tonne of carbon. Several factors contribute to the difference in costs. First, Parks and Hardie recognize much less

land availability than either Adams et al., (1991) or Richards et al. (1993). This means that they move into more expensive land very quickly. Also, as indicated by Tables 9.2.2 and 9.2.4, their annual land costs are estimated at 40-650 \$/ha/yr and their discount rate is 4%. This suggests a capitalized land cost over the ten-year rental contracts of 320 \$/ha to 5300 \$/ha, a rental cost that is higher than that used by Richards et al. (1993) for the outright purchase of land. Also, Parks and Hardie (1993) use lower carbon yield estimates and include only tree carbon in their calculations. Finally, and perhaps most importantly, their costs are annualized over only a 10-year contract period. While this may be appropriate for their analysis of a specific hypothetical government program, it almost certainly overstates the costs of carbon sequestration in a broader context since carbon capture continues for several decades into the future, even after the end of government land rental payments.

In their presentation of levelized costs, van Kooten et al. (1992) also provide higher estimates of carbon costs than either Adams et al. (1991) or Richards et al. (1993). This might be surprising in light of the fact that they do not include land costs in their estimates. The difference can be attributed in part to higher initial establishment costs and low growth rates expected in the Canadian forests. Their carbon capture rates are also low because they apparently only consider the carbon in the tree bole (trunk) and not whole ecosystem carbon.

The two studies of broad geographic/climate regions suggest that the costs of carbon sequestration may be relatively low for all three types of practices - forest plantations, forest management and agroforestry (Dixon, Schroeder and Winjum, 1991; Dixon et al., 1994). Although these costs are calculated using the average storage method, the costs presented here suggest lower estimates than those derived in the North American studies. It is interesting to note that Dixon, Schroeder and Winjum (1991) find relatively little difference among the boreal, temperate and tropical regions with respect to the carbon sequestration costs associated with forest plantations and forest management, which range from \$2 per tonne to \$8 per tonne and \$1 per tonne to \$13 per tonne, respectively. In contrast, the carbon sequestration costs associated with agroforestry are considerably higher in the temperate region, \$23 per tonne, than in the tropics where the costs are \$5 per tonne. In the second study, however, that relation seems to be reversed, where the cost in the tropical areas is \$2 to \$69 per tonne and the cost in North America is \$1 to \$6 per tonne (Dixon et al., 1994). The reason for this switch is apparently due to the fact that the relative costs of initial treatment in the temperate zone were lowered in the second study and the MCS capacity of land was raised.

The two studies of global cost estimates differ significantly. The Nordhaus (1991) estimate of the unit costs of global carbon sequestration through afforestation is much higher than those from the other two groups - \$42 per tonne to \$114 per tonne. This is a bit surprising, given the fact that Nordhaus' land and treatment cost figures are similar to those used by other studies. The difference in results is almost entirely attributable to how the Nordhaus study treats carbon yields. First, Nordhaus (1991) uses average carbon yield factors derived from the review of greenhouse gas policy options conducted by the EPA (1989). These figures are for carbon yields on average commercial timber land and probably substantially

underestimate yields expected from conversions of marginal agricultural land to forestry plantations (see Table 9.2.5 for a comparison with other studies). Second, the analysis limits the total cumulative carbon to 30 tonnes/ha to 50 tonnes/ha, and assumes that this amount occurs over a forty-year period following plantation establishment. These figures are certainly at the low end of the expected carrying capacity of forest plantations (See, e.g., Dixon, Schroeder and Winjum, 1991). Finally, to portray the timing of carbon capture, Nordhaus applies a logistic growth curve that has the effect of delaying carbon uptake relative to the average flow approach or the MCS approach. Combined with a levelization approach to costs, this delay in carbon uptake contributes to an increased unit cost of carbon capture. (Richards et al., 1993 also captures this effect.)

At the other extreme, Sedjo and Solomon (1988) provide land and treatment cost figures that would suggest a cost of carbon sequestration of \$7 per tonne on a cost levelization basis and \$3 per tonne on a flow summation basis. This relatively low cost estimate is due to their optimistic assumption regarding carbon yield, which is based upon growth rates in the Pacific Northwest and Southeast regions of the United States. Applying these rates to a global analysis is probably unrealistic, but it does suggest that at least in some regions carbon sequestration should be relatively inexpensive.

The three studies of individual developing countries provide an interesting contrast. While Masera et al. (1994) estimate that carbon sequestration on forest plantations in Mexico would cost 5 to 11 dollars per tonne, Xu (1994) calculates that carbon could be stored on plantations in China at a negative cost. The latter result stems from the fact that Xu includes revenues from the sale of forestry products in the cost calculations, and that China has a largely unmet demand for timber. The interpretation of cost figures for Ravindranath and Somashekhar (1994) is unclear. While they apparently use a flow summation approach in their cost calculations, they do discuss the application of discounting, at zero and one percent, to the carbon flow, which would suggest a levelized cost method. Their costs range from 0.09 to 2.78 \$/tonne.

9.2.2 Potential Quantities of Carbon

The studies show a wide range of estimates of potential for carbon sequestration (Table 9.2.2.1). At one extreme Sedjo and Solomon (1988) have estimated that if 465 million hectares of land can be secured, 2900×10^6 tons of carbon per year can be removed from the atmosphere in forest plantations. This is nearly one half of current annual global levels of carbon emissions. At the other extreme, Nordhaus (1991) suggests that an average of only 280×10^6 tons per year can be captured over a period of 75 years, even in the presence of a global effort. The difference between these two estimates is almost entirely due to the estimates of carbon yields, since their assumptions on land availability are very similar. At the same time, Dixon et al. (1994) estimate that globally $1100\text{--}2200 \times 10^6$ tons can be captured annually using expanded agroforestry practices alone.

Opportunities in the most northern latitudes appear somewhat limited. Dixon, Schroeder

and Winjum (1991) suggest that summing across all practices, only 2×10^6 tons can be accumulated in the boreal regions. Averaged over their 50 year period, this yields 40×10^6 tons per year. However, Van Kooten et al. (1992) suggest that forestry opportunities in Western Canada alone may provide as much as 13×10^6 tons of carbon capture per year.

In the temperate regions there appear to be significant opportunities. Richards et al. (1993) suggest that in the United States alone, an aggressive tree planting program could yield an average of 400×10^6 tonnes per year for 100 years and a cumulative total of 49×10^6 tonnes if the plantations are undisturbed for 160 years. Dixon, Schroeder and Winjum (1991) are not as optimistic. That study suggests that across all forestry practices a total of 20×10^6 tons of carbon could be accumulated in the entire temperate zone. Over their fifty year analysis period this averages to 400×10^6 tons per year. Because the estimate of land area availability in Dixon, Schroeder and Winjum (1991) is much higher than in Richards et al. (1993), the difference in the estimates must be due to the fact that the latter study uses much higher estimates of potential carbon accumulation per hectare.

The outlook in the tropics is even better than that in the temperate region. Dixon, Schroeder and Winjum (1991) suggests that a cumulative total of 53×10^6 tonnes of carbon could be captured across all forestry practices. Houghton et al. (1993) provide an even more optimistic estimate of the potential in the tropics, 167×10^6 tonnes of carbon accumulation, though they provide no cost figures.

Two other studies that provide estimates of carbon sequestration potential without analyzing costs suggest that Australia and New Zealand could capture carbon at a rate of 7×10^6 tonnes per year and 5×10^6 tonnes per year, respectively, for 25 to 30 years (Barson and Gifford, 1990; Tasman Institute, 1994). For Mexico, India, and China it is estimated that approximately 3.5×10^6 tonnes, 8.7×10^6 tonnes, 9.8×10^6 tonnes, respectively, could be accumulated (Masera et al., 1994; Ravindranath and Somashekhar, 1994; Xu, 1994).

9.2.3 Cost Curves

This discussion has suggested that there is significant variation among the studies with respect to their estimates of the unit costs and potential amounts of carbon sequestration. The studies also differ in how they present the results. Several of the reports (Sedjo and Solomon, 1989; Nordhaus, 1991; New York State, 1991; van Kooten et al., 1992) have presented their results as point estimates; i.e., estimates of the costs of achieving a specified amount of carbon sequestration.¹⁰ Other studies have developed cost curves that illustrate the increasing marginal cost of carbon sequestration as a function of the level of carbon sequestration (Adams et al., 1990; Moulton and Richards, 1990; Dixon, Schroeder, and Winjum, 1991; Parks and Hardie, 1993; Richards et al., 1993). The cost curves provide information that is not conveyed in either point estimates or in the ranges of unit costs listed in Table 9.2.1.1.

Figures 9.2.3.1 and 9.2.3.2 reproduce two of the cost curves for purposes of illustration. Figure 9.2.3.1 shows a cost curve for carbon sequestration in the United States. The dependent variable is the marginal cost of carbon capture expressed in nominal dollars, i.e., the dollars in the year in which the capture takes place. To arrive at this figure the present costs are levelized (inflated) at the discount rate. Note that the marginal costs increase steadily as carbon accumulation rises to 45×10^6 tonnes accumulation, and then rise very rapidly in the range of 45×10^6 tonnes to 49×10^6 tonnes of carbon. The independent variable is tonnes of accumulated and permanently stored carbon in a 160-year period.

Figure 9.2.3.2 presents a similar graph for global carbon sequestration. Costs rise only slightly from 0 to 70 billion tonnes of carbon, but rise extremely sharply thereafter. The units in this second graph are different, however. As with Figure 9.2.3.1, the dependent variable is also expressed in units of dollars per tonne of carbon, but here the definition of a tonne of carbon is based on the MCS method, which expresses a stock of carbon averaged over several rotations, rather than the total accumulation of carbon. The similarity in presentations of these types of results belies the significant underlying differences.

9.3 Studies of the Costs of Reducing Non-Energy GHG Emissions

While much of the work on GHG emission reduction has focussed on energy-related emissions, a growing literature is emerging on non-energy GHG emissions. Table 9.3 summarises some of the major options and reduction potential.

9.3.1 Costs of Reducing Methane Emissions

Methane is emitted from a diverse set of human-related activities which currently represent about 70 percent of global emissions annually (USEPA, 1994). Importantly, methane emissions from these systems represent the waste of a valuable fuel, and the methane can often be recovered where the saved fuel justifies the investment. Recent reports suggest that

substantial reductions in methane emissions can be achieved profitably or at low cost while providing a number of other benefits (RIVM, 1993; USEPA, 1993a; USEPA, 1993b)¹¹. These studies indicate that it may be possible to profitably employ existing technologies and practices and reduce methane emissions from landfills, oil and natural gas systems, coal mining, and ruminant livestock by about 18 to 37 Tg per year over the next 5 to 10 years. These reductions represent about 5 to 10 percent of current anthropogenic emissions. Emissions reductions of about 36 to 97 Tg per year (10 to 30 percent of current anthropogenic emissions) may be possible in the longer term. This section summarizes the results of these reports for each major methane source.

9.3.1.1 Natural Gas and Oil Systems

Cost studies of available technologies and practices for reducing methane emissions from natural gas systems indicate that reductions in emissions on the order of 20 to 80 percent are possible at particular sites for particular types of emissions, depending on site specific conditions (USEPA, 1993a). The major opportunities for profitably achieving such reductions are in countries or regions (1) with world gas prices and where reasonably small incremental investments can modify current operations and practices and save sufficient gas; (2) with old or stressed systems handling large quantities of gas; and (3) where work is underway to reduce emissions of volatile organic compounds or air toxics. For example, recent analyses in the United States show that through incremental investments in a small set of best management practices emissions can be profitably reduced over the next decade by about 30 percent or 1 Tg (USEPA, 1993c). Globally it may be possible to reduce emissions by 4 to 16 Tg per year over the next decade through profitable ventures (USEPA, 1993b).

9.3.1.2 Coal Mining

Methane emissions into the atmosphere can be profitably reduced by up to 50 to 70 percent at gassy mines using available techniques, depending upon site-specific conditions (USEPA, 1993a). The best opportunities for profitably achieving such reductions are for mines which are classified as "gassy," which produce substantial quantities of coal and which are close to demand points for a medium quality fuel. However, with appropriate technical expertise high quality gas can be produced and sold to pipeline systems. Recent analyses in the United States show that emissions from coal mining can be profitably reduced over the next decade by about 35 percent or 1.5 Tg with intensified efforts at about 25 mines (USEPA, 1993c). Globally it may be possible to reduce emissions by 4 to 7 Tg per year over the next decade by profitable expansion of methane recovery techniques (USEPA, 1993b). Reductions of 1.5 to 2.5 Tg per year could be achieved just by using the medium quality gas which is currently recovered in major coal regions around the world but vented to the atmosphere (USEPA, 1993b).

9.3.1.3 Waste Disposal

Methane emissions can be profitably reduced by up to 90 percent and provide additional benefits of improved air and water quality and reduced risk of fire and explosion (USEPA, 1993a). Best opportunities for profitably using captured landfill gas are for (1) landfills that are currently receiving wastes, expected to have more than .5 to 1 million metric tons of waste in place, and have a clearly identifiable energy user or buyer nearby or (2) landfills likely to be subject to air pollutant emissions rules. Recent analyses in the United States show that methane emissions from landfills may be reduced by as much as 7 Tg per year as a by product of an air emissions rule to be promulgated soon. Some of these landfills will be able to comply through revenue generating recovery projects. Globally it may be possible to reduce emissions by 9 to 14 Tg per year over the next decade through methane recovery projects (USEPA, 1993b).

9.3.1.4 Ruminant Animals

Analyses show that available technologies and management practices can reduce methane emissions per unit of product by 5 to 60 percent in many animal management systems (USEPA, 1993a). The greatest near-term potential for the profitable use of better management practices is in countries or regions where animals have not experienced large changes in productivity in the preceding decades, the animals are currently eating poor quality forages, product markets and physical infrastructure exist, and traditions and customs will support the changing practices. In particular, dairy herds in many developing countries offer great potential because the current diets are nutrient deficient, there is daily access to animals so that feed supplementation and other management practices are possible, and the increased production of milk is quickly seen and marketable. Globally, emissions reductions of 1 to 10 Tg per year may be reduced over the next decade by promoting available practices in these regions (USEPA, 1993b).

9.3.1.5 Animal Manures

Available technologies can profitably reduce methane emissions by as much as 80 percent at particular sites (USEPA, 1993a). The best opportunities for profitably using recovered biogas from animal manures are in fairly warm regions with farms with large numbers of animals. For example, in the United States only the large farms (i.e. over 500 head dairy farms and over 1,500 head swine operations) located in fairly warm regions, lagooning their animal manures, and purchasing fairly expensive electricity are expected to recover methane profitably. However, these farms represent about 30 percent of the emissions and could profitably provide about 1 Tg per year reduction in national emissions.

9.3.2 Costs of Reducing Emissions of Other Greenhouse Gases

Nitrous oxide and halogenated substances are the "other greenhouse gases" which make sizable contributions to the increasing radiative forcing in the earth's atmosphere. While

there remains much uncertainty in the emissions of these gases from the different sources, a number of activities are underway around the world to further assess and implement technologies and practices for reducing the emissions of these gases. This section briefly describes these activities. In general, the technologies and practices already in use are economically viable or were pursued for reasons other than for reducing greenhouse gas emissions.

9.3.2.1 Nitrous Oxide

Nitrous oxide is emitted from a variety of industrial and agricultural activities. These human-related activities represent about 20 percent of global emissions annually (IPCC, 1992). Technologies and practices for reducing nitrous oxide emissions from some of the key sources have been identified and are at different stages of use and development, as discussed below (RIVM, 1993).

9.3.2.1.1 Adipic and Nitric Acid Production

Nitrous oxide is produced as a waste gas during the production of adipic acid, which is used primarily in the manufacture of nylon. The production of nitric acid, primarily for fertilizer production with a small percentage as an input into adipic acid production also produces nitrous oxide. These sources are estimated to emit about 0.4 to 0.6 Tg and 0.1 to 0.3 Tg N_2O-N per year, respectively (IPCC, 1992). Over 80 percent of these emissions are from the industrialized countries. Importantly, emissions of nitrous oxide from adipic acid production already reflect a 30 percent emissions abatement accomplished by reductive furnaces being used to reduce emissions of NO_x (RIVM, 1993). Reductive furnaces where applied reduce emissions by about 98 percent. A number of additional options for reducing these emissions with similar reduction efficiencies are under study by the adipic acid producers some of whom expect to have these technologies in place by 1996. Emissions of nitrous oxide from nitric acid production are not currently abated and technologies for reducing these emissions do not appear to be under discussion.

9.3.2.1.2 Fertilizer Use

Nitrous oxide is emitted from cultivated soils due to the application of nitrogen-based fertilizers, primarily from dinitrification processes (RIVM, 1993). Emissions are estimated to be 0.3 to 3.0 Tg-N per year, with about 80 percent of these emissions from the developing countries and countries with economies in transition. Approaches for reducing nitrous oxide emissions from cultivated soils concentrate on the more efficient use of fertilizers since these approaches can result in sizable cost savings. Through testing soils for nutrient deficiencies, applying fertilizers to meet specific plant needs, and using application methods that reduce the loss of nitrogen, more efficient use can be accomplished. While these alternatives need substantial development and demonstration before becoming widely available, the potential for reductions in fertilizer use and greenhouse gas emissions is substantial. For example, the United States expects to reduce fertilizer use by 10 to 30 percent by 2000 by demonstrating such alternatives and educating farmers through

1 agricultural extension networks about the costs savings associated with more strategic and
2 efficient fertilizer use (White House, 1993).

3 9.3.2.1.3 Other Sources

4 Nitrous oxide is also produced from a variety of other sources including biomass burning
5 and mobile and stationary combustion sources. Technologies and practices for controlling
6 emissions from these sources are in the research phase.

7 9.3.2.2 Halogenated Substances

8 Emissions of halogenated substances result for a variety of manufacturing processes and
9 numerous types of equipment and appliances. The halogenated substances of greatest
10 interest to the IPCC are perfluorocarbons (PFCs) and hydrofluorocarbons (HFCs) which are
11 emitted in the largest quantities and are highly potent and long-lived greenhouse gases.
12 They are not ozone depleters and, therefore, are not covered by the Montreal Protocol.
13 Activities are underway to determine low cost, if not profitable, ways to reduce emissions
14 of these gases.

15 9.3.2.2.1 Perfluorocarbons (PFCs)

16 The production of aluminum is thought to be the largest source of emissions of two PFCs,
17 CF₄ and C₂F₆. These emissions are produced primarily by anode events, which occur
18 during the reduction of alumina in the primary smelting process. World emissions are
19 highly uncertain and are estimated on the order of 30,000 metric tons per year and 3,000
20 metric tons per year for CF₄ and C₂F₆, respectively (USEPA, 1993). Approaches for
21 reducing emissions focus on (1) technological upgrades for highly inefficient smelters and
22 (2) practices for reducing the frequency and duration of anode events at more modern
23 smelters such as improved algorithms for controlling automated processes, better
24 management of alumina additions, and training for personnel. Because aluminum smelters
25 are large consumers of energy, the costs of these modifications can be largely offset by the
26 costs of saved energy. The United States estimates that it can reduce PFC emissions from
27 aluminum smelting by 30 to 60 percent by 2000, by promoting profitable changes in
28 current practices (White House, 1993).

29 9.3.2.2.2 Hydrofluorocarbons (HFCs)

30 Emissions of HFCs result as by-products of manufacturing, from the intentional
31 manufacture as CFC and HCFC substitutes, and from use in a variety of applications.
32 Emissions are difficult to estimate on an annual basis because even though almost 100
33 percent of manufactured HFCs will be emitted to the atmosphere eventually, emission rates
34 can vary from low but long term emissions from insulating materials to instantaneous
35 releases when used as an aerosol propellant. Currently, emissions of these gases are
36 relatively small, but emissions can be expected to grow substantially over the next decades
37 as HFCs are used as substitutes for CFCs and HCFCs. For example, the United States

1 expects more than a doubling in these emissions between 1990 and 2000. A number of
2 options for reducing emissions of these gases are being investigated. Options include
3 process changes, substitution of other substances, recycling, and destruction. The United
4 States expects to reduce emissions of HFCs by about 25 percent by 2000 by encouraging
5 product stewardship, by implementing regulations under the Clean Air Act, and by reducing
6 HFC emissions as a by-product of HCFC-22 production.

7 9.3.2.2.3 Other Halogenated Substances

8 Other halogenated substances include sulfur hexafluoride and fluoroiodocarbons. Sulfur
9 hexafluoride is produced for use as insulation for electrical equipment, to degas molten
10 reactive metals, and as a tracer gas. Fluoroiodocarbons may be produced for intentional use
11 as halon alternatives or refrigerants. These substances seem to be emitted in small
12 quantities worldwide. Technologies or practices for reducing or limiting emissions of these
13 gases do not appear to be under discussion.

14 9.4 General Conclusions

15 • Estimates of the cost of GHG emission reduction are sensitive to assumptions about
16 appropriate model structure, demographic and economic growth, the cost and availability of
17 energy demand-side and supply-side options, the desired level and timing of abatement, and
18 the choice of policy instruments. Different assumptions have led to a wide range of
19 emission reduction cost estimates.

20 • Despite significant differences in views, there is agreement that some energy
21 efficiency (perhaps 10-30% of current consumption, depending on baseline assumptions and
22 the implementation time frame) can be realized at negative to slightly positive costs. The
23 existence of such a "no regrets" potential depends upon the existence of substantial market
24 or institutional imperfections that prevent cost-effective emission reduction measures from
25 occurring. The key question is whether such imperfections can be removed cost-effectively
26 by policy measures.

27 • Energy-related emissions can be reduced through both demand-side (energy
28 efficiency) and supply-side (alternative sources of supply) options. In the short term,
29 demand side options are cheapest in most countries.

30 • Estimates of the costs of stabilizing CO₂ emissions vary widely as a result of
31 differences both in the baseline scenarios used (e.g. how much energy efficiency or what
32 rate of economic growth is contained in the baseline scenario), and in the calculated costs
33 of various policy measures.

1 • There has been much more analysis to date of emission reduction potentials and
 2 costs for industrialized countries than for other parts of the world. Moreover, many existing
 3 models are not well suited to study economies in transition or developing country
 4 economies. Much more work is needed to develop and apply models outside of developed
 5 countries.

6
 7 • The overall cost of abatement programs will ultimately be determined by the rate of
 8 capital replacement, the discount rate, and the effect of R&D. Appropriate long-run signals
 9 to encourage R&D will reduce long-run costs. The implementation of any "no regrets"
 10 potential will increase the time available to learn about climate risks and to bring new
 11 technologies to enter the market-place.

12
 13 • Infrastructure decisions are critical because they can enhance or restrict the number
 14 and type of future options, and different infrastructure decisions can lead to very different
 15 cost outcomes. This issue is of particular importance to developing countries, where major
 16 infrastructure decisions will be made in the near term.

17
 18 • If the climate issue is formulated in terms of stabilizing atmospheric concentrations,
 19 the choice of emissions time path is critical in determining the overall price-tag. It is
 20 important to identify those paths that minimize the costs of achieving a particular
 21 concentrations target.

22
 23 • The overall impact of a carbon tax will depend not only on the size of the tax, but
 24 also on the uses to which the revenues are put. If carbon tax revenues are used to reduce
 25 more distortionary taxes, overall emission reduction costs will be reduced. Inefficient tax
 26 recycling could, however, increase costs.

27
 28 • There is need for both detailed (bottom-up) analysis of technological options and
 29 also more aggregate (top-down) analysis of economic effects. Whereas historically these
 30 two approaches have been associated with very different cost estimates, this need not be the
 31 case. Indeed widely differing methods can produce quite similar results when calibrated to
 32 the same set of input assumptions.

33
 34 • Given differences in marginal emission reduction costs among countries,
 35 international cooperation can significantly reduce the global price-tag for emissions
 36 reduction. Economic efficiency would be enhanced by carrying out emissions reduction
 37 where it is cheapest to do so.

38
 39 • Estimates of the costs of stabilizing CO₂ emissions at 1990 levels in *OECD*
 40 *countries* vary widely. Many bottom-up studies suggest that the costs of achieving this
 41 target over the next few decades may be negligible. Given rising baseline emissions over
 42 the longer term, however, many top-down studies suggest that the annual costs of
 43 stabilizing emissions may ultimately exceed
 44 1-2% of GDP.

1 • The costs of stabilizing emissions for *economies in transition* may be small relative
 2 to OECD countries. The potential for cost-effective reductions in energy use is apt to be
 3 considerable but the realizable potential will depend upon what economic and technological
 4 development path is chosen. A critical issue is the future of structural changes in these
 5 countries that are apt to change drastically the level of baseline emissions and the emission
 6 reduction costs

7
 8 • Analyses suggest that there may be substantial low-cost emission reduction
 9 opportunities for *developing countries*. However, these are likely to be insufficient to offset
 10 rapidly increasing emissions baselines, associated with, for example, increased economic
 11 growth. In the absence of a highly favorable allocation of carbon emission rights, the likely
 12 magnitude of emissions reduction will be particularly costly for developing countries.

¹ See for example, Nordhaus and Yohe (1983), Edmonds and Reilly (1987) and Manne and Richels (1994).

² In fact, with the exception of the Quest model in the European Community, no model was able to really assess the effects on trade balances or on delocation of big consuming industries because of the lack of a model of international trade.

³ The Pareto efficiency of abatement strategies based on a uniform carbon tax or tradeable emission quotas (regardless of the quota allocation) has recently been contested at a theoretical level by Chichilnisky and Heal (1994), and their paper has triggered various responses; the ongoing debate on this issue is not pursued further here.

⁴ There may be second order general equilibrium effects on global abatement costs from changes in regional demand patterns, terms of trade and investment paths, due to region-specific income and price elasticities of demand, and investment propensities.

⁵ These extreme quota allocation rules, neither of which is likely to be an acceptable basis for a global abatement coalition, were chosen for purely illustrative purposes.

⁶ As panel A in Figure 9.1.5.1.4.3 shows, towards the end of the 110 year simulation period even allocating all emission rights to developing countries is insufficient to compensate them for income losses from a global emission stabilisation agreement, making it necessary to allocate "negative emission rights" to (some) developed regions under this allocation rule.

⁷ Recall from Section 9.1.1.1.6 that a positive discount rate also favors deferring reductions.

⁸ Goldemberg et al. (1988) *Energy for a Sustainable World*. New Delhi: Wiley Eastern Ltd.

⁹ See for example the "Jérémie" and "Noé" scenarios by B. Dessus (1990)

¹⁰ Nordhaus presented a range for the cost estimates associated with a target level.

¹¹ RIVM 1993 is the proceedings of an international IPCC workshop on methane and nitrous oxide held in Amersfoort, the Netherlands, February 3-5, 1993; USEPA 1993a is a Report to Congress developed by the United States Environmental Protection Agency (USEPA) building upon efforts of the US/Japan Working Group on Methane for the Response Strategies Working Group of the IPCC which solicited methane related information from all IPCC country representatives. USEPA 1993b is a follow-on to the first USEPA report which examines the applicability of available technologies and practices in specific countries. These reports are based on numerous supporting studies, some of which are listed at the end of this section.

9.5 References

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(Labels are not attached to all points given danger of crowding. For key see Table 9.1.1)



Source: Grubb et al (1993).

Figure 9.1.1.2.2 EMF Reference and Emission Reduction Scenarios

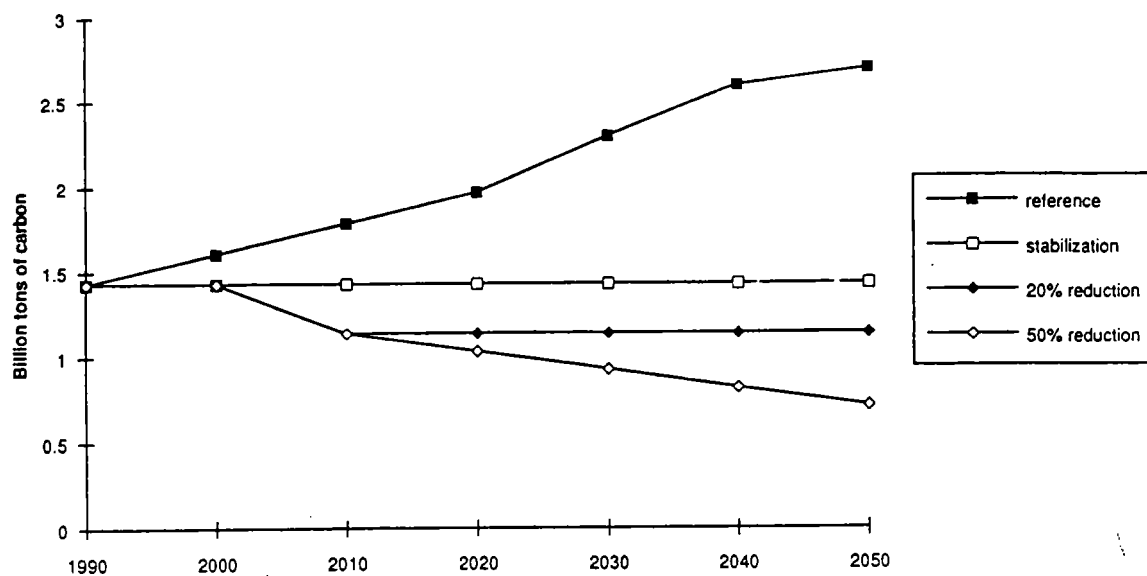
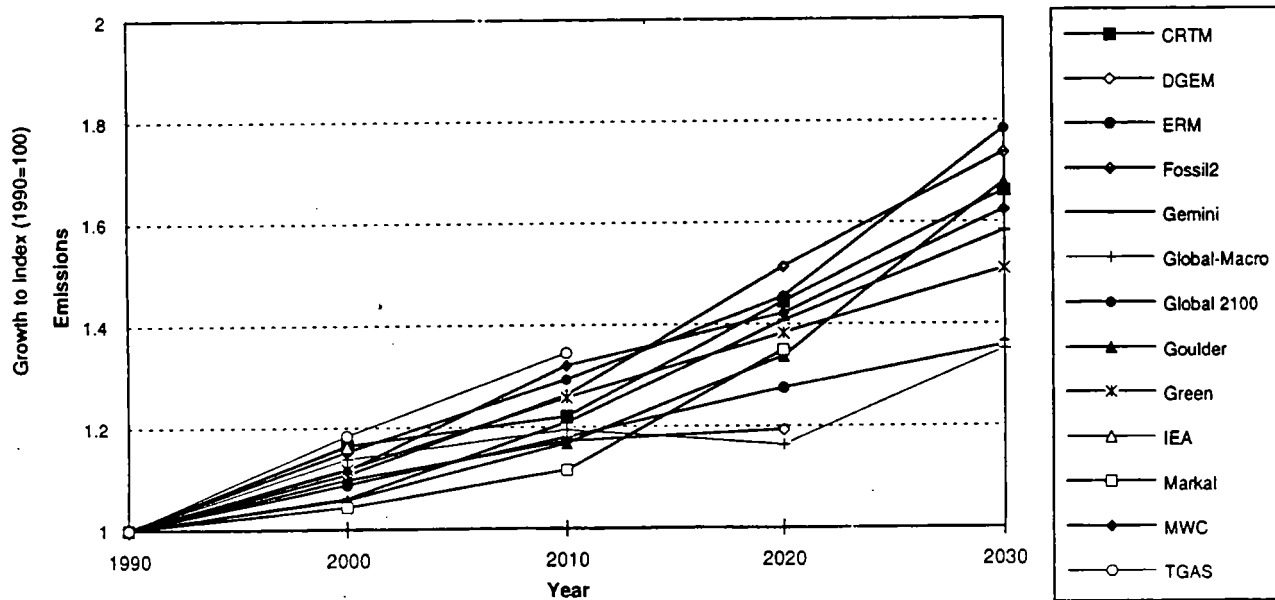
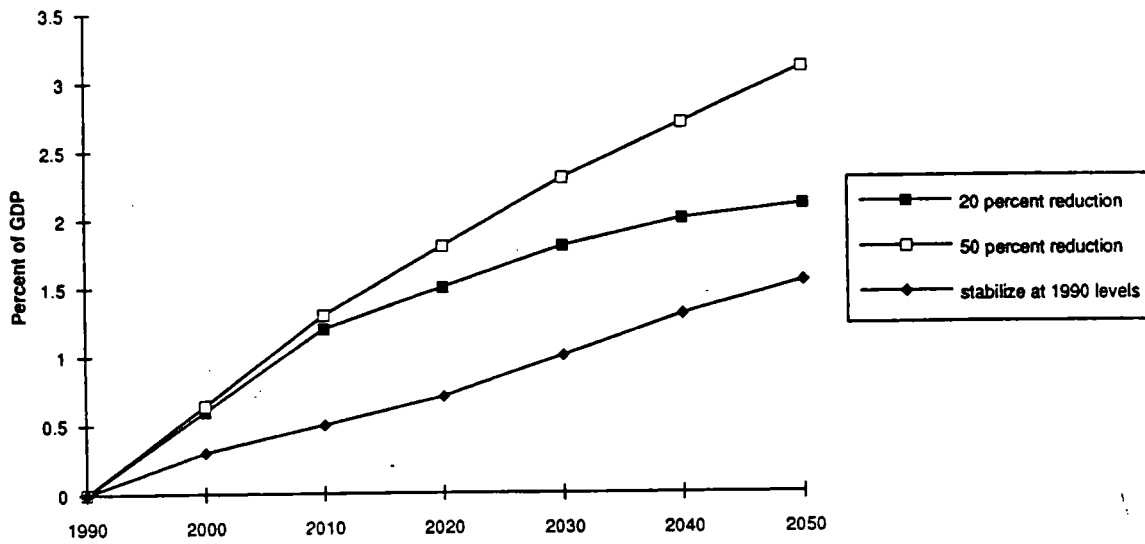


Figure 9.1.1.2.1 U.S. Carbon Emissions



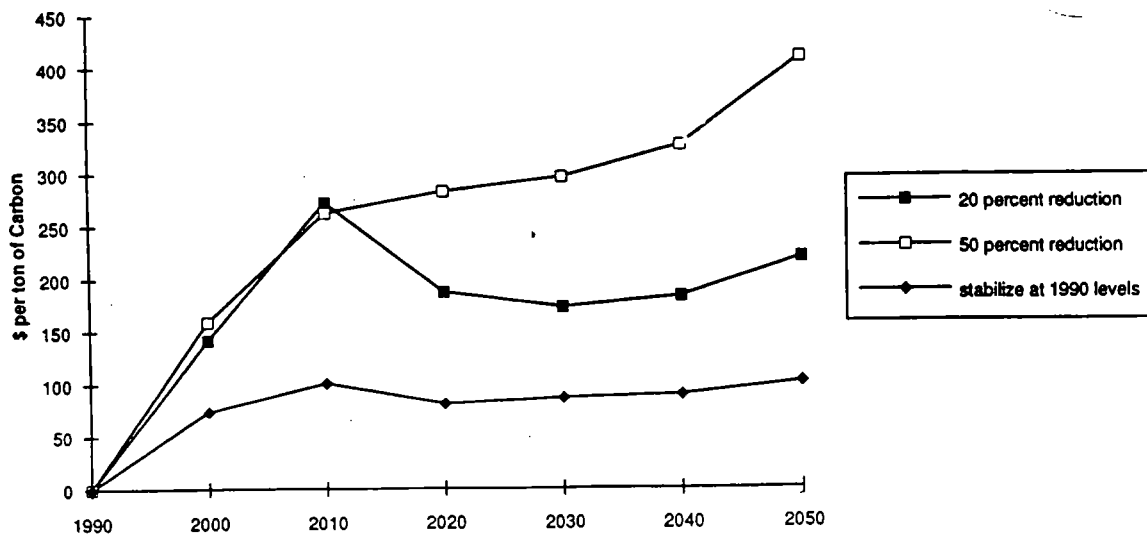
Source: EMF (1993).

Figure 9.1.1.1.4.1 U.S. GDP Loss Projections – Average of all Models



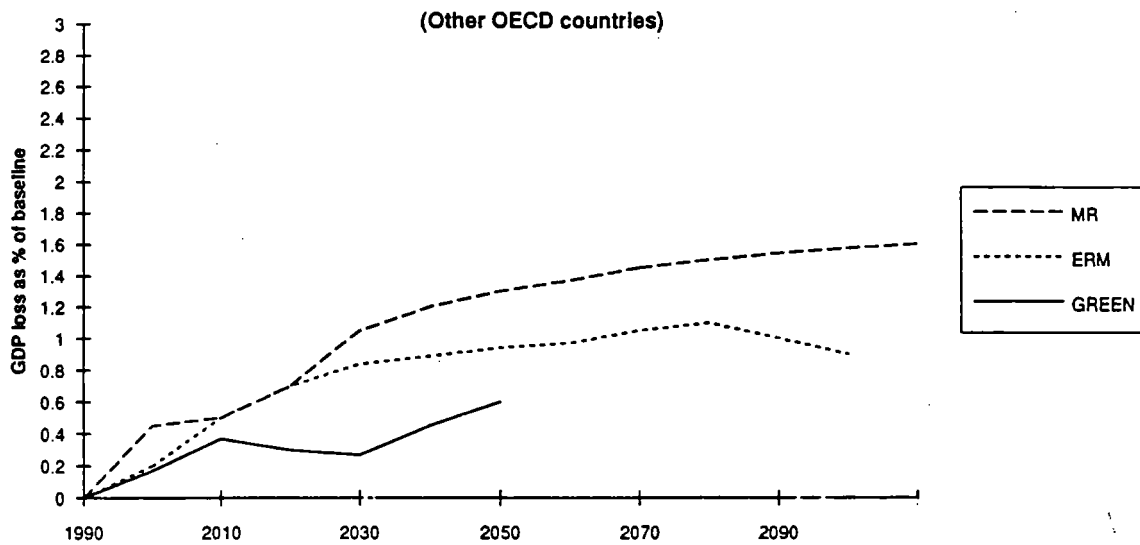
Source: EMF (1993).

Figure 9.1.1.1.3.1 U.S. Carbon Taxes – Average of All Models



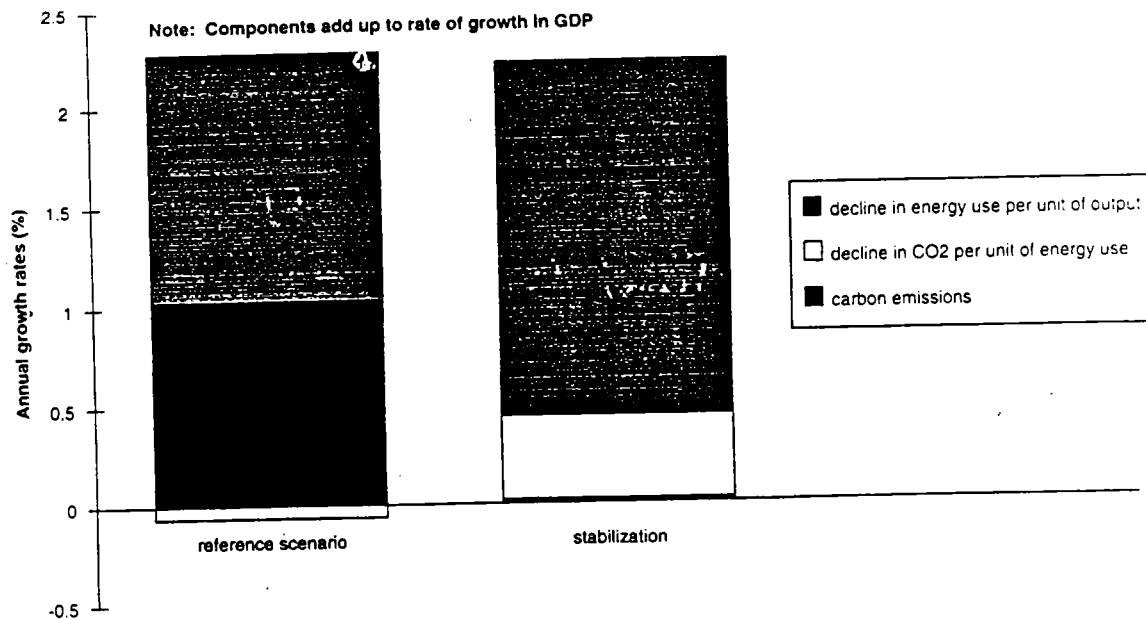
Source: EMF (1993).

Figure 9.1.2.1.1.1 GDP Losses in the Stabilization Scenario



Source: OECD (1993).

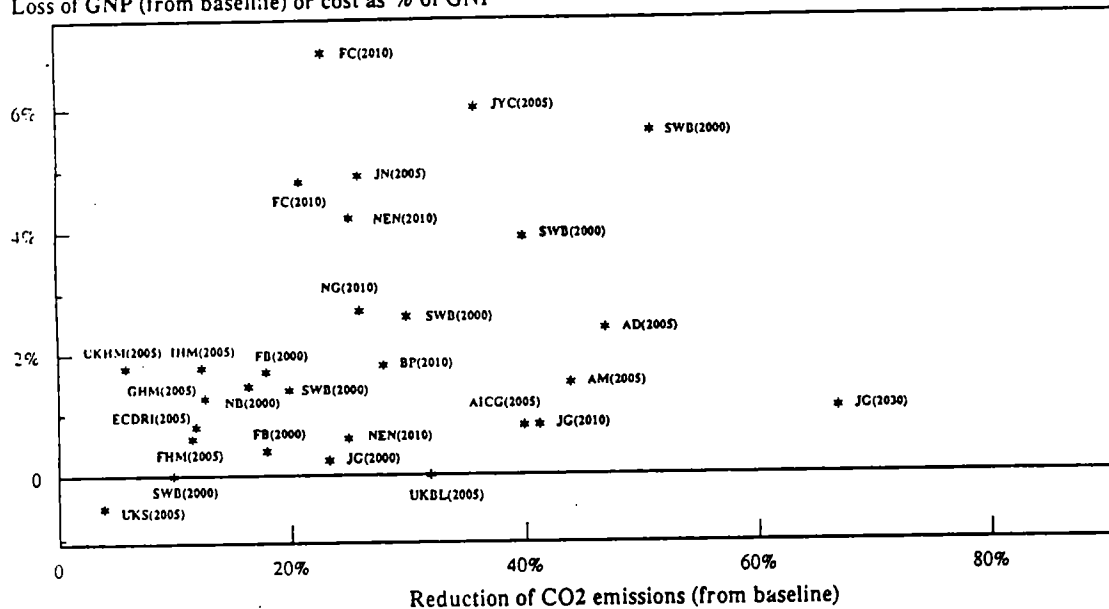
Figure 9.1.1.1.5.1 Decoupling Between Carbon Emissions and GDP Annual Growth Rates (1990-2010)



Source: EMF (1993).

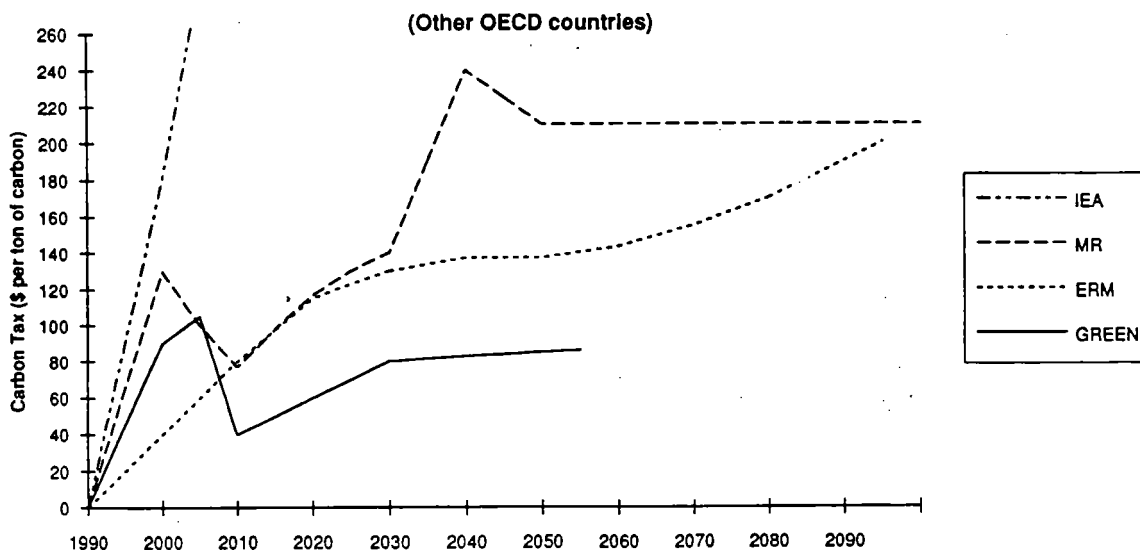
Figure 9.1.2.1.2.1 Non-U.S. OECD Studies: Cost of CO₂ Abatement Relative to Baseline Projection
(Labels are not attached to all points given danger of crowding. For key see Table 9.1.2.1.2.1)

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



Source: Grubb et al (1993).

Figure 9.1.2.1.2.2 Carbon Taxes in the Stabilization Scenario



Source: OECD (1993).

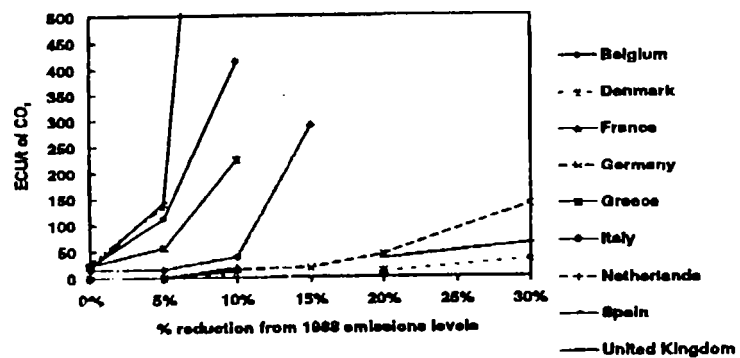
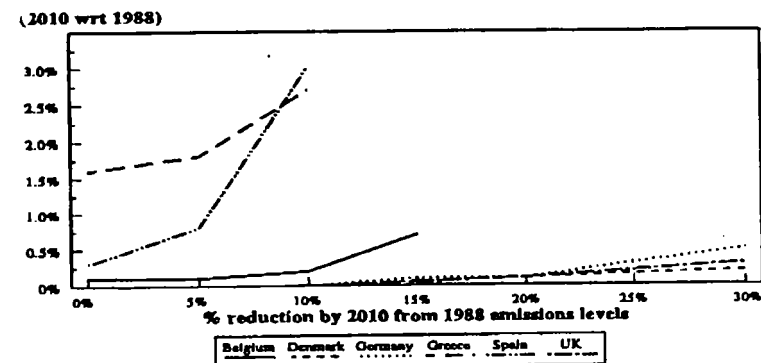


Figure 9.1.2.2.3.1



Source: Coherence (1991); Table 4.4

Figure 9.1.2.2.3.2 Cost as a percentage of 1988 GDP.

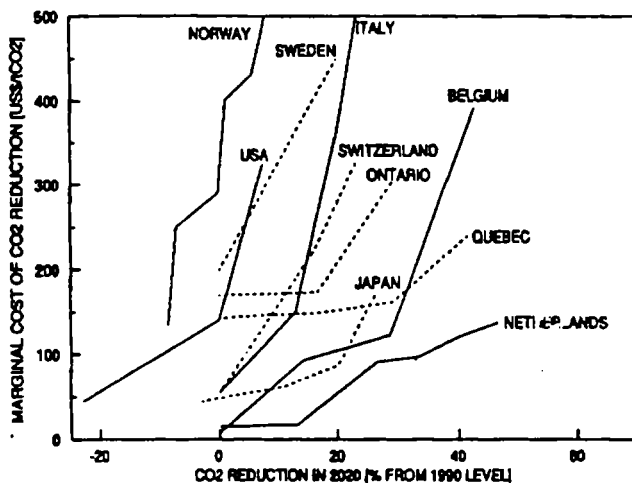
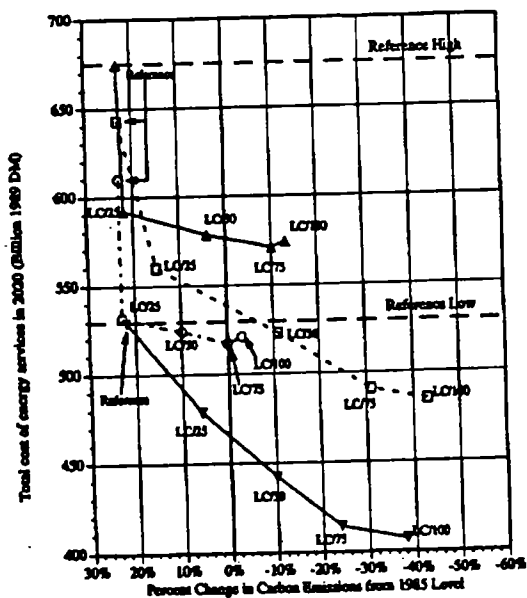


Figure Marginal Cost of CO₂ Emission Reduction among Countries
9.1.2.2.3.4

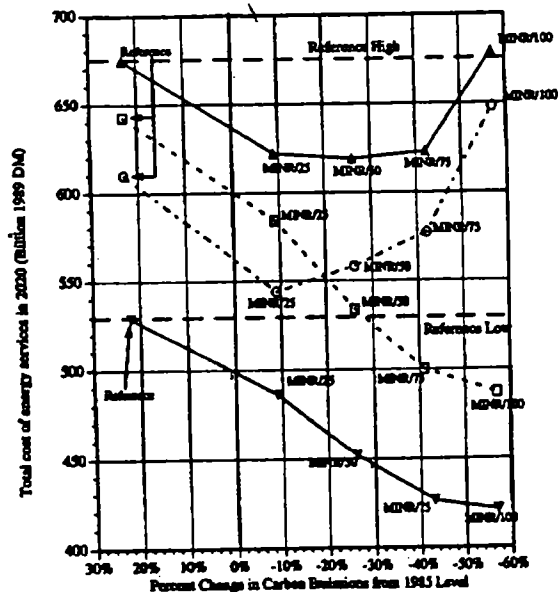
9.1.2.2.3.3

Figure Sensitivity Analysis of the Cost of Carbon Reductions in EC-5, All Sectors

1a: Least Cost Case



1b: Minimum Risk Case



- □ - Low Capital Cost/High Fuel Price Case
- ○ - High Capital Cost/Low Fuel Price Case
- △ - Low Capital Cost/Low Fuel Price Case
- ◆ - High Capital Cost/High Fuel Price Case

1985 EC-5 Carbon emissions = 532 Mt C

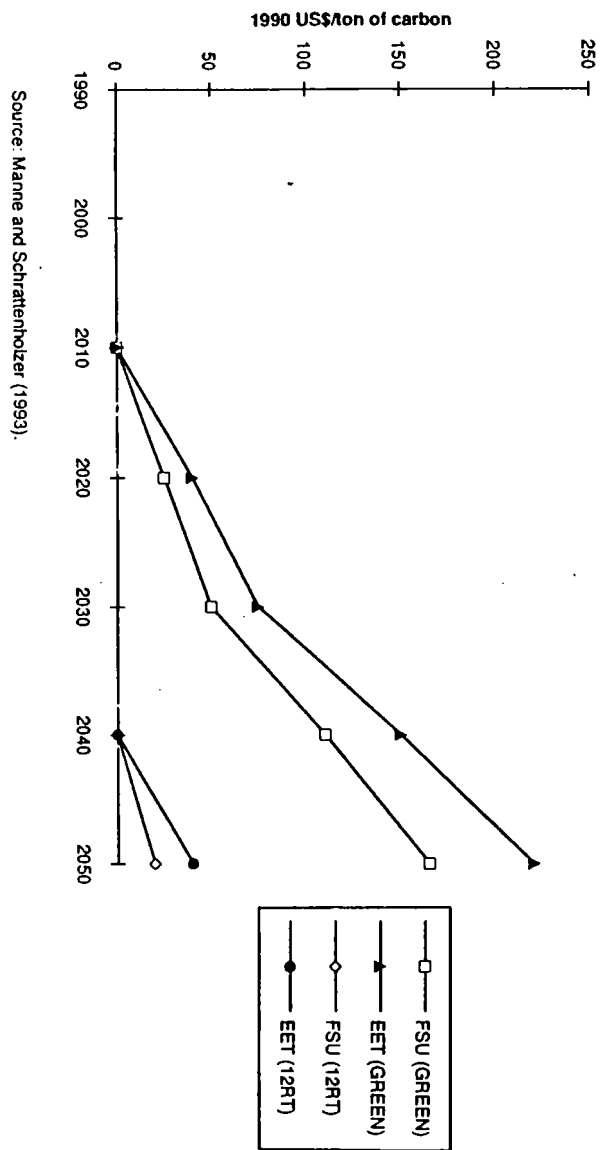


Figure 9.1.3.1.1 Comparison of Carbon Taxes in the Stabilization Scenario

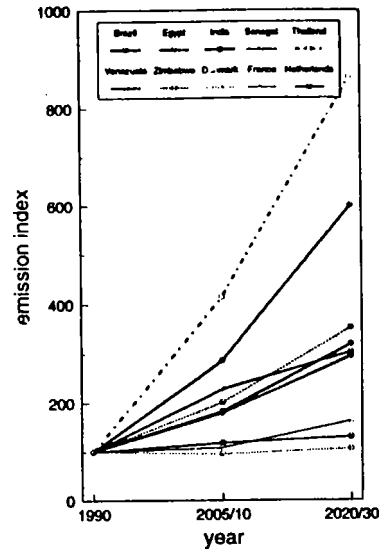


Figure 9.1.4.2.1.1 UNEP Studies: Reference Scenarios

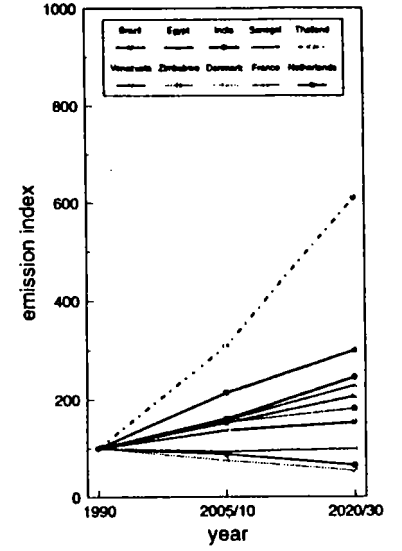


Figure 9.1.4.2.1.2 UNEP Studies: Abatement Scenarios

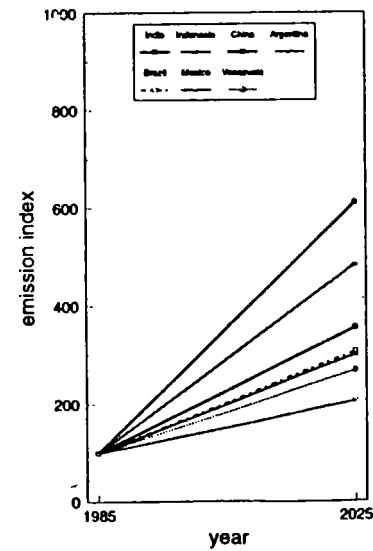


Figure 9.1.4.2.1.3 LBL Studies: High Emission Scenarios

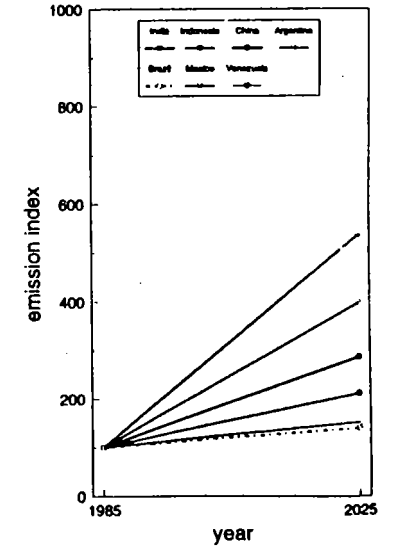


Figure 9.1.4.2.1.4 LBL Studies: Low Emission Scenarios

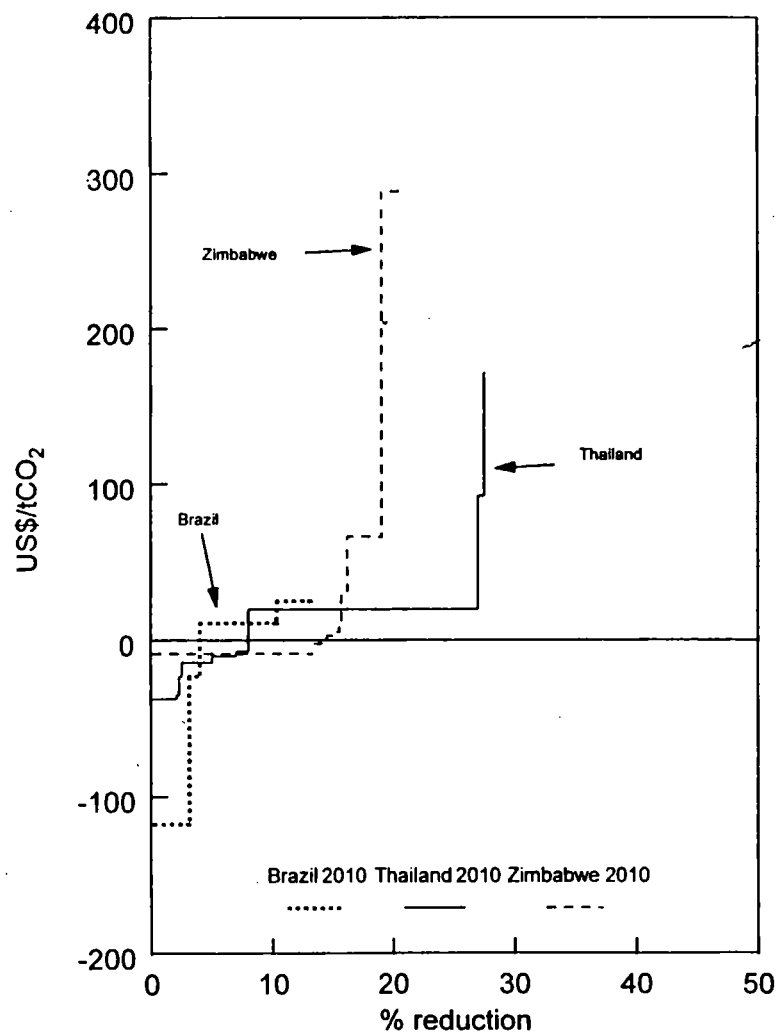


FIGURE 9.1.4.2.2.1

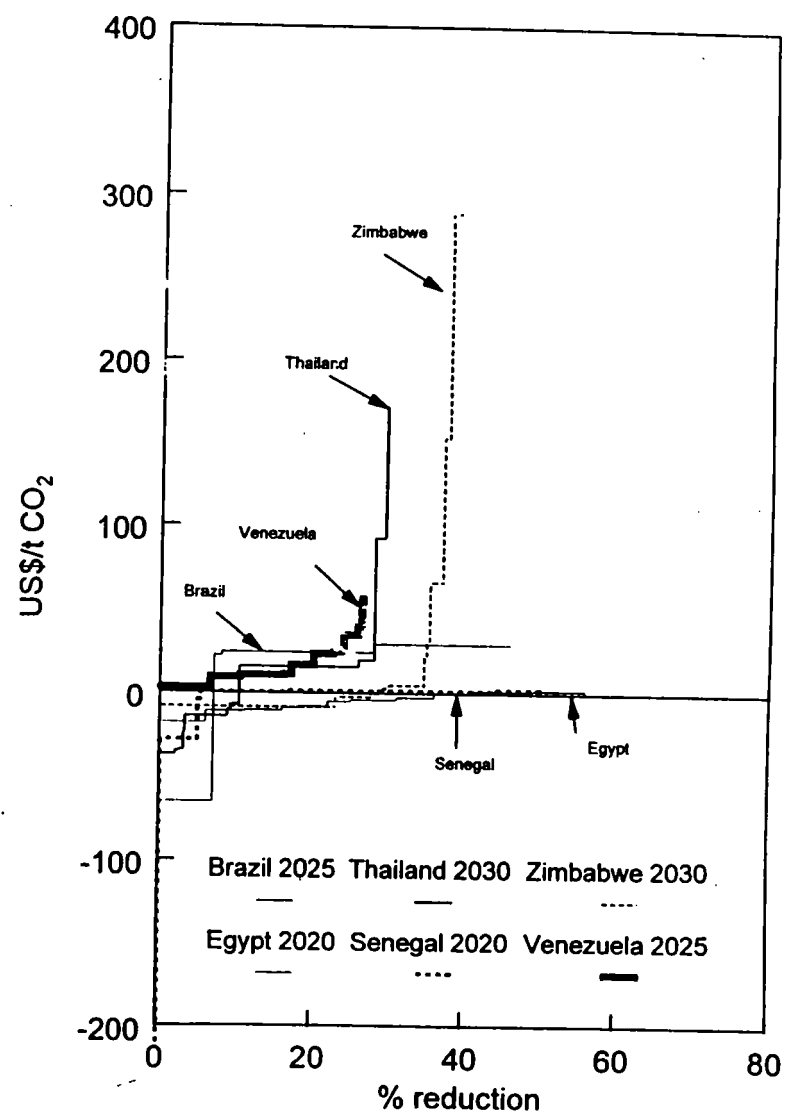
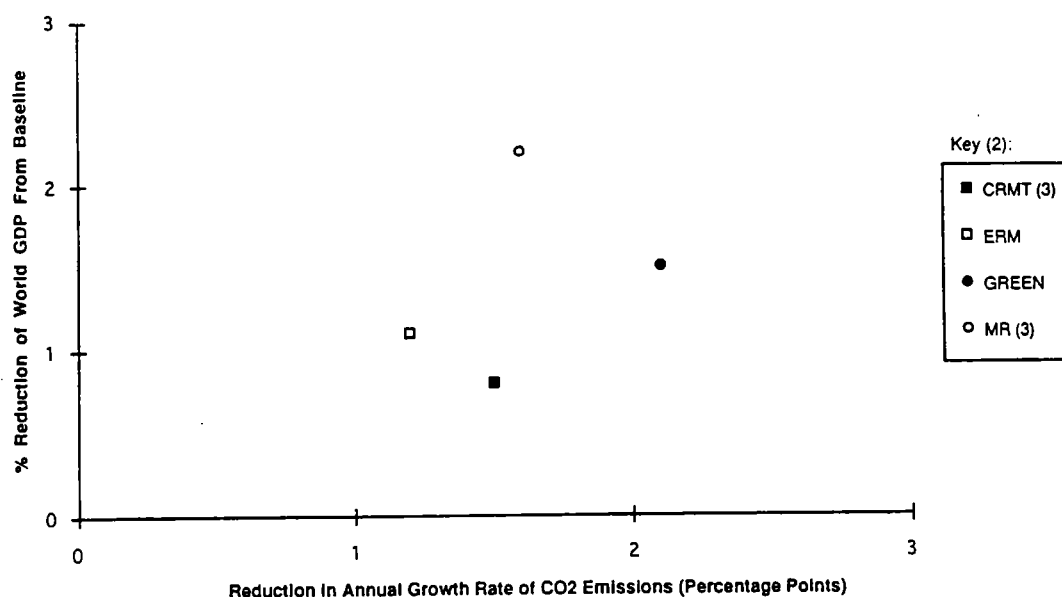


FIGURE 9.1.4.2.2.2

Figure 9.1.5.1.1 Estimated CO₂ Abatement Cost In 2020 (1)
(Stabilization of Emissions Relative to 1990 Levels)



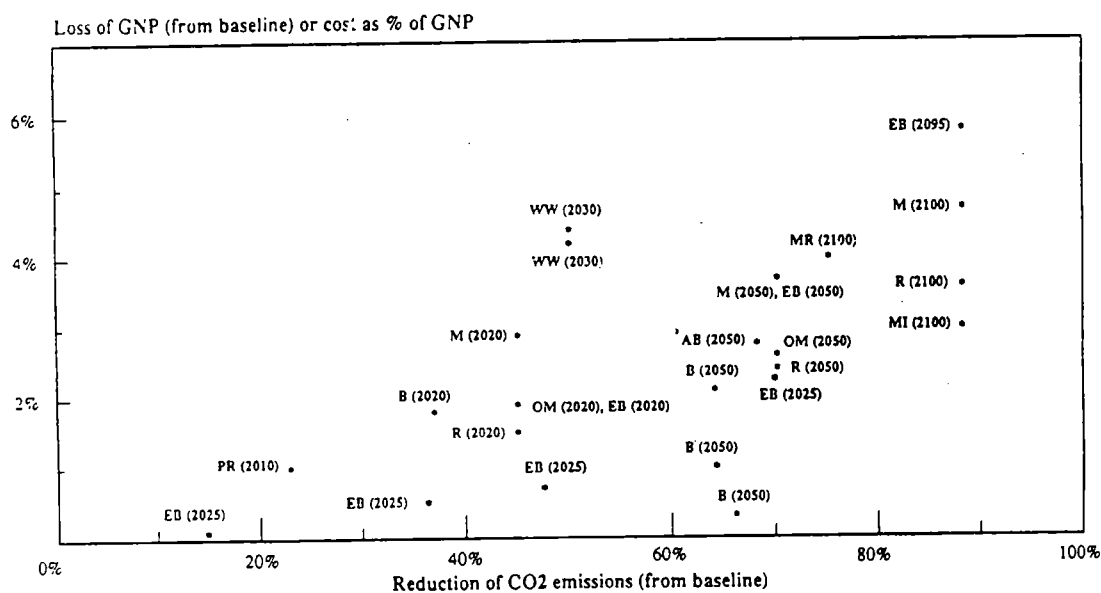
(1): No emission trading between regions.

(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.

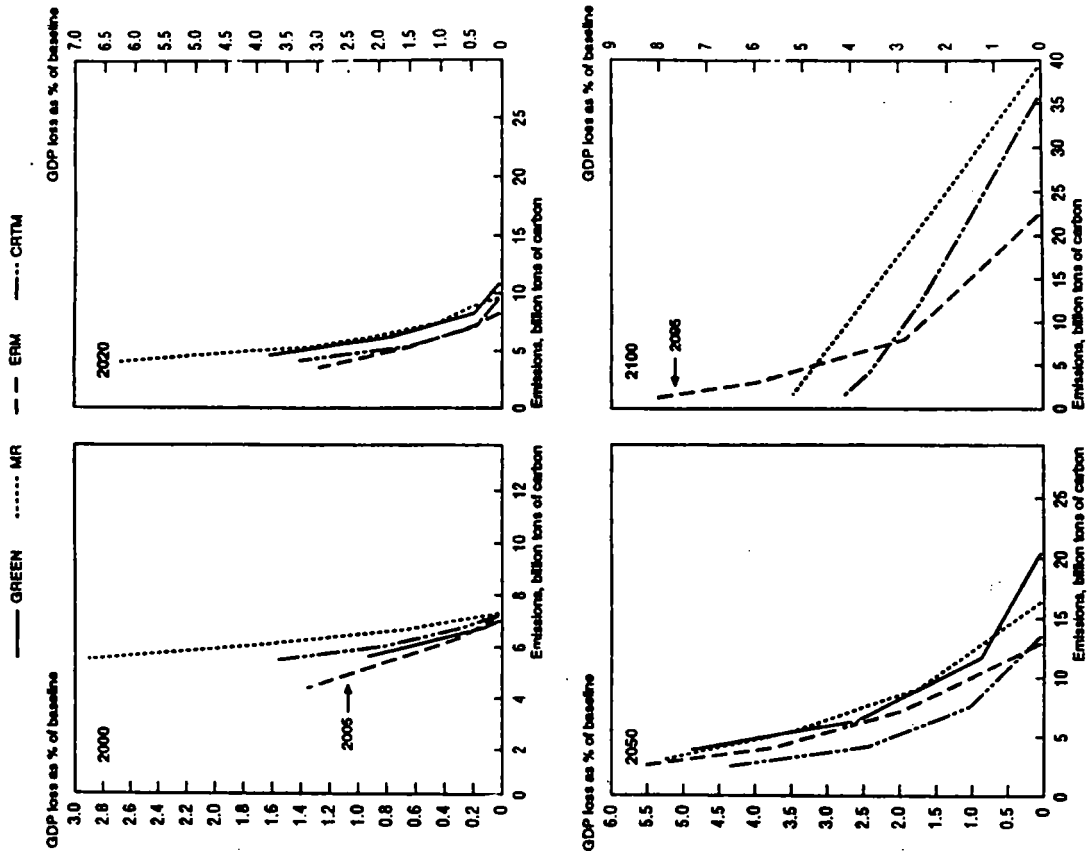
Source: OECD (1993).

Figure 9.1.5.1.1 Global Studies of CO₂ Abatement Costs Relative to Baseline Projection
(Labels are not attached to all points given danger of crowding. For key see Table 9.1.5.1.1)



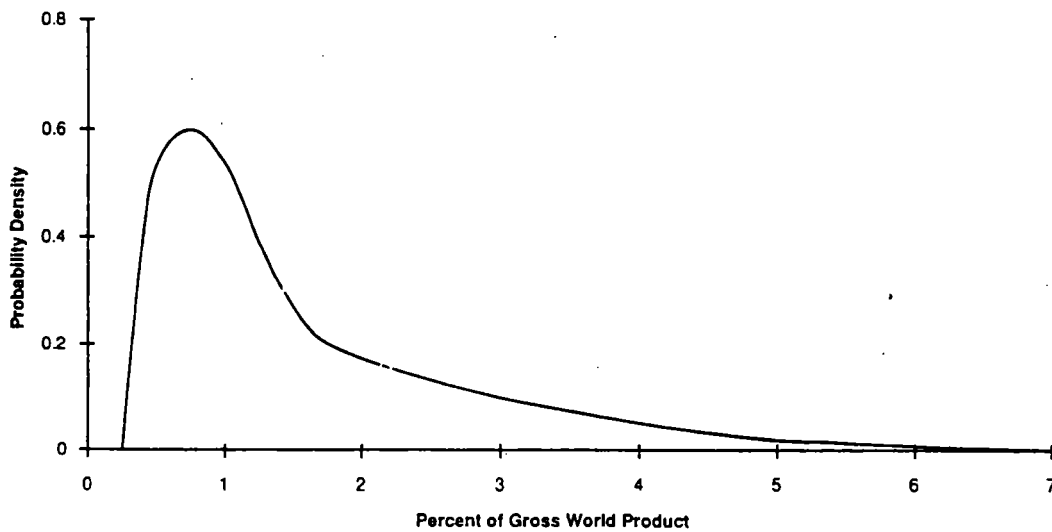
Source: Grubb et al (1993).

Figure 9.1.5.1.2.1 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 9.1.5.1.1.2 The Costs of Stabilizing Global Carbon Emissions



Source: Manne and Richels (1993).

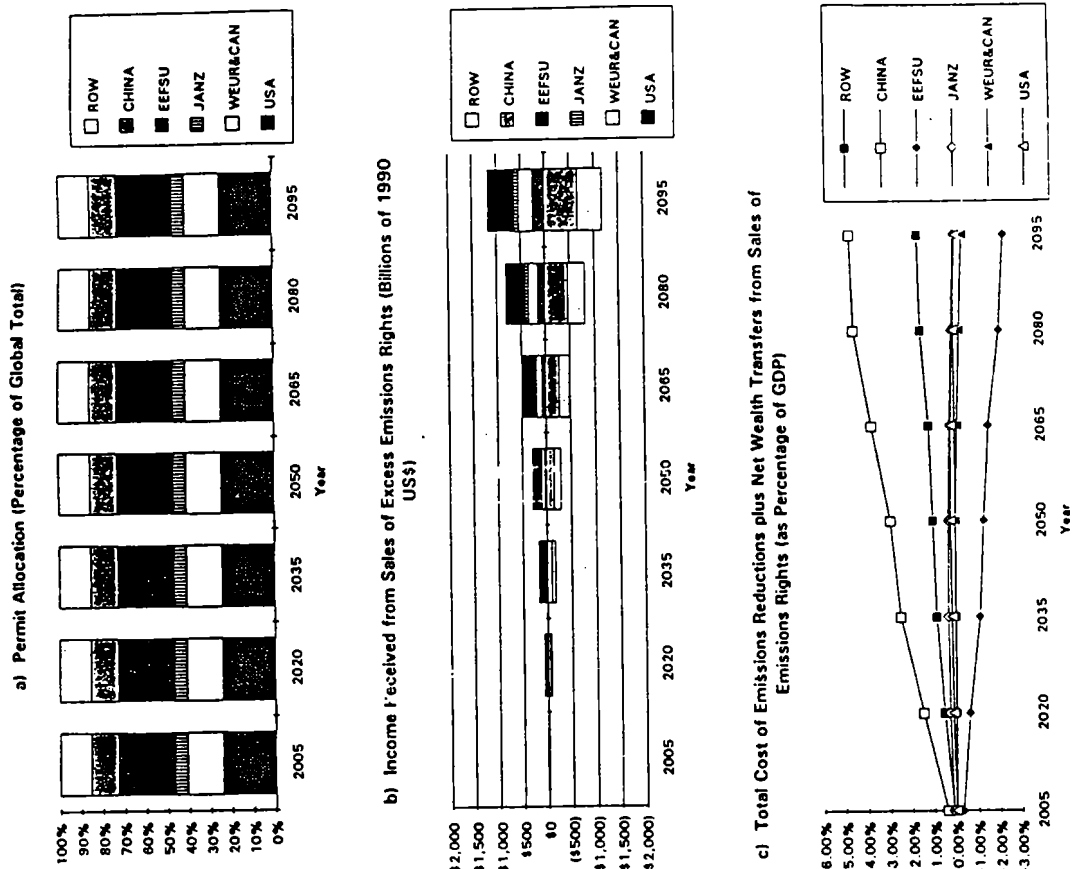
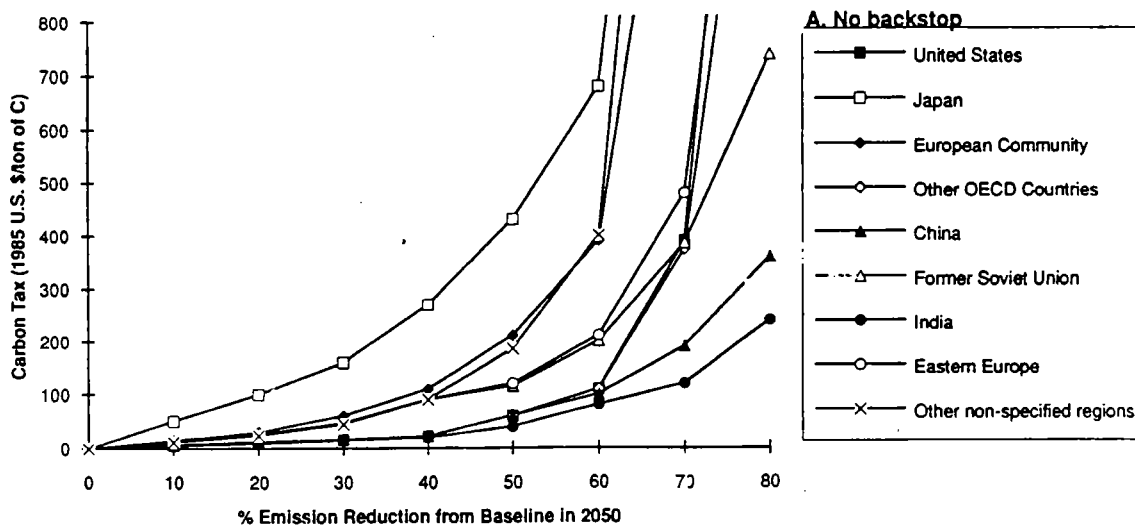


Figure 9.1.5.1.4.1 Grandfathered Emissions Rights Principle

Source: Edmonds et al (1993)

Figure 9.1.5.1.3.1 Regional Carbon Tax Required for Equi-Proportional CO2 Emission Reductions from Baseline



Source: OECD (1994).

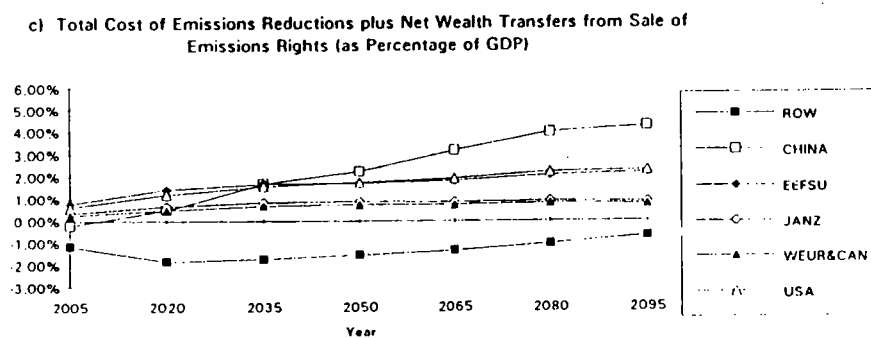
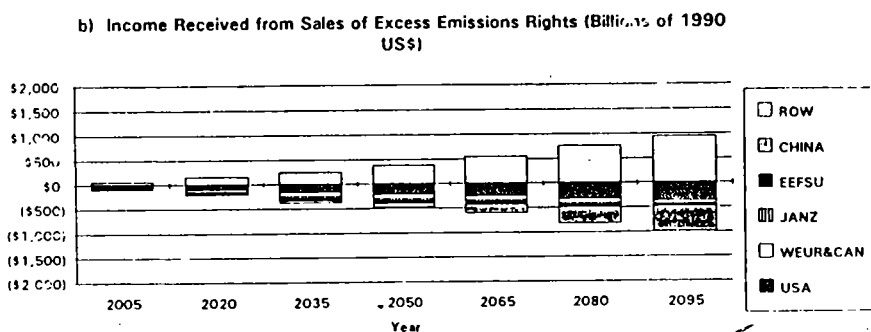
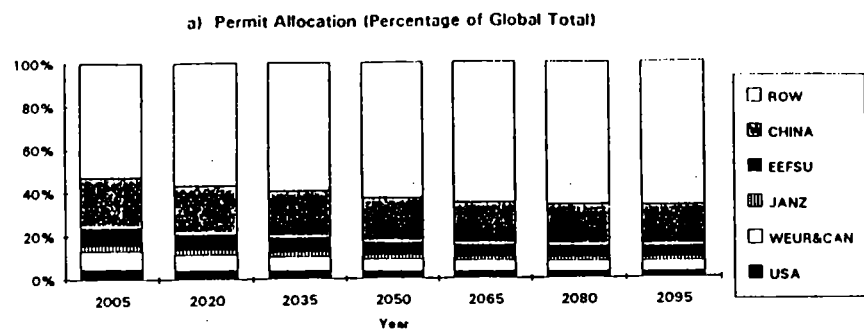


Figure 9.1.5.1.4.2 Equal per Capita Emissions Rights Principle

Source: Edmonds et al (1993).

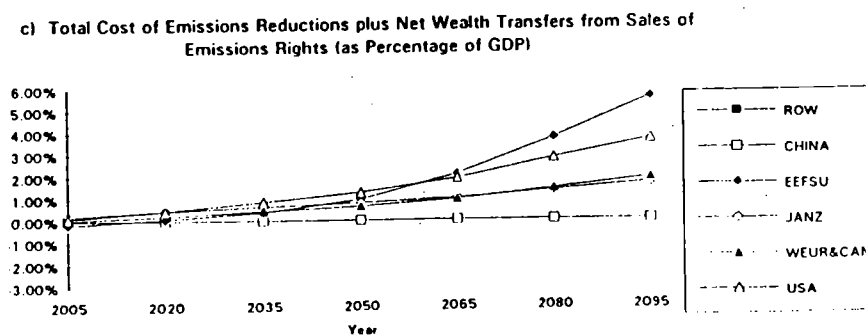
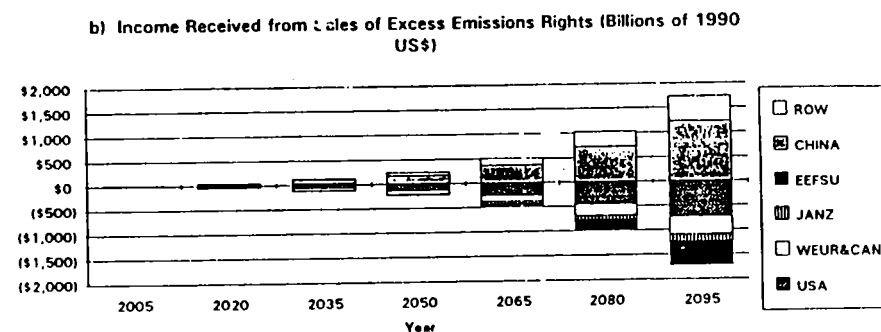
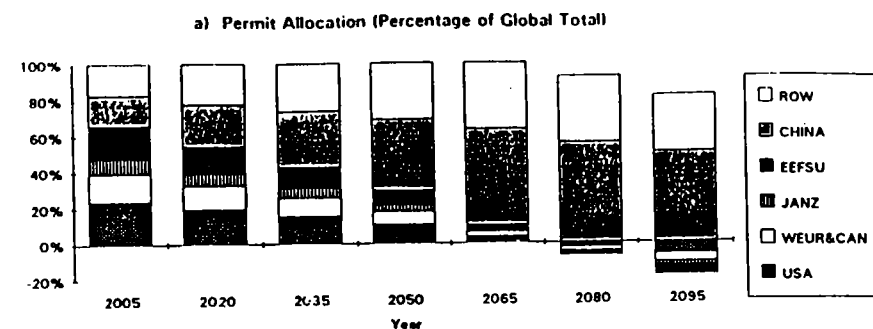


Figure 9.1.5.1.4.3 No Net Cost to Developing Nations Emissions Rights Principle

Source: Edmonds et al (1993).

Figure 9.1.5.2.1. Reference Case range Adopted for Comparison: CO₂ Emissions (Pg c/yr)

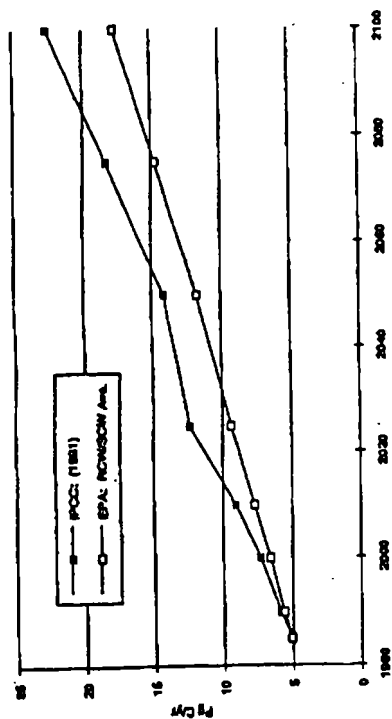
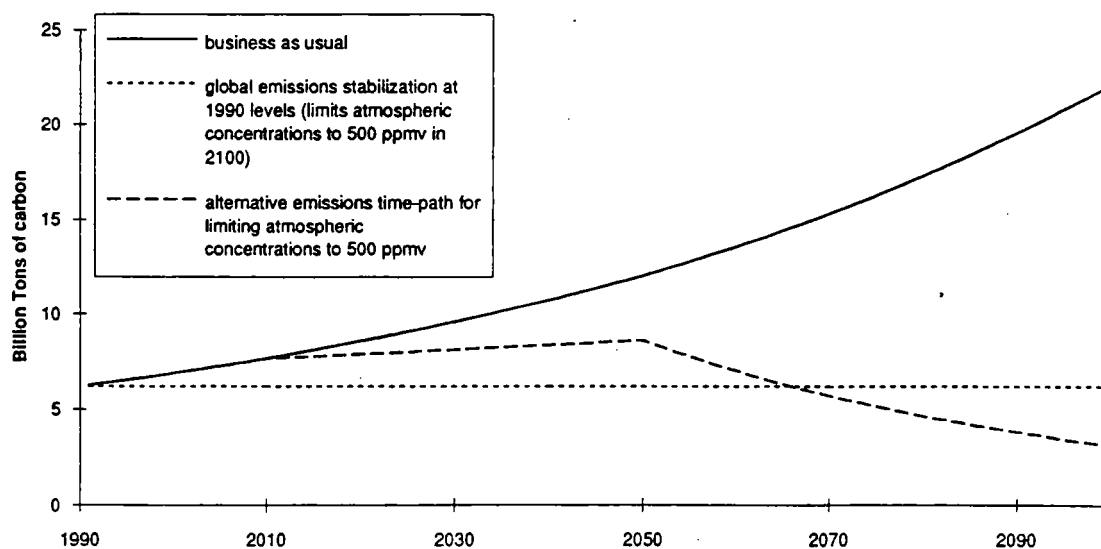
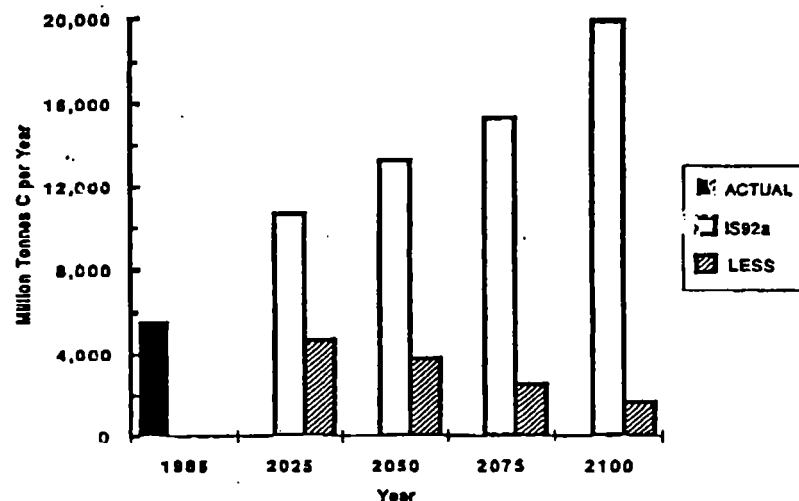


Figure 9.1.5.1.6.1 Global Carbon Emissions

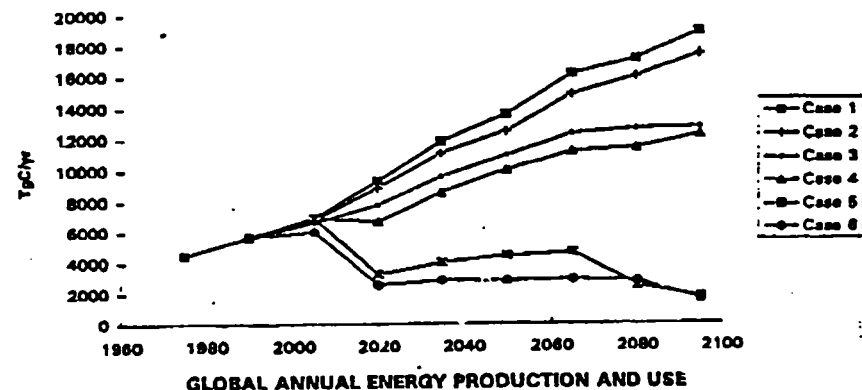


Source: Richels and Edmonds (1994).

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9.1.5.2.2

Figure : Global CO₂ emissions from fossil fuel burning for the LESS Base Case (see Table 4.1.5), with a comparison to the emissions for the IPCC IS92a Scenario.

IPCC Energy Supply Mitigation Options: A Low CO₂ Emissions Supply System Review Draft
GLOBAL ANNUAL FOSSIL FUEL CO₂

9.1.5.2.3

Figure : Global annual CO₂ emissions from fossil fuel burning (top) and global annual primary energy production and use (bottom) for 6 alternative cases constructed by Edwards *et al.* (1994) for the IPCC, Working Group II, Energy Supply Mitigation Options.

Case 1 is the reference scenario with features very similar to the 1992 IPCC scenario IS92a; the exogenous end-use energy intensity improvement rate is 0.5%/year by 2005, rising to 1.0%/year by 2035, and reaching 1.5%/year by 2065. Case 2 emphasizes energy-efficient power generation from fossil fuels (with efficiencies reaching 66% by 2035) but is otherwise like Case 1. In Case 3, hydrogen from natural gas, biomass, and electrolytic sources is used in fuel cells for transportation, and solar and wind power become highly competitive. Case 4 is like Case 3 except that compressed hydrogen is used instead of liquefied hydrogen. Case 5 is like Case 4 except that biomass prices are more competitive. Case 6 is like Case 5 except that the exogenous energy end-use intensity improvement rate reaches 2.0%/year by 2050.

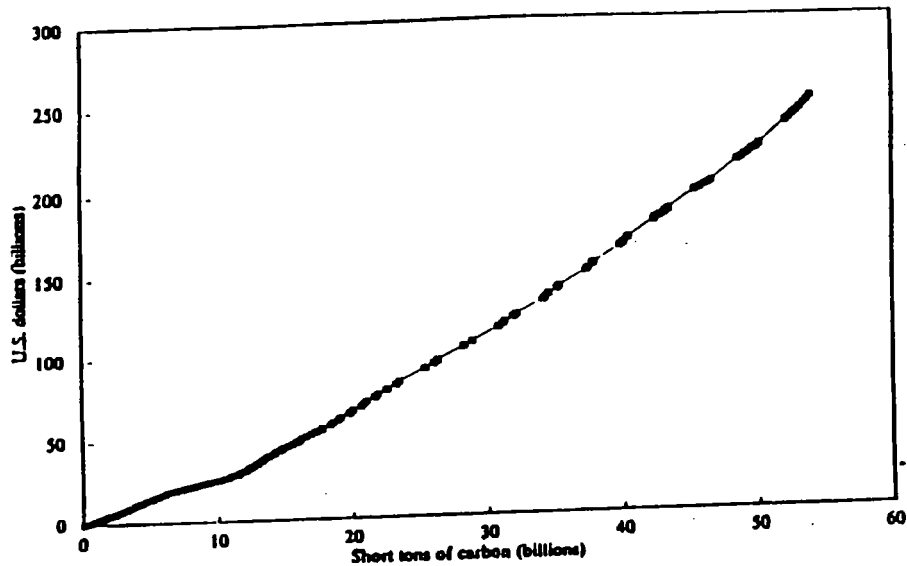
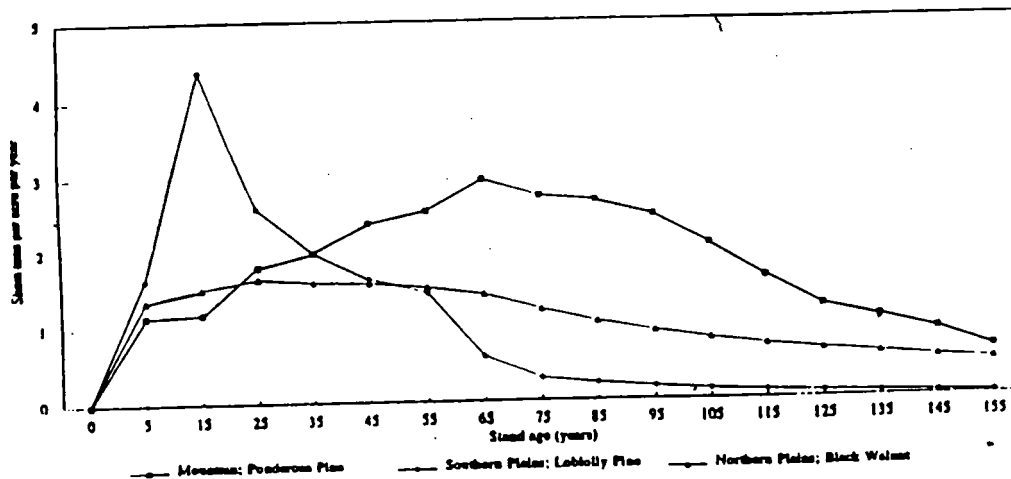


Fig. 9.2.3.1 Total cost curve for carbon sequestration under a 160-year program, expressed in present (1992) dollars.

Reproduced from Richards, Moulton, and Birdsey (1993)

Rate of Annual Carbon Fixation as a Function of Forest- Stand age for three Region/Species Combinations



Reproduced from Richards, Moulton and Birdsey (1993)

Fig. 9.2.3.2 Marginal initial costs of sequestering carbon in forest systems employing forestation and forest management practices

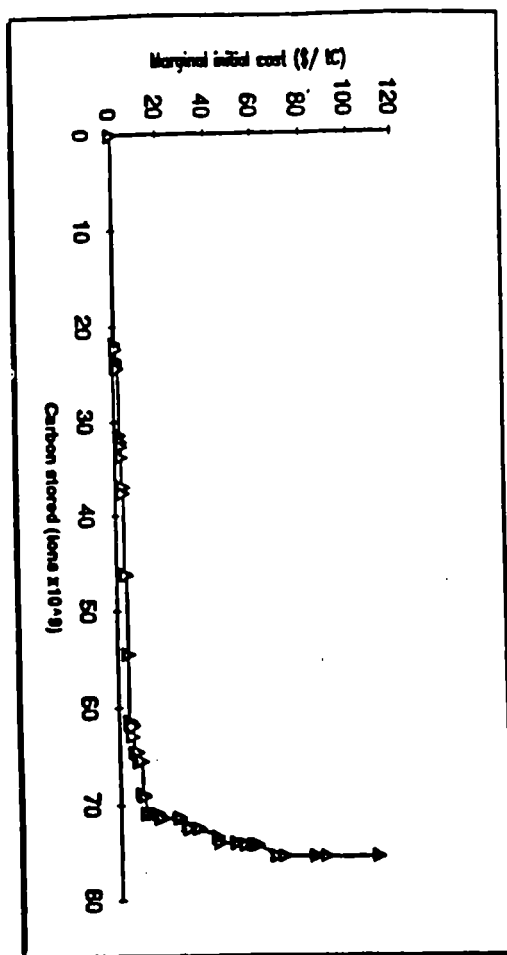


Table 9.1.1.1.1 Models used in Energy Modeling Forum (EMF) Study

Model/Modelers	Model type	Time horizon	Regions
CETA (Peck and Teisburg)	Aggregate economic equilibrium	2100	1 global
CRTM (Rutherford)	Disaggregated economic equilibrium	2100	5 global
DGEM (Jorgenson and Wilcoxon)	Disaggregated economic equilibrium	2050	US
ERM (Edmonds and Reilly)	Energy-sector equilibrium	2095	9 global
Fossil 2 (Belanger and 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 9.1.1.1.2.1 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 9.1.1.1.3.1 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

Source: EMF (1993).

Table 9.1.1 U.S. CO₂ Abatement Cost Modelling Studies

(Source: Grubb et al., 1993)

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, Nicoletti et al (1992)	OMG (2020)	26%, 45%, 60%	0.2%, 1.1%, 2.4%
Oliveira-Martins, Nicoletti et al (1992)	OMG (2050)	45%, 75%, 84%	0.4%, 1.3%, 2.4%
OTA (1991)	O (2015)	23%, 53%, 53%	-0.2% ^e , -0.2% ^e , 1.8%
Rutherford (1992)	RG (2020)	26%, 45%, 60%	0.5%, 1.3%, 2.5%
Rutherford (1992)	RG (2050)	84%, 45%, 70%	2.4%, 1.2%, 2.5%
Rutherford (1992)	RG (2100)	67%, 88%, 96%	1.8%, 2.6%, 2.8%
Shackleton et al (1993)	SJW (2010), SLINK (2010)	22%, 2%	-0.6%, 0.1%
Shackleton et al (1993)	SDRI (2010), SG (2010)	5%, 28%	-0.4%, 0.2%
U.S. Energy Choices (1991)	USEC (2030)	67.5%	-0.6%

^a If the model used is a global model, the Key includes the letter "G" before the date.^b The first two results use multilateral taxes, others use unilateral taxes; taxes are flat only in the first and third estimates, rising in other estimates.^c Values represent different assumptions in technological developments; an optimistic, an intermediate, and a pessimistic view.^d Arising from 11 specified regulatory changes; estimated from claimed savings of \$85 billion per year.^e The benefit shown in the OTA cost estimates is only an indicative value; no explicit modelling value has been calculated.Table 9.1.1.1.7.1 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%

Source: Shackleton et al. (1993).

9.1.1.2.2.1
Table 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/s	-	6				
Office of Technology Assessment, 1991	1987	2015	2.3	-				
US EPA, 1990	1988	2005	2.5	7				
		2010	2.5	7				
SEI/Greenpeace, 1993	1988	2030	2.1	8				
Carlsmith et al, 1990	1988	2010	2.5	7	5	1	5	0.2
Chandler & Kolar, 1990	1985	2030	2.5	7	2.5	1	2.5	1
Chandler & Nicholls, 1990	1989	2000	-	-	27	141	29	
		2000			100			
Chandler, 1990	1989	2010	2.5	7	4.8	0.8		0.2
Lovins & Lovins, 1991	1988	n/s	-	5				
Mills et al, 1991	1988	2000	2.5	6				
Nordhaus, 1990	n/s	n/s	-	-				
Rubin et al, 1992	1989	n/s	-	6				

9.1.1.2.2.2
Table 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/s	24	0	0
		40	0.8	9
Office of Technology Assessment, 1991	2015	23	-0.2	
		53	-0.2/1.8	
US EPA, 1990	2005	3	0	0
	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 & Nicholls, 1990	2000	7		
		20		82**
Chandler, 1990	2010	0		0
		20		92
Lovins & Lovins, 1991	n/s	58*	0	0
Mills et al, 1991	2000	21	-1.2	-23 i
Nordhaus, 1990	n/s	6		13
Rubin et al, 1992	n/s	35	0	0 - <0
RIGES	2025	61	<0	<0
FFEF	2030	75	<0	<0

Table 9.1.2.1.3.1 Effects of different types of tax revenues recycling at the Community level:
GDP losses on the last year (Energy tax of 10\$/bl)

	HERMES ¹ 4 countries	QUEST ² EUR 12 (1995)	DRI ³ EUR 11 (2005)	HERMES-LINK ⁴ 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%		
VAT cut with mixed policy			-0.36% ⁵	

¹ Rate of change after seven years by reference to the baseline (Zagami et al., 1991).

² Rate of change after seven years (DG II-CEC, 1992, p. 52) (in English).

³ Tax revenue is shared between reduction in personal income tax (30%), employer's social security (30%), reduction in corporate taxes (10%) and incentives for energy conservation (30%) (DRI report of 1993).

⁴ Bureau du Plan - Erasme "Un redéploiement fiscal au service de l'emploi" (Rapport à la DOXI-CEC) 1993.

⁵ Calculation from results on the averaged reduction of the rate of growth.

Table 9.1.2.1.2.1 Non-U.S. OECD CO₂ Abatement Cost Modelling Studies

(Source: Grubb et al., 1993)

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)	ECORI (2005)	12%	0.8%
Finland	Christensen (1991)	FC (2010)	23%, 21%	6.9%, 4.8% ^c
France	Hermès-Midas (1992: Karadeloglou)	FHM (2005)	11%	0.7%
Germany	Hermès-Midas (1992: Karadeloglou)	GHM (2005)	13%	1.3%
Italy	Hermès-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	Gjostrod et al (1990)	NG (2010)	26%	2.7%
Sweden	Bergman (1990)	SWB (2000)	10%, 20%, 30%, 40%, 51%	0%, 1.4%, 2.6%, 3.9%, 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	Hermès-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 "C" 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.

Table 9.1.2.1.3.2 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
	DRJ ⁽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
	DRJ ⁽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
	DRJ ⁽²⁾	-0.39	-0.13	-0.39	-0.39	-0.26	-0.39	
Inflation	Hermés	0.45	0.80	2.12	0.86	0.80	0.20	0.95
	DRJ	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 DRJ 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.

Table 9.1.2.1.4.1 Comparison of the emissions reduction between energy tax and carbon tax

	Geographical field	Horizon	Carbon tax	Energy tax
Global 2100 (Tax : 10\$/bl)	Europe	2030	-50%	-46.5%
Hermes-Midas (Tax : 10\$/bl)	France	2005	-10.83%	-9.27%
	Germany	2005	-12.95%	-7.12%
	UK	2005	-6.55%	-4.40%
	Italy	2005	-12.74%	-3.10%
Melodie (Tax : 200 \$/t)	France	2010	-15.7%	-12.6%
Midas (10 \$/bl)	Germany	2005	-11.63%	-7.52%
	UK	2005	-3.98%	-3.29%

Table 9.1.2.2.3.1 : 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

CO ₂ 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	136	-	-	-	-
Spain	18	143	1556	-	-	-
United Kingdom	0	0	12	-	35	63

Source : COHERENCE (1991), p. 50.

9.1.2.2.3.2
Table 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	-253.7
Connection to district heating network	2.1	-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	-53.7
Conservation in industry	1.4	-40.0
Conservation in agriculture	0.4	-38.6
Combined cycle - natural gas (1000 MW)	1.8	-8.6
Biogasification (1500 MW)	7.6	-4.3
Wind turbines (1800 MW)	7.0	0.0
Central natural gas comb. (4000 MW)	9.4	12.9
Solar collectors for hot water	0.3	30.0
Insulation in office buildings	0.7	81.4
Photovoltaics (800 MW)	2.9	185.7
Fuel cells (1000 MW)	1.0	614.3
Total CO ₂ reductions	46.9	

9.1.2.2.3.3

Table 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 9.1.3.2.1.1. Cost of carbon dioxide emissions reduction

Country	Study	Forecast year	CO ₂ 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
	Komonov (1993)	Kon-2005	50	0.3
	Makarov et al (1991)	Mak-2005	23	0.5
	Makarov et al (1991)	Mak-2020	44	1
	Manno (1992)	Man-2020	45	3.1
	Manno (1992)	Man-2050	70	6.4
	Manno (1992)	Man-2100	88	5.6
	Oliviera Martins et al (1992)	OM-2020	45	1.7
	Oliviera 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	Jazray (1990)	Jaz-2005	17	-0.1
Poland	Lesch & Nowak (1991)	L&N-2005	37	-0.1
	Lesch & Nowak (1991)	L&N-2005	53	-0.1
	Stnacki et al (1991)	Stn-2005	44	0
	Stnacki et al (1991)	Stn-2030	62	0.3
	Radwancki et al (1993)	Rad-2010	27	0
	Radwancki et al (1993)	Rad-2030	39	0
Czechoslovakia	Kostalova et al (1991)	Kos-2005	27	0
	Kostalova et al (1991)	Kos-2030	39	0

NOTE: Bold face denotes a bottom-up study.

TABLE 9.1.4.2.1

Energy & Environmental Division, LBL, 1991.
CO ₂ emissions from developing countries. India, Indonesia, China, Argentina, Brazil, Mexico, Venezuela.
High and low emission scenarios 1985-2025. Country specific reductions between 13% and 54% reduction in 2025.
Energy system model, STAIRS.
Asian Development Bank, 1993.
National Response Strategy for Global Climate Change: People's Republic of China.
Business as usual with high and low economic growth and policy scenario 1990-2050. CO ₂ reduction of 23% from baseline in 2050.
Energy system model combined with macroeconomic assessment.
UNEP Collaborating Centre on Energy and Environment, 1994.
UNEP Greenhouse Gas Abatement Costing Studies. Brazil, India, Egypt, Senegal, Thailand, Venezuela and Zimbabwe.
Reference and abatement scenario. Emission reduction targets for 2005/10 and 2020/30 covering 12.5% to 50% reductions from baseline.
Construction of abatement cost curves using energy system models.
Davidson, Ogunlade, 1993.
Carbon Abatement Potential in Western Africa. Ghana, Sierra Leone and Nigeria.
High and low emission scenarios 1985-2025. Reductions from baseline in 2025: Ghana 38%, Sierra Leone 25%, Nigeria 24%.
Energy system model, STAIRS.
La Rovere, E., Legey, L. P. L. Miguez, J. D. G., 1994.
Alternative Energy Strategies for Abatement of Carbon Emissions in Brazil.
Three alternative economic growth scenarios, abatement scenario using high economic growth scenario as baseline. Reductions in 2010 8% and 50%, reductions in 2025 5% and 50% from baseline.
Input-output model used to forecast energy requirements, scenarios taking Japan, Spain and Colombia as focal points. Energy system analysis.
Asian Energy Institute, 1992.
Collaborative Study on Strategies to limit CO ₂ emissions in Asia and Brazil. Brazil, China, India, The Islamic Republic of Iran, South Korea and Thailand.
Emission reduction scenarios for 1988/90 to 2000/2015.
Calculation of investment cost for individual abatement technologies.
Greenpeace, 1993.
Towards a Fossil Free Energy Future. Global study including regional assessment for Africa, Centrally Planned Asia, Latin America and South and East Asia.
Reduction scenario 1988-2100. Global reductions from 1988 level: 50% in 2030, 100% in 2100.
Energy system model and macroeconomic assessment of the impact of carbon taxes on final energy prices.

Table 9.1.4.1.1 Comparative Results from Five Models for Carbon Emission and GDP Losses for China and the World

Model*	% Av. Annual Carbon Emission Growth		% GDP Loss in Year 2100 over BAU						Major Policy Option for Carbon Emission Abatement
	BAU Scenario		Scenario I		Scenario II				
	World	China	World	China	World	China			
CRTM	1.6	2.5	4.0	3.5	3.5	5.0	-		
ERM	1.2	2.5	7.0	6.0	4.5	13.0	Fuel substitution		
GREEN	2.0	3.8	3.6	1.5	3.0	5.5	Energy conservation		
IEA	2.0	3.2	-	-	-	-	Energy conservation		
MR	1.7	2.2	5.2	5.0	4.5	5.0	Fuel substitution		

* Terminal year for ERM, GREEN and IEA models are 2095, 2050, and 2005 respectively, and Year 2100 for other two models

* Terminal year for ERM, GREEN and IEA models are 2095, 2050, and 2005 respectively, and Year 2100 for other two models

9.1.4.2.1.1

Table 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	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	3.2	3.2	4.0	3.5		
SOUTH KOREA (4)	0.4	5.0		3.1		2.8		
MEXICO (1)	1.7	4.4	2.7	2.1	2.8	1.9		
NIGERIA (5)	3.0	4.0	2.6	1.9	4.6	3.8		
SENEGAL	3.0	3.2	3.2	2.4	3.5	2.6		
SIERRA LEONE (5)	2.3	3.0	2.2	1.7	3.5	3.0		
THAILAND	0.9	4.8	4.8	4.2	5.5	4.6		
THAILAND (4)	2.0	8.0		7.8		7.8		
VENEZUELA	2.1	3.8	2.5	1.9	3.1	2.1		
VENEZUELA (1)	1.7	4.0	3.4	3.2	2.5	1.9		
ZIMBABWE	2.4	4.2	2.8	1.9	3.2	1.5		
LATIN AMERICA (2)	1.5	3.3	2.7		3.2			
LATIN AMERICA (3)	1.3	3.2		0.9		-0.6		
SOUTHEAST ASIA (2)	1.4	4.6	3.9		5.1			
SOUTHEAST ASIA (3)	1.6	4.1		1.5		-0.2		

(1) Energy & Environmental Division, LBL; CO₂ Emissions from Developing Countries: Better Understanding the Role of Energy in the Long Term; July 1991.

(2) IPCC, 1992; Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment.

(3) Stockholm Environment Institute - Boston Centre Towards a Fossil Free Energy Future; April 1993.

(4) Asian Energy Institute; Collaborative Study on Strategies to Limit CO₂ Emissions in Asia and Brazil; 1992.

(5) Davidson 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.

9.1.4.2.1.2

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

Country	REFERENCE			ABATEMENT		
	Energy/GDP	C/Energy	C/GDP	Energy/GDP	C/Energy	C/GDP
ARGENTINA (1)	0.9	1.0	0.9	0.6	1.0	0.5
BRAZIL	0.8	1.5	1.1	0.8	0.9	0.7
BRAZIL (1)	0.8	1.1	0.9	0.3	0.8	0.3
CHINA (6)	0.5	0.8	0.4	0.5	0.8	0.4
EGYPT	0.6	1.2	0.8	0.3	1.0	0.3
GHANA (5)	0.9	1.5	1.4	0.8	1.7	1.3
INDIA	0.7	0.9	0.6	0.6	0.8	0.5
INDIA (1)	0.9	1.0	0.9	0.9	1.0	0.9
INDONESIA (1)	1.2	1.1	1.3	1.1	1.1	1.2
SOUTH KOREA (4)				0.6	0.9	0.6
MEXICO (1)	0.6	1.0	0.6	0.5	0.9	0.4
NIGERIA (5)	0.7	1.7	1.1	0.5	2.0	1.0
SENEGAL	1.0	1.1	1.1	0.8	1.1	0.8
SIERRA LEONE (5)	0.7	1.6	1.2	0.6	1.8	1.0
THAILAND	1.0	1.2	1.1	0.9	1.1	1.0
THAILAND (4)				1.0	1.0	1.0
VENEZUELA	0.7	1.3	0.8	0.5	1.1	0.6
VENEZUELA (1)	0.9	0.7	0.6	0.8	0.6	0.5
ZIMBABWE	0.7	1.2	0.8	0.4	0.8	0.4
LATIN AMERICA (2)	0.8	1.2	1.0			
LATIN AMERICA (3)				0.3	-0.7	-0.2
SOUTHEAST ASIA (2)	0.8	1.3	1.1			
SOUTHEAST ASIA (3)				0.4	-0.1	0.0

(1) Energy & Environmental Division, LBL; CO₂ Emissions from Developing Countries: Better Understanding the Role of Energy in the Long Term; July 1991.

(2) IPCC, 1992; Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment.

(3) Stockholm Environment Institute - Boston Centre Towards a Fossil Free Energy Future; April 1993.

(4) Asian Energy Institute; Collaborative Study on Strategies to Limit CO₂ Emissions in Asia and Brazil; 1992.

(5) Davidson Olungade; Carbon Abatement Potential in Western Africa; in P. Hayes, K. Smith, eds., The Global Greenhouse Regime: Who Pays?; 1993.

(6) Asian Development Bank; National Response Strategy for Global Climate Change: People's Republic of China; Nov. 1993.

9.1.4.2.2.1

Table 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

(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	2084	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

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 9.1.4.2.4.1

Country	CO ₂ reduction option	reduction (%)	MAC (US\$)
Brazil	Electricity saving (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 CO₂ 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 CO₂ 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 CO₂ reduction	50	
Thailand	Efficient airconditioners	2	-36
	Electronic ballast	1	-27
	Compact fluorescent lamps (service sector)	6	-14
	Compact fluorescent lamps (residential sector)	2	-9
	Nuclear electricity	18	20
	Highly efficient gasoline cars	1	92
	Total CO₂ reduction	30	
Venezuela	Reduced flaring and leakage of methane	7	3
	Efficient boilers and kilns	10	10
	Freight transport	1	13
	Efficient electric motors in the industrial sector	2	17
	Passenger transport	4	21
	Electric sector	0.6	35
	Other energy savings in the industrial sector	2	39
	Efficient electric appliances	0.4	52
	Total CO₂ 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 CO₂ reduction	38	

Table 9.1.5.1.3.1 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.

Source: OECD (1993).

Table 9.1.5.1.1 Global CO₂ Abatement Cost Modelling Studies

(Source: Grubb et al., 1993)

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, Nicoletti 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 9.1.5.21
Summary Comparison of Results

	1988	2000	2010	2030	2100
Fossil Free Energy Scenario					
Global GDP (Billion 1985 US\$)	\$18,351	\$23,451	\$30,116	\$41,771	\$212,863
Delivered Energy (EJ)	238	255	251	232	448
Primary Energy (EJ)	338	398	400	384	987
From Renewables (%)	13%	21%	29%	32%	100%
From Solar/Wind (%)	0%	5%	8%	31%	79%
From Biomass (%)	7%	10%	13%	24%	18%
Primary Energy/CO ₂ (tJ/t)	64	68	71	148	-
Energy/GDP (tJ/\$)	21	17	13	9	6
CO ₂ /GDP (Tg/\$)	0.32	0.24	0.19	0.08	0.00
IPCC91: Reference Case*					
Global GDP (Billion 1985 US\$)	\$18,340	\$24,858	\$32,781	\$58,488	\$255,103
Delivered Energy (EJ)		Not Yet Available			
Primary Energy (EJ)	348	460	571	797	1841
From Renewables (%)		Not Yet Available			
From Solar/Wind (%)		Not Yet Available			
From Biomass (%)		Not Yet Available			
Primary Energy/CO ₂ (tJ/t)	60	63	61	62	73
Energy/GDP (tJ/\$)	19	18	17	14	6
CO ₂ /GDP (Tg/\$)	0.32	0.28	0.28	0.23	0.08
EPA: Reference Case (RCW/SCW avg.)**					
Global GDP (Billion 1985 US\$)	\$15,520	\$22,532	\$28,242	\$49,427	\$230,395
Delivered Energy (EJ)	238	288	333	420	639
Primary Energy (EJ)	302	384	451	585	1067
From Renewables (%)	7%	8%	10%	13%	18%
From Solar/Wind (%)	0%	0%	1%	2%	7%
From Biomass (%)	0%	0%	1%	3%	5%
Primary Energy/CO ₂ (tJ/t)	39	58	58	68	60
Energy/GDP (tJ/\$)	19	17	15	12	4
CO ₂ /GDP (Tg/\$)	0.33	0.29	0.28	0.20	0.07
EPA: "Rapid Reductions" (RCWR)***					
Global GDP (Billion 1985 US\$)	\$15,520	\$24,758	\$34,130	\$64,448	\$380,813
Delivered Energy (EJ)	232	348	384	346	471
Primary Energy (EJ)	302	334	408	545	799
From Renewables (%)	7%	10%	38%	88%	77%
From Solar/Wind (%)	0%	1%	2%	4%	8%
From Biomass (%)	0%	0%	26%	34%	38%
Primary Energy/CO ₂ (tJ/t)	39	61	92	218	533
Energy/GDP (tJ/\$)	19	14	12	8	2
CO ₂ /GDP (Tg/\$)	0.33	0.22	0.13	0.04	0.00

Source: Leach and Typpak (1980), IPCC (1981)

* For the IPCC scenario, the values shown are for 1980, not 1988.

** For the U.S. EPA and IPCC, the 1988, 2010, and 2030 values were interpolated based on 1985, 2000, 2025, and 2050 results.

*** Primary energy totals include traditional biomass fuels.

**** Note that 1988 biomass estimates reflect UN estimates (UN, 1990) and could be low by a factor of 2 (See Hall, 1981).

Table 9.2.1: Land Area Availability

Study	Region	Area Available for Practice (ha x 10 ⁶)		
		Forest Plantation	Forest Management	Agroforestry
Sedjo and Solomon (1988) ^a	Global	465	—	—
Greiner (1988)	Tropics	621	137	—
Adams et al. (1990) ^b	United States	114	—	—
Barnon and Gifford (1990)	Australia	1.6	—	—
Moulton and Richards (1990)	United States	112	31	—
Nordhaus (1991)	Global	510	—	—
Dixon, Schroeder and Winjum (1991)	Boreal	Not specified ^c	Not specified ^c	Not specified ^c
	Temperate	Not specified ^c	Not specified ^c	Not specified ^c
	Tropical	Not specified ^c	Not specified ^c	Not specified ^c
Dixon, Winjum and Krankina (1991)	Latin America	214	—	372
	Africa	222	—	305
	Asia	115	—	159
	North America	42	—	7
New York State (1991)	New York State	0.1	0.2	—
van Kooten et al. (1992)	Canada	8.6	19.7	—
Houghton et al. (1993)	Latin America	44	634	717
	Africa	178	26	888
	Asia	29	393	270
Parks and Hardie (1993)	United States	10.4 ^d	—	—
Richards et al. (1993)	United States	102	—	—
Dixon et al. (1994)	South America	—	—	65-380
	Africa	—	—	300-440
	South Asia	—	—	130-225
	North America	—	—	90-140
Tasman Institute (1994)	New Zealand	5	—	—
Masera et al. (1994)	Mexico	18.2-19.6	18.7	—
Ravindranath and Somanath (1994)	India	41.3	36.9	96
Xu ^e	China	110.5	19.2	70.5

(a) The estimate by Sedjo and Solomon (1988) was based on a carbon budget goal of 2.9 x 10⁶ tonnes per year. It is not based on an assessment of land actually available, but rather land needed to meet the goal.

(b) The land area was constrained by the carbon budget goal, not by availability.

(c) Land area availability was not specified by practice. Therefore, costs and yields could not be matched with land areas available. The land area for dryland ecoregions was split between temperate and tropical categories.

(d) The land area was constrained by budget, not by availability.

(e) Community woodlots, timber forestry and softwood forestry are included in the forest plantation category; natural regeneration and enhanced natural regeneration are included in the forest management category.

(f) The planting areas and sandy waste area are included in the forest plantation category; open forest is included in the forest management category; dry cropland is included in the agroforestry category.

Table 9.2.2: Land Costs

Study	Region	Land Costs		
		Forest Plantation	Forest Management	Agroforestry
Sedjo and Solomon (1988)	Global	400 US\$/ha	—	—
Adams et al. (1990)	United States	Not reported separately ^(a)	—	—
Moulton and Richards (1990)	United States	360-8400 US\$/ha	120-1440 US\$/ha	—
Nordhaus (1991)	Global	20-200 US\$/ha	—	—
Dixon, Schroeder and Winjum (1991)	Boreal	0	0	0
	Temperate	0	0	0
	Tropical	0	0	0
Dixon, Winjum and Krankina (1991)	Latin America	0	—	0
	Africa	0	—	0
	Asia	0	—	0
	North America	0	—	0
New York State (1991)	New York State	0-1200 US\$/ha	0	—
Van Kooten et al. (1992)	Canada	0	0	—
Parks and Hardie (1993)	United States	40-650 US\$/ha/yr ^(b)	—	—
Richards et al. (1993)	United States	275-5135 US\$/ha	—	—
Dixon et al. (1994)	South America	0	—	0
	Africa	0	—	0
	South Asia	0	—	0
	North America	0	—	0
Masera et al. (1994)	Mexico	0	0	—
Ravindranath and Somashekhar (1994) ^(c)	India	16 US\$/ha	16 US\$/ha	0
Xu ^(d)	China	0	0	0

- (a) The opportunity cost of land was derived within a mathematical programming model as the consumer welfare loss associated with the withdrawal of agricultural land from production.
- (b) The land costs were expressed as annual rental payments to landowners within a subsidy program.
- (c) These figures are referred to as land rent but are included in the total investment costs, which appear to be initial costs only. It is not clear whether these figures represent a one time cost or an annual rent.
- (d) It is not clear whether land costs are included in investment costs (see Table 9.2.3).

Table 9.2.3: Treatment Cost

Study	Region	Treatment Costs (US\$/ha)		
		Forest Plantation	Forest Management	Agroforestry
Sedjo and Solomon (1988)	Global	400	—	—
Adams et al. (1990)	United States	140-520	—	—
Moulton and Richard (1990)	United States	140-520	—	—
Nordhaus (1991)	Global	400-450	—	—
Dixon, Schroeder and Winjum (1991)	Boreal	125-450	50-250	—
	Temperate	25-800	0-1600	1000
	Tropical	250-320	50-500	250-750
Dixon, Winjum and Krankina (1991)	Latin America	150-800	10-85	—
	Africa	30-1400	3-60	—
	Asia	150-375	15-30	—
	North America	50-1200	10-400	—
New York State (1991)	New York State	660	288	—
van Kooten et al. (1992)	Canada	300-500	650-1000	—
Parks and Hardie (1993)	United States	350 ^(a)	—	—
Richards et al. (1993)	United States	190-690	—	—
Dixon et al. (1994)	South America	—	—	500-3500
	Africa	—	—	500-3500
	South Asia	—	—	500-3500
	North America	—	—	500-3500
Masera et al. (1994) ^(b)	Mexico	387-700	NA	—
Ravindranath and Somashekhar (1994)	India	367-550	77-205	39
Xu (1994)	China	46-828	11-31	14-240

(a) Parks and Hardie (1993) categorize treatment according to hardwood and softwood treatments. The figure listed here is for hardwood treatment. The costs for softwood are cited but not listed.

(b) Although there are costs associated with forest management in Masera et al. (1994) it is not clear how to interpret the figures.

Table 9.2.5: Treatment of Carbon Flows

Study	Region	Yield Method	Estimate of Carbon Yield		
			Forest Plantation	Forest Management	Agroforestry
Sedjo and Solomon (1988)	Global	Average flow	6.24 tonnes/ha/yr	—	—
Adams et al. (1990)	United States	Average flow	2.0-10.9 tonnes/ha/yr	—	—
Moulton and Richards (1990)	United States	Average flow	2.0-10.9 tonnes/ha/yr	0.0-7.6 tonnes/ha/yr	—
Nordhaus (1991)(a)	Global	Yield curve	0.8-1.6 tonnes/ha/yr	—	—
Dixon, Schroeder and Winjum (1991)	Boreal	MCS	15-40 tonnes/ha	4-20 tonnes/ha	—
	Temperate	MCS	30-175 tonnes/ha	10-125 tonnes/ha	15-160 tonnes/ha
	Tropical	MCS	25-125 tonnes/ha	20-200 tonnes/ha	50-150 tonnes/ha
Dixon, Winjum and Krankina (1991)(b)	Not specified	—	—	—	—
New York State (1991)	New York State	Average flow	2.1 tonnes/ha/yr	1.1 tonnes/ha/yr	—
Van Kooten et al. (1992)	Canada	Average flow	0.6-0.8 tonnes/ha/yr	0.6-2.1 tonnes/ha/yr	—
Parks and Hardie (1993)	United States	Average flow	0.4-0.8 tonnes/ha/yr	—	—
Richards et al. (1993)(c)	United States	Yield curve	0.0-9.4 tonnes/ha/yr	—	—
Dixon et al. (1994)	South America	MCS	—	—	39-195 tonnes/ha
	Africa	MCS	—	—	29-53 tonnes/ha
	South Asia	MCS	—	—	12-228 tonnes/ha
	North America	MCS	—	—	90-198 tonnes/ha
Masera et al. (1994)(d)	Mexico	MCS	25-150 tonnes/ha	121-134 tonnes/ha	—
Ravindranath and Somashankar (1994)(e)	India	Standing carbon	76-121 tonnes/ha	62-87 tonnes/ha	25 tonnes/ha
Xu (1994)(f)	China	MCS	22-146 tonnes/ha/yr	9-15 tonnes/ha	6-33 tonnes/ha

(a) Nordhaus (1991) develops logistic yield curves based on estimated carrying capacity, average flows and time to maturity.

(b) Dixon, Winjum and Krankina (1991) concentrated on forestry activities and their costs rather than on carbon yields.

(c) The range represents the lowest yield year for the slowest growing species to the highest yield year for the highest yield species.

(d) Carbon yield for forest management is estimated as avoided emissions from deforestation.

(e) These figures appear to count total carbon standing at 50 years, but may use MCS since rotations are considered for some practices.

(f) In addition to the components included in MCS, carbon stored in wood products.

Table 9.2.4: Discount Rate Applied to Financial Outlays

Study	Annual Discount Rate
Sedjo and Solomon (1988)	Not specified
Adams et al. (1990)	10%
Moulton and Richards (1990)	10%
Nordhaus (1991)	8%
Dixon, Schroeder and Winjum (1991)	5%
Dixon, Winjum and Krankina (1991)	Not specified
New York State (1991)	10%
Van Kooten et al. (1992)	10%
Parks and Hardie (1993)	4%
Richards et al. (1993)	5%
Dixon et al. (1994)	Not specified
Masera et al. (1994)	10%
Ravindranath and Somashankar (1994)	12-17.25%
Xu (1994)	Not Specified

Table 9.2.6: Treatment of Forest Products in Carbon Sequestration Studies

Study	Forest Product Treatment
Adams et al. (1990)	Explicitly includes timber harvest, but does not include value of products in the benefits accounting, effect of release of carbon on carbon accounting not clear.
Barson and Gifford (1990)	Describes three scenarios of decay rates of wood products described, but effect on carbon accounting unclear.
Moulton and Richards (1990)	Does not consider forest products.
Nordhaus (1991)	Discusses land purchased and turned into permanent forest cover, does not consider harvest.
Dixon, Schroeder and Winjum (1991)	Assumes: products are harvested, 100 percent release of stored carbon at time of harvest, no accounting for value of forest products.
Dixon, Winjum and Krankina (1991)	Does not address carbon flows or stocks, benefits of harvest implicitly considered in forestry practice costs analysis via derivation of internal rate of return on investment.
New York State (1991)	Subtracts value of timber products from costs of carbon sequestration.
Van Kooten et al. (1992)	Does not consider forest products.
Parks and Hardie (1993)	Does not consider forest products.
Richards et al. (1993)	Discusses land purchased and turned into permanent forest cover, does not consider harvest.
Dixon et al. (1994)	Discusses effects of harvest qualitatively, does not quantify.
Tasman Institute (1994)	Accounts for carbon loss at harvest, assumes 100 percent loss at harvest.
Masera et al. (1994)	Discusses harvest of timber, carbon and cost accounting methods unclear.
Ravindranath and Somashekhar (1994)	Includes value of forest products in cost accounting.
Xu (1994)	Explicit inclusion of forest products as a component of carbon storage and net costs.

Table 9.2.7: Ecosystem Components Included in Carbon Sequestration Studies

Study	Ecosystem Carbon Components Included
Sedjo and Solomon (1988)	Above- and below-ground tree
Adams et al. (1990)	Above- and below-ground tree, soil, understory, litter
Barson and Gifford (1990)	Above- and below-ground tree, soil, understory
Moulton and Richards (1990)	Above- and below-ground tree, soil, understory, litter
Nordhaus (1991)	Not specified
Dixon, Schroeder and Winjum (1991)	Above- and below-ground tree
Dixon, Winjum and Krankina (1991)	Above- and below-ground tree
New York State (1991)	Above- and below-ground tree
Van Kooten et al. (1992)	Tree bole only ^(a)
Houghton et al. (1993)	Above- and below-ground biomass
Parks and Hardie (1993)	Above- and below-ground tree
Richards et al. (1993)	Above- and below-ground tree, soil, understory, litter
Dixon et al. (1994)	Above- and below-ground tree ^(a)
Tasman Institute (1994)	Above- and below-ground tree, understory, litter
Masera et al. (1994) ^(a)	Above- and below-ground tree, soils
Ravindranath and Somashekhar (1994)	Above- and below-ground tree, understory, soils
Xu (1994)	Above- and below-ground tree, litter and wood products

(a) Implied in text, but not explicitly stated.

Table 9.2.8: Summary Statistic Applied to Studies

Study	Summary Statistic Used
Adams et al. (1990)	Levelized costs ^(a)
Moulton and Richards (1990)	Levelized costs
Nordhaus (1991)	Levelized costs
Dixon, Schroeder and Winjum (1991)	Average storage method
Dixon, Winjum and Krankina (1991)	Average storage method
New York State (1991)	Levelized costs
Van Kooten et al. (1992)	Flow summation ^(a)
Parks and Hardie (1993)	Levelized costs
Richards et al. (1993)	Levelized costs/discount method
Dixon et al. (1994)	Average storage method
Masera et al. (1994)	Average storage method
Ravindranath and Somashekhar (1994) ^(a)	Flow summation
Xu (1994)	Average storage method

- (a) Levelized costs are not explicitly derived, but are implicit in the form of the model.
 (b) Van Kooten uses a flow summation method in the text and expresses a clear preference for this approach. Levelized costs are provided in an appendix.
 (c) Because the carbon accounting method is unclear (see Table 9.2.5) it is unclear whether the costs are derived using the flow summation method (if carbon accounting is based on standing carbon) or the average storage method (if carbon accounting is based on MCS).

Table 9.2.1: Unit Costs of Carbon Sequestration

Study	Region	Method	Cost of Carbon Sequestration (Dollars)		
			Forest Plantation	Management	Agriculture
Sedjo and Solomon (1988) ^(a)	Global	Levelized	7	—	—
Adams et al. (1990)	United States	Flow summation	3	—	—
Moulton and Richards (1990) ^(a)	United States	Levelized	20-61	—	—
Nordhaus (1991)	Global	Levelized	9-41	6-47	—
Dixon, Schroeder and Winjum (1991)	Boreal	Flow summation	3-9	2-9	—
Dixon et al. (1994)	Tropical	Levelized	42-114	—	—
New York State (1991)	Tropical	Average Storage	5-8	7	—
Van Kooten et al. (1992)	New York State	Average Storage	3-6	1-15	23
Parks and Hardie (1993)	Canada	Average Storage	7	1-9	5
Richards et al. (1993) ^(a)	United States	Flow summation	16-57	12	—
Dixon et al. (1994)	United States	Levelized	6-18	8-23	—
Masera et al. (1994)	South America	Levelized	10-500	39-108	—
Ravindranath and Somashekhar (1994) ^(a)	Africa	Flow summation	9-46	—	—
Xu (1994)	South Asia	Flow summation	2-9	—	4-41
	North America	Average Storage	—	—	4-69
	Latin America	Average Storage	—	—	2-66
	India	Average Storage	5-11	—	1-6
	China	Flow summation	0.13-1.06	0.3-3	—
		Average Storage	0.09-1.22	0.95-2.78	—
			(1.7)-2	(2)-1	(12)-(11)

- (a) Sedjo and Solomon do not provide a unit cost figure for carbon sequestration. The figures presented here are based on their cost and yield estimates treated over 40 years with a 5% discount rate on financial outlays.
 (b) The flow summation method is not used in these reports. The figures are supplied here for purposes of comparison with other studies.
 (c) The interpretation of these figures is unclear. See discussion in text.
 (d) Figures in parentheses indicate negative costs.

Table 9.3 Summary of Economically Viable Options for Reducing Methane, N₂O, PFC, and HFC Emissions

Source	Global Emissions (Tg/yr) ¹	Available Options for Reducing Emissions Profitably	Reductions Possible at Site-Specific Projects ²	Near-term Profitable Reductions Possible World-wide (Tg/yr) ³
METHANE				
Natural Gas Systems	30 - 65	YES	20 - 80%	4 - 16
Coal Mining	24 - 40	YES	30 - 90%	4 - 7
Waste Disposal	20 - 40	YES	up to 90%	9 - 14
Ruminant Livestock	65 - 100	YES	5 to 60%	4 - 10
Animal Manures	10 - 18	YES	up to 80%	over 1
Wastewater Treatment	30 - 40	NA ⁴	-	-
Rice Cultivation	60 - 100	under development	-	-
Biomass Burning	29 - 68	unde. development	-	-
NITROUS OXIDE				
Adipic Acid Production	.3 to .6	under development	up to 90%	not examined
Nitric Acid Production	.1 to .3	not examined	-	not examined
Fertilizer Use	.3 to 3	under development	up to 30%	not examined
PFCs				
Aluminum Production	.03	YES	up to 90%	not examined
HFCs				
Intentional Manufacture	NA	not examined	-	not examined
Manufacturing By-product	NA	YES	up to 50%	not examined
Applications	NA	not examined	-	not examined

¹ USEPA (1994) for methane emissions; see text for other greenhouse gases

² USEPA (1993a)

³ USEPA (1993b)

⁴ Methane emissions from wastewater treatment are largely from lesser developed countries and large capital investments may be necessary to construct effective wastewater management facilities - in these cases the captured methane is not expected to substantially offset the investments.

Table 9.2.1: Potential Carbon Sequestration

Study	Region	Forest Plantation	Forest Management	Agroforestry
Sedjo and Solomon (1988)	Global	2900 x 10 ⁹ tonnes/year	—	—
Adams et al. (1990) ^a	United States	640 x 10 ⁹ tonnes/yr	—	—
Barnon and Gifford (1990) ^a	Australia	7 x 10 ⁹ tonnes/yr	—	—
Moulton and Richards (1990) ^a	United States	633 x 10 ⁹ tonnes/yr	110 x 10 ⁹ tonnes/yr	—
Nordhaus (1991) ^a	Global	280 x 10 ⁹ tonnes/yr	—	—
Dixon, Schneider and Wigum (1991) ^a	Boreal	2 x 10 ⁹ tonnes	—	—
	Temperate	30 x 10 ⁹ tonnes	—	—
	Tropical	53 x 10 ⁹ tonnes	—	—
New York State (1991) ^a	New York State	0.8 x 10 ⁹ tonnes/yr	0.2 x 10 ⁹ tonnes/yr	—
Van Kooten et al. (1992) ^a	Canada	6 x 10 ⁹ tonnes/yr	13 x 10 ⁹ tonnes/yr	—
Houghton et al. (1993) ^a	Latin America	2.3 x 10 ⁹ tonnes	13.2 x 10 ⁹ tonnes	49.1 x 10 ⁹ tonnes
	Africa	13.6 x 10 ⁹ tonnes	0.4 x 10 ⁹ tonnes	52.6 x 10 ⁹ tonnes
	Asia	1.9 x 10 ⁹ tonnes	15.0 x 10 ⁹ tonnes	18.7 x 10 ⁹ tonnes
Richards et al. (1993) ^a	United States	150 x 10 ⁹ tonnes/yr	—	—
Dixon et al. (1993) ^a	Global	49 x 10 ⁹ tonnes	—	1100-2300 x 10 ⁹ tonnes/yr
Tscharn (1994) ^a	New Zealand	5 x 10 ⁹ tonnes/yr	1.5-2.3 x 10 ⁹ tonnes	—
Masera et al. (1994) ^a	Mexico	3.7 x 10 ⁹ tonnes	2.6 x 10 ⁹ tonnes	2.4 x 10 ⁹ tonnes
Ravindranath and Somashekhar (1994) ^a	India	8.5 x 10 ⁹ tonnes	0.2 x 10 ⁹ tonnes	1.1 x 10 ⁹ tonnes
Xu (1994)	China	—	—	—

(a) Adams et al. (1990) does not specify the period over which this carbon capture rate could be maintained.

(b) This carbon capture rate is maintained over 25 years.

(c) This carbon capture rate is maintained over 40 years.

(d) This is the average carbon capture rate over an assumed 40 year growing period with planting spread over 35 years, so that actual carbon capture is spread over 75 years.

(e) Dixon, Schneider and Wigum (1991) do not differentiate total potential yield on the basis of forestry practice, this is MGS for all practices averaged over a 50-year period.

(f) Rates are maintained over 60 years for plantation forests and 50 years for forest management.

(g) This is MGS. Period of time over which MGS is not specified.

(h) Calculations are based on 10 year period only. However, sequestration is likely to continue over longer period.

(i) Richards et al. (1993) report potential cumulative carbon yield of 49 x 10⁹ tonnes over a 160-year period. Of that 40 x 10⁹ tonnes occur in the first 100 years. Hence, there is a potential average carbon capture rate of 400 x 10⁹ tonnes per year for 100 years.

(j) This is MGS over 50 years.

(k) This carbon capture rate is maintained over 30 years.

(l) This is apparently total standing carbon at 50 years.

CHAPTER 10
INTEGRATED ASSESSMENT OF CLIMATE CHANGE:
AN OVERVIEW AND COMPARISON OF APPROACHES AND RESULTS

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SUMMARY

Assessment is integrated when it draws on a broader set of knowledge domains than are represented in the research product of a single discipline. Assessment is distinguished from disciplinary research by its purpose: to inform policy and decision, rather than to advance knowledge for its intrinsic value. Integrated assessment is identified by the breadth of knowledge sources on which it draws; it is to be distinguished from those (infrequent) instances in which a significant policy issue can be well informed by clear presentation of a body of knowledge held within a single discipline. Distinguishing integrated assessment from other assessment is important because integrated assessment poses distinct and more difficult challenges.

Integrated assessment can in principle serve three purposes. First, integrated assessment can help assess potential responses to climate change, either by using a benefit-cost formulation to compare costs of responses to the severity of the impacts they are intended to prevent, or by using a cost-effectiveness formulation to compare the relative effectiveness and cost of different responses to meet a specified target. Second, by providing a coherent, systematic framework to structure present knowledge, integrated assessment can bring two important benefits: it can promote a broad view of the climate issue that may facilitate more systematic searching for possible responses and avoid prematurely settling on one or a few proposed responses; and it can provide a consistent representation of current uncertainties, permitting identification and prioritization of those that are most important in practical terms -- those most important to reduce in order to understand what should be done.

Third, it can help to address the most fundamental policy question about global climate change, its importance relative to other matters of human concern.

A variety of methods to conduct integrated assessment are possible. Current projects on global climate have largely, but not exclusively, pursued integration through a formal integrating model, though the centrality and manner of use of the model vary among projects. Other integration methods that have been tried include special senior commissions or panels whose members span the required range of expertise, who integrate knowledge judgmentally through their deliberations; formal models of problem subcomponents, linked through external, judgmental combination of results rather than through a formal integrating model; and collaborative inter-disciplinary research teams whose continuing interactions develop collective skills at exchanging and sharing knowledge across their fields.

Integrated assessment models can be classified as being: (1) either more or less complex in representing the natural science processes associated with climate change, and (2) either explicitly incorporating uncertainty or not explicitly incorporating uncertainty. The models that are less complex and that do not explicitly incorporate uncertainty were the first integrated assessment models, and results produced by a number of models in this category have already been published in a number of places. Although highly aggregated in their representation of the natural science processes governing climate change and not explicitly incorporating uncertainty, they typically include the dynamics of capital stock adjustments inside and outside of the energy sector, and often consider multiple world regions; thus, they are simple in some respects, but not in others.

The models that are more complex and that do not explicitly incorporate uncertainty add significant detail to the natural science modules. This added detail makes it easier to incorporate various interactions and feedbacks among the various modules. For example, the fertilization effect of higher atmospheric concentrations of CO₂ in the atmosphere on the growth of vegetation, and feedback effect of this growth on CO₂ concentrations might be considered in models in this category, but not in the simpler models where the terrestrial biosphere is not explicitly represented.

The models that are less complex, but that do explicitly incorporate uncertainty generally imbed very simple aggregate integrated assessment models (often even simpler than the aggregated deterministic models) within a decision or risk assessment framework. This allows for extensive testing of the sensitivity of key model outputs to variations in model inputs and parameters. This is particularly important if there are significant non-linearities and asymmetries in the processes represented in the model. The inputs, parameters, decisions, and objectives to which results are most sensitive to plausible variations would merit further study. If meaningful objectives for policy and a comprehensive set of policy options can be identified, then an explicit value of information can be calculated for reducing all or part of the uncertainty associated with each uncertain input by some specific date.

The final type of integrated assessment model seeks to incorporate all significant complexities and uncertainties into the same analytical framework. This is a formidable task, but one that can be immensely valuable if completed successfully.

Although the year 2100 optimal control rates - percentage reductions in carbon emissions relative to baseline emissions - and carbon taxes (equivalent to the marginal cost of efficient carbon emission reductions) produced by the integrated assessment models vary widely, they are not all that disparate in the 1990s - a 8-20% optimal control rate and a \$5-\$15 optimal carbon tax. This reflects the time dynamics of climate change; the costs of control are related to decreases in the rate of emissions as soon as the controls are applied, while the benefits of control are related to temperature change which responds to changes in atmospheric concentrations of greenhouse gases with a long lag, with atmospheric concentrations responding only slowly to changes in emissions rates because of the large stock of greenhouse gases already in the atmosphere. Thus, the marginal costs of controlling greenhouse gases tend to be highly non-linear with respect to changes in the carbon emissions rate, while the marginal benefits tend to be delayed and much more linear. Even with a relatively low discount rate this implies an optimal control rate that is modest over the next decade.

The four biggest challenges facing integrated assessment modelers are: (1) developing a credible way to represent and value the impacts of climate change, (2) developing a credible way to handle low probability, but potentially catastrophic events, and (3) developing realistic representations of the dominant processes and policies in the developing countries, and (4) model integration and management.

INTRODUCTION

The historic Framework Convention on Climate Change (FCC), signed by 154 countries at the UN Conference on Environment and Development (UNCED) in Brazil in June 1992 (see Grubb et al, 1993), had as its central goal the stabilization of atmospheric greenhouse gas concentrations at a level that would prevent dangerous anthropogenic interference with the climate system. It also stated that this goal should be realized soon enough that ecosystems could adapt naturally to climate change, that food production would not be threatened, and that sustainable economic development could proceed (FCC, Article 2). The text does not specify, though, what the operational meaning of "dangerous anthropogenic interference" is, how its occurrence or the risk of its occurrence could be detected, or what measures, applied at what level of stringency would be justified in avoiding it. The other central concepts in the objective, natural adaptation of ecosystems, threats to food production, and sustainable economic development, are also not articulated precisely. Nor could they be.

Rendering the Convention's goal into operational specifics will require further deliberations, informed by the best available synthesis of the scientific, technical, economic, and socio-political knowledge that can help define and assess the risks of climate change, ecosystem responses, human adaptive response, and the feasibility, effectiveness, cost, and side effects of potential response measures. Synthesizing and communicating such knowledge in support of policy deliberations is the function of assessment.

Assessment¹ is integrated when it draws on a broader set of knowledge domains than are represented in the research product of a single discipline (Parson, 1994). Assessment is distinguished from disciplinary research by its purpose: to inform policy and decision, rather than to advance knowledge for its intrinsic value. Integrated assessment is identified by the breadth of knowledge sources on which it draws; it is to be distinguished from those (infrequent) instances in which a significant policy issue can be well informed by clear presentation of a body of knowledge held within a single discipline. Distinguishing integrated assessment from other assessment is important because integrated assessment poses distinct and more difficult challenges.

¹Here we depart from conventional IPCC terminology where assessment generally refers to reviews and evaluations of the scientific literature in various fields, and use the term integrated assessment model to refer to systems of equations that attempt to integrate information from and across disciplines to help in the process of developing policy responses.

The broader the set of knowledge domains that must be synthesized to inform a policy or decision, the greater the intellectual and managerial problems that must be overcome to do the assessment well and make it useful to its audience. How integrated any particular assessment must be depends on the issue or decision to be informed. Perhaps more than any other policy issue, global climate change requires integrated assessment. Making rational, informed social decisions on climate change potentially requires knowledge of the human activities that affect greenhouse gas emissions; the atmospheric, oceanic, and biological processes that link emissions to atmospheric concentrations; the climatic and radiative processes that link atmospheric concentrations to global and regional climate; the ecological, economic, and socio-political processes that link changed climate to valued impacts; and the processes by which such evaluations are made. Any progress in understanding, and responding to, an issue of such complexity will require the capacity to integrate, reconcile, organize, and communicate knowledge across domains - that is, to do integrated assessment. This need has been widely recognized, in calls to advance methods of integrated assessment, and in the large number of projects now underway. While there have been past examples of integrated assessments of major environmental issues (e.g., the American CIAP Project, Grobecker et al 1974, and the European acid rain studies integrated in the RAINS model, Alcamo et al 1990), the current level of integrated assessment activity on global climate change is unprecedented.

Purposes of Integrated Assessment

Integrated assessment can in principle serve three purposes. First, integrated assessment can help assess potential responses to climate change, either by using a benefit-cost formulation to compare costs of responses to the severity of the impacts they are intended to prevent, or by using a cost-effectiveness formulation to compare the relative effectiveness and cost of different responses to meet a specified target. Whichever of these formulations is employed, integrated assessment performs this function by making consistent, contingent, appropriately qualified predictions of the likely cost and effect of specified responses.

Second, by providing a coherent, systematic framework to structure present knowledge, integrated assessment can bring two important benefits: it can promote a broad view of the climate issue that may facilitate more systematic searching for possible responses and avoid prematurely settling on one or a few proposed responses; and it can provide a consistent representation of current uncertainties, permitting identification and prioritization of those that are most important in practical terms -- those most important to reduce in order to understand what should be done. Since the most important uncertainties from the perspective of policy relevance will not necessarily be the most important for

advancing basic understanding, this function of integrated assessment can be of the highest importance.

Third, it can help to address the most fundamental policy question about global climate change, its importance relative to other matters of human concern. Gaining insight into this question will require comparing the aggregate social effect of climate change, and potential responses to it, with the aggregate social effect of other changes and risks likely to arise over the same period of time.

In fulfilling these purposes, integrated assessment supplements, but does not replace, disciplinary research. A disciplinary research program in the natural or social sciences, even one including components representing every relevant discipline that could contribute to informing policy choice, will not normally emphasize synthesis of knowledge across domains and so cannot typically do the jobs of assessing consequences of potential responses, or prioritizing decision-relevant uncertainties and research needs. Current experience suggests that cross-disciplinary integration to fill these needs does not happen spontaneously, and can be both difficult and costly. But this does not mean that integrated assessment can replace disciplinary research, even for providing policy-relevant knowledge. While integrated assessment is needed to identify and prioritize policy-relevant gaps in knowledge, the gaps so identified can normally only be filled by disciplinary research, whether in the natural or social sciences.

Modes of Integration, and Assessment Purposes

Integrated assessments can be integrated over different dimensions and to different degrees. In contributing to general policy-relevant understanding, studies using many different dimensions and degrees of integration, from the broadest to the narrowest, may make important contributions. In informing the deliberations or decisions of a particular policy audience, though, the appropriate form and extent of integration is determined by the needs of the audience. When there is a specific audience or decision to inform, a useful assessment will seek to represent the kinds of policies and decisions they are concerned with, at a resolution that corresponds to their responsibilities and concerns, while taking appropriate opportunities to help broaden their understanding of the issue. An area of active current exploration is the development of global-scale climate assessments with "end-to-end" integration: integration that combines assessment of emissions and abatement measures with impacts and adaptation measures. Such projects, implicitly or explicitly, pursue a benefit-cost framing of the climate issue to inform decisions of optimal global emissions abatements and efficient means of achieving them. The implied audience of such assessments is a decision-maker with authority to balance the extent and form of

abatement measures, adaptive and compensatory measures, and possibly geoengineering. Assessments of this kind are likely to help inform general understanding of appropriate responses to the climate issue. Broad balancing of abatement and adaptation measures will be done, implicitly or explicitly, and it is clearly desirable that whatever knowledge is available to inform such broad trade-offs be presented to those involved in such choices. Such assessments, though, are not the only kind that can be useful, or necessarily the most appropriate for informing many specific policy decisions. Certain policy audiences may need assessments that are integrated either more broadly, or less broadly, than "climate end-to-end". Certain international deliberations and negotiations may need assessments that are integrated even more broadly. At this level, it may not be possible to address the climate issue without making judgments of its significance relative to other environmental issues, and other policy issues. To engage choices of this breadth, assessments may be required that facilitate comparing the potential impacts of climate change and other issues. End to end assessment of climate change may be a necessary component of such assessment, but not by itself sufficient. For questions of such breadth, the most useful assessments may be those that focus not on a single environmental issue but on basic policy choices and long-term technological trends in areas of human activity that affect a variety of environmental and other issues, such as agriculture or energy. On the other hand, most policy audiences are likely to need less broadly integrated assessments. This may be so even for assessments to inform international negotiations, if as often happens a pre-existing political commitment either to a simple heuristic principle like the Precautionary Principle or to a specific numerical policy target truncates the consideration of responses (Parson and Zeckhauser, 1994; Levy, 1993). In such cases the most useful assessment would adopt a cost-effectiveness approach, comparing emission types, sources, gases, and regions, to determine feasible, low-cost ways to meet specified abatement goals. Other audiences for integrated assessment may have responsibility for managing resources that suffer climate impacts, but little or no influence over global emissions. This would be the case for domestic officials of any small country or region. For such authorities the crucial dimension of integration will be across dimensions of impact -- sector, location, group, and time -- under an illustrative set of climate-change scenarios. Such assessment could inform their decisions about long-term climate-dependent investment, emergency response measures, zoning, and insurance and compensation schemes, that form the bulk of adaptation response. Recent empirical study suggests the most useful, and most used, assessments have tended to be conducted at relatively fine levels of spatial or sectoral aggregation, by or for those agents directly bearing potential impacts or responsible for implementing proposed responses, to inform specific decisions under their authority (Clark, 1994).

Integrated Modeling and Other Methods of Integration

A variety of methods to conduct integrated assessment are possible. Current projects on global climate have largely, but not exclusively, pursued integration through a formal integrating model, though the centrality and manner of use of the model vary among projects. Other integration methods that have been tried include special senior commissions or panels whose members span the required range of expertise, who integrate knowledge judgmentally through their deliberations; formal models of problem subcomponents, linked through external, judgmental combination of results rather than through a formal integrating model; and collaborative inter-disciplinary research teams whose continuing interactions develop collective skills at exchanging and sharing knowledge across their fields. Other integrating devices are not yet thoroughly developed but may hold substantial promise. These include simulations or policy exercises, devices for joint deliberation by researchers and policy-makers in a hypothetical policy setting, employing knowledge available from a variety of sources including existing literatures, formal models, and expert judgment (Brewer 1986; Parson 1995b). Doing integrated assessment by building an integrating model has several evident advantages. Constructing a model imposes common standards of coherent, precise communication on project participants, imposes common data definitions, and standards of consistency and scale on problem sub-domains, and can facilitate the incorporation of new knowledge in an assessment. Attendant disadvantages are that the modeling may force more precise representation than the underlying knowledge in particular domains allows, may imposing inappropriate restrictions, and may direct excessive project effort toward technical problems of model convergence, hence giving aggregate results that say as much about algorithmic artifacts as they do about component understanding. Integration through integrated modeling may be particularly weak in representing policies and decisions realistically, and in reflecting knowledge of relevant social, political, institutional, and negotiation processes.

The Current State of Integrated Assessment Activity

Most present projects in integrated assessment share an emphasis on constructing integrating models, a national to global scale, a rather coarse spatial and sectoral resolution, and weak representation of policies and political processes. Despite its importance, the field of integrated assessment is relatively immature and lacks a shared body of professional knowledge and standards of "best practice". Such knowledge requires more experience to develop; in its absence, it would be ill-advised to pursue a single, authoritative vision of integrated assessment. On many intellectual and managerial dimensions, there are many plausible ways of meeting the challenges of integrate assessment and no evident single right way. Consequently, there is much to be gained from the parallel pursuit of diverse approaches, including both more and less modeled approaches. The balance of this chapter discusses the structure, modeling approaches, and major weaknesses

of present integrated assessment modeling projects, and reviews preliminary results.

STRUCTURAL ORGANIZATION OF INTEGRATED ASSESSMENT MODELS

Figure 1 shows a typical conceptual block diagram for an "end-to-end" climate change assessment model. This diagram implies the possibility of substantial interactions and feedbacks among the processes represented within each module, but that only a limited set of information is passed sequentially from one module to the next. Feedbacks can be carried through in subsequent iterations through the whole system, but equilibrium is driven by the values for the information that passes between modules. Thus, the way the diagram is drawn has operational as well as conceptual significance. One definition of an integrated assessment model is a model that projects future economic activity and the links between it and greenhouse gas emissions, between emissions and atmospheric concentrations, between atmospheric concentrations and climate change, between climate change and the physical impacts on economies and ecosystems that result, between those physical impacts and their economic valuation. Following Parson (1994), however, for our purposes here we define any climate change focused model that links together information and analysis from disciplines that have not traditionally been combined as an "integrated assessment" model. Operationally, this definition covers any model that encompasses two or more of the blocks shown in Figure 1. This expanded definition allows us to include consideration of some of the more innovative work that has been done on the linkages and feedbacks among the various components of the climate change cause and effect analysis system.

Some research teams dismiss the linear structure shown in Figure 1 as being overly simplistic; in their view interactions and feedbacks between the individual modules shown in Figure 1 exert great influence on the results that emerge from the overall assessment process and may be of direct importance to both analysts and policy makers. At a minimum, these researchers would prefer a conceptual representation like that shown in Figure 2. Here we allow for linkages and feedbacks among modules in both directions. In addition, consideration of the requisite interactions and feedbacks may require more process disaggregation within each module than when information is passed forward one module at a time.

In addition to the degree of complexity (including disaggregation) considered within and between modules, a third major design consideration in an integrated assessment model is the treatment of the considerable uncertainties about virtually every major relationship in the climate change assessment system. Future population and economic growth are uncertain, future greenhouse gas emissions given population and economic activity are uncertain, future greenhouse gas concentrations given emissions are uncertain, future climate given atmospheric concentrations of greenhouse gases

are uncertain, future physical impacts of climate change are uncertain, and the future valuation of the physical impacts attributable to climate change are uncertain.

Uncertainty can be handled in a number of ways in integrated assessment modeling. Extensive sensitivity analysis can be performed on key model inputs and parameters, or explicit subjective probabilities can be assessed for these inputs and parameters and input into a formal risk or decision analysis framework. If a formal risk or decision analysis approach is pursued, it is generally possible to calculate the value of information with respect to wholly or partially resolving the uncertainty associated with each key input or parameter. The usefulness of this calculation depends on the accuracy of the risk assessment model, when the uncertainty will be reduced and by how much, and the accuracy of the projection of how much the information will cost. If these tasks can be completed credibly, the results can be extremely useful in setting research priorities.

Overview of Existing Integrated Assessment Models

Prior to 1992, only two integrated assessment of climate change models had appeared in the literature (Nordhaus, 1989, 1991); Rotmans (1990). Since 1992 a host of new models have emerged. Table 1 lists 16 integrated assessment models that are in active use or are under active development; in addition, a number of additional modeling efforts are underway, so the number of existing integrated assessment models might be expected to double or more in the next few years. Even within the group of models listed in Table 1, though, there is a wide variation in level of model maturity. Some models are fully operational and documented, others are up and running, but not yet fully operational or documented, still others are in module development and testing phases, with some modules not yet fully specified. It is anticipated that all the models shown here will be fully operational, albeit in preliminary versions in some cases, by the end of 1995. The modeling in this area is so active that even models that are fully operational are continually being refined and updated substantially every 3-6 months. Table 2 summarizes the current development status and most recent documentation available for the 16 models listed in Table 1.

The models included in Table 1 can be compared structurally according to the amount of emphasis they place on each of the six blocks shown in Figure 1. The results of this process are shown in Table 3. Note that some of the models do not explicitly consider the relationships included in each of the blocks. In particular, several of the key models omit direct modeling of economic activity and rely on exogenous greenhouse gas emission trajectories. In addition, more than half of the existing models consider both the physical impacts and their valuation through aggregate damage functions that relate economic damages directly to mean global temperature change.

Although Table 3 addresses the degree of complexity of the models in the various modules, it does not consider how the models deal with intermodule interactions, or with uncertainty. These are covered in Tables 4 and 5, respectively. Table 4 shows that very few of the operational models include interactions and feedbacks between modules other than a straight pass through of information from one module to the next. The Image-2 and AIM models are notable exceptions.

Several key model features, including how uncertainty is handled, are shown in Table 5. Only 7 of the 16 models reviewed explicitly deal with uncertainty, and only 3 of those (ICAM-2, PAGE, and PEF) allow the user to execute full value of information calculations. Another issue regarding uncertainty is that some of the models work with a deterministic model, superimposing a probabilistic structure on the exogenous inputs and parameters to determine optimal public policy decisions under uncertainty; this type of formulation does not, however, directly consider the impact of uncertainty on the decision making of individual producers and consumers in the economic system.

Some additional information regarding the key inputs to - and outputs from - the models is provided in Table 5. The key inputs and outputs follow from the coverage and degree of complexity of the modules included in the models.

State of the Art in Integrated Assessment Modeling

It is difficult to characterize the state of the art in integrated assessment modeling of climate change simply - a great deal of model development is underway at present, involving a large number of research teams, with members drawn from a myriad of relevant disciplines, focusing on different dimensions of the problem, using different types of methodologies. Nonetheless, a focus on the tradeoffs between natural systems model complexity, economic model complexity, and effort devoted to the explicit incorporation of uncertainty can help us understand the model development that has been completed, that is occurring today, and that is planned or anticipated for the future.

Integrated assessment models can be classified as being: (1) either more or less complex in representing the natural science processes associated with climate change, (2) either more or less complex in representing the economic processes associated with climate change, and (3) either explicitly incorporating uncertainty or not explicitly incorporating uncertainty. The models that are less complex and that do not explicitly incorporate uncertainty were the first integrated assessment models, and results produced by many of the models in this category have already been published. Although highly aggregated in their representation of the natural science processes governing climate change and not explicitly incorporating uncertainty, they typically include the dynamics of capital stock adjustments inside and outside of the energy sector, and often consider multiple world regions; thus, they are simple in some respects, but not in others. It is also possible that further disaggregation and more explicit treatment of uncertainty would not

lead to different insights than produced by these simpler deterministic models.

The models that are more complex and that do not explicitly incorporate uncertainty add significant detail to either the natural science or economics modules. This added detail makes it easier to incorporate various interactions and feedbacks among the various modules. For example, the fertilization effect of higher atmospheric concentrations of CO₂ in the atmosphere on the growth of vegetation, and feedback effect of this growth on CO₂ concentrations might be considered in models in this category, but not in the simpler models where the terrestrial biosphere is not explicitly represented. On the other hand, a model with a complex economics module might consider the impact of climate change on agricultural output, or the impact of a carbon tax on capital investment, a key driver of the growth in economic output. Figure 3 shows the relative emphasis of the models on economic system versus natural system complexity.

The models that are less complex, but that do explicitly incorporate uncertainty generally imbed very simple aggregate integrated assessment models (often even simpler than the aggregated deterministic models) within a decision or risk assessment framework. This allows for extensive testing of the sensitivity of key model outputs to variations in model inputs and parameters. This is particularly important if there are significant non-linearities and asymmetries in the processes represented in the model. The inputs, parameters, decisions, and objectives to which results are most sensitive to plausible variations would merit further study. If meaningful objectives for policy and a comprehensive set of policy options can be identified, then an explicit value of information can be calculated for reducing all or part of the uncertainty associated with each uncertain input by some specific date. Figures 4 and 5 put the uncertainty dimension together with the natural system and economic system model complexity dimensions, respectively.

Differences in Treatment of Uncertainty

Figure 4 places the models reviewed here in a two dimensional natural systems model complexity/uncertainty space. The models in the upper left hand quadrant generally include simple aggregate representations of the three natural systems modules included in Figure 1; those in the upper right hand quadrant add significant detail in one or more sectors; those in the lower left hand quadrant generally imbed simplified deterministic representations of each module in a decision or risk assessment framework - here uncertainties are explicitly incorporated in the analysis via the use of subjective probabilities on key inputs and model parameters; and those in the bottom right hand quadrant attempt to incorporate both uncertainty and complexity in the analysis. Some general comments can be made about the models in each category.

The models in the upper left hand quadrant of Figure 4 were the first integrated assessment models, and results produced by them have already been published in a number of places. Although

neither complex in their representation of the natural science processes governing climate change and not explicitly incorporating uncertainty, they typically include the dynamics of capital stock adjustments inside and outside of the energy sector, and often consider multiple world regions; thus, they are simple in some respects, but not in others. It is also possible that further disaggregation and more explicit treatment of uncertainty would not lead to different insights than produced by these simpler deterministic models.

The models in the upper right hand quadrant of Figure 4 add significant detail to the natural science modules of Figure 1. This added detail makes it easier for to incorporate various interactions and feedbacks among the various modules shown in Figure 1. For example, the fertilization effect of higher atmospheric concentrations of CO₂ in the atmosphere on plant growth, and feedback effect of more plant growth on CO₂ concentrations might be considered in models in this category, but not in the simpler models where the terrestrial biosphere is not explicitly represented.

The models in the lower left hand quadrant of Figure 4 generally imbed very simple deterministic integrated assessment models (often even simpler than those in the upper left hand quadrant) within a decision or risk assessment framework. This allows for extensive testing of the sensitivity of key model outputs to variations in model inputs and parameters. This is particularly important if there are significant non-linearities and asymmetries in the processes represented in the models. The inputs and parameters to which results are most sensitive to plausible variations would merit further study. If a meaningful objective for policy and a comprehensive set of policy options can be identified, then an explicit value of information can be calculated for reducing all or part of the uncertainty associated with each uncertain input by some specific date.

The modeling approaches in the lower right hand quadrant of Figure 4 are the most ambitious - they seek to incorporate all significant complexities and uncertainties into the same analytical framework. This is a formidable task, but one that can be immensely valuable if completed successfully. Successful completion of this enterprise will require model integration and management that has rarely been achieved in the past.

FIRST RESULTS FROM INTEGRATED ASSESSMENT MODELS

It has only been since 1992 that most of the integrated assessment of the climate change models have been constructed. By the end of 1994, however, results from a number of these models had already been published. This section gives an overview of these results, highlighting the insights that seem most relevant to the current debate on appropriate global change policies. The variety of different approaches that have been employed to study the climate change issue make the comparison and reconciliation difficult.

In what follows, we group the available model results (described previously) into two main categories: (1) results from cost-benefit type models, and (2) results from systems models that include many linkages and interactions between the several key elements of the climate/biosphere system, but do not directly produce cost/benefit results.

There are also large differences in the outputs that individual modelers report from their integrated analyses, and the time periods for which those outputs are reported. Some of the more common outputs from the cost-benefit type models are projections of the cost of controlling greenhouse gas emissions, the damages resulting from climate change, the "control rate," stated in terms of the percentage reduction in greenhouse gas emissions in each year relative to level of emissions projected to occur in the absence of new policy initiatives, and the carbon tax required in each year to limit greenhouse emissions to the levels specified in the scenario under consideration. Since the initial control rate and initial carbon tax results have emerged as de facto standards in the literature owing to their critical importance to the policy debate, much of our discussion here revolves around results for those two metrics.

Given the large uncertainties inherent in the various elements of the climate system, it is not surprising that analysts have pursued a number of alternative approaches to incorporating those uncertainties into their analyses. The discussion here deals with results obtained from these approaches in the following order:

(1) results from deterministic analyses, (2) sensitivity analyses over key model inputs/parameters, (3) analyses where all model inputs and parameters are treated stochastically, and (4) uncertainty analyses that focus on the implications of a small number of uncertainties that seem particularly relevant to the policy issues being addressed. We end our discussion of integrated assessment models with a number of modeling challenges that have been identified as high priority areas for future improvements in integrated assessment modeling.

Results from Deterministic Analyses

In this section we consider results from integrated assessment models run with all inputs and parameters set at that median or best guess values. Notwithstanding the immense uncertainties inherent in the climate change issue, a number of analysts have suggested that the results from the deterministic analyses provide a useful benchmark for near-term decision making, if not an adequate approximation of the results obtained from more complex approaches that explicitly include consideration of the key uncertainties.

There are a growing number of published studies that attempt to balance the deterministic costs and benefits of controlling greenhouse gas emissions. As of the end of 1994 these included: Nordhaus (1989, 1991, 1994) Cline (1992); Manne and Richels (1993); and Peck and Teisberg (1992, 1993, 1994).

Table 6 shows the key results from the models that balance the costs and benefits of greenhouse gas emissions reductions. For example, the "optimal run" results from the DICE model (Nordhaus, 1994) show a 1995 control rate - percentage reduction in emissions relative to baseline greenhouse gas emissions - of 8.8 percent with an associated carbon tax² of \$5.29 per ton of carbon, and about a 15 percent control rate by 2100 with an associated carbon tax of about \$20 per ton of carbon. This program leads to an increase in the discounted present value of consumption of \$271 Billion 1989 dollars or about .04% of discounted baseline consumption. Similar results are obtained from the CETA, MERGE models, and the Kolstad (1993) studies .

A study by Hammit, Lempert, and Schlesinger (1992) traces out alternative control strategies to attain certain temperature constraints; while not determining an optimal path, this study shows that a "moderate control strategy" is less costly than an aggressive approach if either the temperature-concentrations sensitivity (T_{2xCO_2}) is low or if the allowable temperature change is above 3° C.

In The Economics of Global Warming, Cline (1992) analyzes the time profile of abatement and damage costs under a policy of limiting carbon emissions to 4 Giga-tons annually and similarly reducing other greenhouse gas emissions. The abatement cost curve is low at first, then peaks at about 3.5% of gross world product, and thereafter declines to a plateau of about 2.5% as a consequence of widening technological alternatives.

The cost-benefit decision for greenhouse policy involves a tradeoff between substantial abatement costs early in the horizon, in return for avoidance of potentially large damages later in the horizon. The discounting of future costs and benefits relative to current ones is critical in such a tradeoff. On the grounds that policy makers should be risk averse, Cline also weights a representative high-damage case three times as heavily a low-damage case. Discounting at a zero rate of time preference, he finds that the overall benefit-cost ratio for aggressive action limiting carbon emissions to 4 Giga-tons is a favorable 1.3. Thus, the Cline deterministic case results in a much more aggressive optimal control policy than most of the other studies. Much of the difference in results stem from Cline's assumption of risk aversion on the part of national and international policy makers and his use of a zero rate of pure time preference; the other studies generally employing a pure rate of time preference of about 3 percent and no risk aversion by policy makers. In fact, Cline has shown the optimal control rate in 2100 in the DICE model would be 50% if a

² Although carbon taxes are used to reduce carbon emissions in the model results discussed here, the values given can be interpreted as the marginal cost of efficiently reducing carbon emissions by the desired amount. Efficiency in this context means simply that lower cost emission reduction measures are always implemented before higher cost ones.

zero rate of pure time preference is employed as opposed to the 15% reported above for the 3 percent rate of time preference in the DICE baseline. Moreover, as discussed below, Nordhaus (1994) reports that the pure rate of time preference is the input to which DICE results are most sensitive. The subject of the appropriate rate of pure time preference is a major focus of chapter 4 of this report.

Although the year 2100 optimal control rates and carbon taxes shown in Table 6 vary widely, they are not all that disparate in the 1990s. This reflects the time dynamics of climate change; the costs of control are related to decreases in the rate of emissions as soon as the controls are applied, while the benefits of control are related to temperature change which responds to changes in atmospheric concentrations of greenhouse gases with a long lag, with atmospheric concentrations responding only slowly to changes in emissions rates because of the large stock of greenhouse gases already in the atmosphere. Thus, the marginal costs of controlling greenhouse gases tend to be highly non-linear with respect to the control rate while the marginal benefits tend to be delayed and much more linear. Even with a relatively low discount rate this implies an optimal control rate that is modest over the next decade.

Sensitivity Analyses

Given the sizable uncertainties inherent in virtually every major input and model parameter employed in any analysis of global climate change, it is important to assess the implications of the key uncertainties on model results. A common first step in this effort is sensitivity analysis which involves looking at how key model outputs respond to changes in input or parameter values over plausible ranges.

Table 7 shows control rate and carbon tax sensitivities for several models. For example, for the CETA model the initial control rate moves from 0% (2%) below baseline emissions in the base case in 1990-2000 (2090-2100) to 11% (82%) in 1990-2000 (2090-2100) when the sensitivity of global mean surface temperature to a doubling in the atmospheric concentration of CO₂ is increased from 1° C to 5° C. In addition, the initial carbon tax rate moves from \$2/tonne (\$9/tonne) below baseline emissions in the base case in 1990-2000 (2090-2100) to \$29/tonne (\$198/tonne) in 1990-2000 (2090-2100) over the same range of global mean surface temperature sensitivities. Similarly, in the DICE model the initial control rate moves from 9% (14%) below baseline emissions in the base case in 1995 (2095) to 19% (28%) in 1995 (2095) when the pure rate of time preference is changed from its base value of 3% to 1%.

Another type of sensitivity analysis involves focusing in on a small number of more carefully designed scenarios that are expected to lead to fundamental changes in key model outputs. A recent analysis of carbon-free advanced energy technologies was performed by Edmonds, et al. (1994b). In this study the implications of advanced energy technologies (including very low cost biomass

fuels) on greenhouse gas emissions and temperature change were investigated. Obviously, the introduction of very low cost non-carbon fuels leads to lower carbon emissions and less temperature rise in the long run (post 2050). A surprising result of this analysis, though, is an increase in temperature prior to 2050 as the replacement of carbon-based fuels with carbon-free fuels leads to less sulfur emissions and, therefore, less climate-cooling sulfur aerosols in the atmosphere.

Baseline Projections and Uncertainty

Manne and Richels (1993) have argued that any deterministic projection of baseline carbon emissions may be upwardly biased because individual energy consumers should already be reducing their consumption of carbon-based fuels because of the possibility of constraints on carbon emissions in the future. For example, Figure 6 shows the implicit carbon tax they compute in the year 2000 as a function of the probability that a constraint limiting U.S. carbon emissions to year 1990 levels. For example, if consumers feel there is a 50-50 chance that carbon emissions will be constrained in 2010, they will reduce carbon emissions in 2000 as if a carbon tax of \$17.50 were already in place.

Results from Stochastic Simulation Models

Stochastic simulation models generalize the sensitivity analysis idea by including probability distributions on all major inputs and model parameters. Each input distribution is sampled and the value chosen is used in the subsequent calculations of the model, and the process is continued until probability distributions are derived for each output variable of the model (this process is sometimes referred to as Monte Carlo simulation. The PAGE (Hope, et al., 1993) and ICAM-2 models (Dowlatabadi, 1994) are prominent examples of integrated assessment models that take this approach.

An analysis with PAGE of no control and stringent control options results in a recommendation for adaptation rather than mitigation as a first best policy initiative. Conditions under which both adaptation and aggressive mitigation options ought to be pursued are also identified.

It is also possible to do a more comprehensive type of sensitivity analysis with the stochastic simulation approach by computing the partial rank correlation coefficient of output measures of interest with respect to variations in each input. For example, Hope, et al. (1993) report that "cheaper preventative costs of CO₂" and "no action CO₂ emissions (i.e., baseline emissions) of CO₂ have the greatest effect on total cost uncertainty, and "global temperature sensitivity to doubling of CO₂ and "half life of global warming response to change in forcing" have the greatest effect on total impact uncertainty.

Uncertainty, Decision Analysis, and the Value of Information

Climate change may have severe impacts on individuals and societies. On the other hand, the impacts may not be very severe at all. Individuals and societies often attempt to reduce the impact of low probability - high consequence events through various

means. Nordhaus (1994) groups activities designed to mitigate the effects of uncertainty on economic welfare into three categories: (1) traditional insurance, (2) consumption smoothing, and (3) precautionary investments.

Traditional insurance involves pooling together large groups of people each of whom is subject to a small probability of a large loss (like having their house burn down). Thus, each individual pays the a priori expected value of a loss plus a small transaction fee to get compensated for the catastrophe should it occur. The pooling necessary to implement this approach requires that the occurrence of the catastrophe among the members of the population be more or less independent; this is not the case with climate change for which the impacts are likely to be pervasive throughout the globe. On the other hand, since some individuals (e.g., people who live on coastlines) will be impacted more severely than others, traditional insurance may help allocate the costs of the total damages resulting from climate change in a way that improves welfare. Even this capability to re-allocate the costs of climate change through traditional insurance may also be somewhat limited, though, because those who are most vulnerable may be known in advance or can be easily identified when the impacts of climate change start to be felt.

Consumption smoothing over time amounts to the social equivalent of "saving up for a rainy day." If there are significant thresholds in the impacts of climate change, it is possible that societies will incur large adjustment or mitigation costs. Thus, welfare may be improving by saving capital now to consume when the threshold impacts occur.

The third type of policy that can be used to mitigate the uncertainty associated with climate change are precautionary investments in mitigation, adaptation, or information. Such actions enable societies to hedge against the possibility of bad climate outcomes before the major uncertainties determining the severity of the climate change problem have been resolved.

It appears that all three types of policies for coping with climate change uncertainty are valuable. In terms of overall payoff, however, the traditional insurance approach is the most tactical and the precautionary societal investment the most strategic. Thus, a number of precautionary investment analysis have started to appear in the literature. One innovative example is the stochastic optimization model driven analysis included in chapter 4 of Buying Greenhouse Insurance: The Economic Costs of CO₂ Emission Limits (Manne and Richels, 1992). This analysis only deals explicitly with the cost of CO₂ emission reductions, but it is assumed that U.S. decision makers must act initially without knowing what ultimate limit on carbon emissions will emerge from further scientific research and international negotiation. However, it is assumed that by 2010 it will be revealed whether: (1) no limits will be necessary, (2) a 20% emissions reduction will be required, or (3) a 50% reduction will be required. Each of these future policy outcomes is assigned a probability of

occurrence. This formulation makes the idea of hedging against a range of future outcomes explicit with the initial control rate and carbon tax for the optimal hedging strategy (the one that maximizes the expected future utility of consumption) lying between the maximum control and no-control strategies, with the exact level depending on the probabilities assigned to the different control outcomes. Put differently, there is a risk premium associated with emitting carbon owing to the fact that carbon emissions may be constrained (and possibly severely constrained) in the future.

In Managing the Global Commons: The Economics of Climate Change, Nordhaus (1994) performs a decision analysis with his dynamic global cost-benefit model (DICE) using an innovation 5 state of the world representation (derived from an extensive stochastic simulation analysis with the model) of the relevant uncertainties associated with climate change. He concludes that "Roughly speaking, the optimal carbon tax doubles when uncertainty is taken into account, and the optimal control rate increases by slightly less than half. The increased stringency of controls results from the interaction of different uncertain variables, whereby extreme events may cause significant economic costs (Nordhaus; 1994, p. 188)."

STRENGTHS AND LIMITATIONS OF INTEGRATED ASSESSMENT MODELS AND DIRECTIONS FOR FUTURE RESEARCH

The four biggest challenges facing integrated assessment modelers are: (1) developing a credible way to represent and value the impacts of climate change, (2) developing a credible way to handle low probability, but potentially catastrophic events, and (3) developing realistic representations of the dominant processes and policies in the developing countries, and (4) model integration and management.

Representation and Valuation of Impacts of Climate Change

Existing general circulation models produce mean steady-state global temperature projections that are very uncertain. The process of projecting transient regionalized changes in the key climate variables - e.g., temperature, precipitation, etc., that lead to impacts on economies and ecosystems in a way that is consistent with the operation of the global circulation models is in its infancy, making them subject to considerable additional uncertainties. The climate information required to most effectively project the impacts has in many cases not yet been determined, the most appropriate measures of climate impacts have not yet been determined, and ecosystems may not currently be in equilibrium. Finally, it may be necessary for this information to be input to valuation methods that are still under development and not tightly linked to the natural systems impacts in order to provide policy makers with the information they need to decide what to do.

Consideration of Low-Probability High-Consequence Events

The first results from integrated assessment models which considered only the expected costs and benefits of controlling greenhouse gases, have generally concluded that only a modest current level of control is warranted. However, it may not be expected conditions, but relatively low probability catastrophic events, that are irreversible or from which it would be very difficult to recover, that should be our main concern. Unfortunately, lack of data, understanding of the relevant processes, and analytical intractability has prevented such events from receiving adequate attention in the integrated assessments that have been performed to date. The implications of these low-probability high-consequence events on current decisions have just started to be investigated through the use of integrated assessment models (c.f., Nordhaus, 1994; Peck and Teisberg, 1994).

Critical Issues in Developing Countries

In general, the processes and policy options relevant to climate change are easier to assess in the twenty four industrialized countries of the OECD. This stems from the fact that these countries have been studied more intensively and that their populations and economies are growing relatively slowly. The data and understanding of critical processes and issues in the hundred and forty odd non-OECD countries is more limited. Many of these countries are in a state of rapid development or dynamic change, making projections of key economic drivers and social organizations over even short periods of time extremely difficult. Moreover, the contribution of these countries to climate change, and their responses to it are likely to be driven by other more pressing concerns than climate change. Three of the most critical such issues in the developing countries are land use, land tenure and population.

The way land is used is a key determinant of the net emissions and accumulation of greenhouse gases in the atmosphere, and of the impacts of climate change. However, land use and land tenure decisions in the developing countries will be driven by development goals and local pollution concerns rather than climate change concerns over at least the next several decades. Therefore, it is important to track trends in land use and land tenure in order to project the contribution of the developing countries to global climate change and how they will be impacted by any changes that might occur. Only a few of the operational integrated assessment models (e.g., Alcamo, et al., 1994; Morita, et al., 1993) track land use at all, and even those models are limited by lack of good data regarding current land use patterns in the developing countries, as well as a lack of understanding about who controls land use decisions at present, who is likely to control it in the future, and what criteria will be used in allocating land to alternative uses.

Another fundamental uncertainty that complicates assessments of the magnitude of the global climate change problem, and the effectiveness of policy responses to it is future population growth, especially in the developing countries. In general, more

population means more economic activity, and more greenhouse gas emissions. Again, though, trends and policies regarding future population growth will depend on phenomena (the spread of diseases, the level of income, the cultural norms), and policies (e.g., regarding education, health care, and birth control, etc.) than explicit consideration of the implications of population on climate change in the future. Virtually all of the existing integrated assessment models (the TARGETS models, Rotmans, et al., 1994, may soon be the first exception) take future population growth as given. Moreover, the projections used generally all come from one or two international agencies that use very simple projection methodologies.

The extent to which a better understanding and modeling of land use, land tenure and population growth in the developing countries will alter the insights regarding the climate change problem and potential policy responses to it produced by the current set of aggregate integrated assessment models is an open question. There is no doubt though that adding detail in these areas would improve the credibility of the models, especially in the developing countries.

Model Integration and Management

The complexity and multi-disciplinary nature of the climate change issue creates another challenge for integrated assessment modelers - linking a vast amount of data, analysis, and computer code developed by different researchers together into a unified whole. It is particularly important to maintain consistency between the assumptions made in different parts of the analysis and the integrity of the information passed from one module to another. For example, some of the early integrated assessments made very optimistic assumptions about technical change in some parts of the analysis, but not in others.

The State of the Art in Integrated Assessment Modeling

A number of approaches to integrated assessment of climate change are being pursued. Each of these approaches has strengths and weaknesses relative to the others. Moreover, each modeling team has chosen to focus on different aspects of the climate change issue. At this point in time, the significant complexities and uncertainties associated with the operation of the climate system, and how it impacts and - is impacted by - human activities, make it impossible to know exactly what to focus on and what methodology to employ. Thus, there is an advantage to the use of multiple research teams pursuing a plethora of alternative approaches. The approaches may provide complementary insights into the causes and effects of climate change, or provide identical re-enforcing results that increase our confidence level about the results from any one approach.

There is also a natural complimentary between the different types of analyses in that the more aggregate models (particularly if imbedded in a probabilistic framework) can be used to focus the development of the more complex models, and the more complex models can, in turn, be used as one source of parameter values for the

1 more aggregated models, and to test the effects of the aggregation
2 employed in them on the results of interest. Moreover, the simple
3 models can be used to cross check results from the more complex
4 models for consistency (i.e., they can be used as benchmarks), and
5 to help communicate results from them to the policy development
6 community and to the public. Finally, as each research team
7 continually modifies its work plan, and builds on the work of the
8 others, all the approaches may tend to look similar. Even if this
9 were to be the case at some point in the future, it is not clear
10 which approach pursued today would lead most efficiently to that
11 ultimate model. This once again suggests the efficacy of pursuing
12 a multitude of alternative analytic approaches to the study of
13 climate change, and potential responses to it.

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Table 1
INTEGRATED ASSESSMENT MODELS

AIM (Asian-Pacific Integrated Model)	Tsuneyuki Morita (NIES, Japan) Yuzuri Matsuoka (Kyoto University) Mikiko Kainuma (NIES, Japan)
CETA (Carbon Emissions Trajectory Assessment)	Stephen Peck (EPRI) Thomas Teisberg (Teisberg Assoc.)
CSERGE (Center for Social and Economic Research into the Global Environment)	David Maddison (University London) Sam Fankhauser (University London)
DICE (Dynamic Integrated Climate Economy)	William Nordhaus (Yale University)
GCAM (Global Change Assessment Model)	Joe Edmonds (Pacific Northwest Lab) Hugh Pitcher (PNL) Norm Rosenberg (PNL) Tom Wigley (UCAR)
ICAM-2 (Integrated Climate Assessment Model)	Hadi Dowlatabadi (Carnegie Mellon) Granger Morgan (Carnegie Mellon)
IMAGE 2.0 (Integrated Model to Assess the Greenhouse Effect)	Joseph Alcamo (RIVM, Netherlands) Eric Krellenman (RIVM, Netherlands) Maarten Krol (RIVM, Netherlands) Rik Leemans (RIVM, Netherlands) Ge Zuidema (RIVM, Netherlands)
ISM (Integrated Science Model for assessment of climate change)	Atul Jain (Lawrence Livermore Lab.) Haroon S. Kheshgi (Exxon) Don Muebles (Lawrence Livermore)
MAGICC (Model for the Assessment of Greenhouse gas Induced Climate Change)	Tom Wigley (UCAR) Mike Hulme (Univ. East Anglia, UK) Sarah Raper (Univ. East Anglia, UK)
MERGE (Model for Evaluating Regional and Global Effects of GHG Reductions Policies)	Alan Manne (Stanford) Robert Mendelsohn (Yale) Richard Richels (EPRI)
MiniCAM (Mini Climate Assessment Model)	Joe Edmonds (Pacific Northwest Lab) Hugh Pitcher (PNL) Richard Richels (EPRI) Tom Wigley (UCAR)
MIT	Henry Jacoby (MIT) Ron Prinn (MIT) John Reilly (USDA/MIT)
NEW EARTH 21	Yasumasa Fujii (Yokohama Univ.) Yoichi Kaya (University Tokyo) Kenji Yamaji (CRIEPI)
PAGE (Policy Analysis of the Greenhouse Effect)	Chris Hope (Cambridge University) John Anderson (Env. Res. Management) Paul Werman (Env. Res. Management)
PEF (Policy Evaluation Framework)	Dave Cohan (DFI) Joel Scheraga (EPA) Susan Herrod (EPA) Rob Stafford (DFI)
TARGETS (Tool to Assess Regional and Global Environmental and Health Targets for Sustainability)	J. Rotmans (RIVM) M.B.A. van Asselt (RIVM) A.J. de Bruin (RIVM) M.G.J. den Elzen (RIVM) J. de Greef (RIVM) H. Hilderink (RIVM) A.Y. Hoekstra (RIVM) H.W. Koster (RIVM) W.J.M. Martens (RIVM) L.W. Niessen (RIVM) H.J.M. de Vries (RIVM)

Table 2
DEVELOPMENT STATUS OF INTEGRATED ASSESSMENT MODELS

Model	Status	Reference
AIM	Preliminary Version Operational	Morita, et al. (1994)
CETA	Operational, With Regional and Uncertainty Variants Under Development	Peck and Teisberg (1992)
CSERGE	Preliminary Version Operational	Maddison (1994)
DICE	Operational, With Regional and Uncertainty Variants Under Development	Nordhaus (1994)
GCAM	Various Stages of Module Testing	Edmonds, et al. (1994a)
ICAM-2	ICAM-1 Operational, ICAM-2 in Advanced Module Testing	Dowlatabadi and Morgan (1993)
IMAGE 2.0	Operational	Alcamo (1994)
ISM	Operational	Jain, et al. (1994)
MAGICC	Operational With Demonstration Prototype Links to Impacts Modules	Wigley, et al. (1993)
MERGE	Operational, With Uncertainty Variant Under Development	Manne, et al. (1993)
MiniCAM	Operational	Edmonds, et al. (1994b)
MIT	Various Stages of Module Testing	MIT (1994)
NEW EARTH 21	Simple Damage Function Being Added to Operational Carbon Emissions Model	Fujii, et al. (1993)
PAGE	Operational	Commission of the European Communities (1992)
PEF	Prototype Operational, Enhanced Version Under Development	Cohan, et al. (1994)
TARGETS	Prototype Operational; Formal Release Fall 1994	Rotmans, et al. (1994)

Table 3
EMPHASIS ON COMPONENTS IN INTEGRATED ASSESSMENT MODELS

Model	Economy	Emissions	Atmospheric Chemistry	Climate	Physical Impacts	Economic Impacts
AIM	Simple	Moderately Complex	Moderately Complex	Very Complex	Very complex	Not Included
CETA	Moderately Complex	Moderately Complex	Simple	Simple	Simple Damage Function	
CSERGE	Simple	Not Explicitly Represented	Simple	Simple	Simple Damage Function	
DICE	Moderately Complex	Simple	Simple	Simple	Simple Damage Function	
GCAM	Very Complex	Moderately Complex	Moderately Complex	Moderately Complex	Moderately Complex	Moderately Complex
ICAM-2	Simple	Moderately Complex	Moderately Complex	Moderately Complex	Very Complex	Moderately Complex
IMAGE-2	Not Included	Moderately Complex	Very Complex	Very Complex	Very Complex	Not Included
ISM	Not Included	Not Included	Very Complex	Very Complex	Not Included	Not Included
MAGICC	Not Included	Not Included	Very Complex	Very Complex	Complex Climate Interface	Not Included
MERGE	Moderately Complex	Moderately Complex	Simple	Simple	Simple Market and Non-Market Damage Functions	
MiniCAM	Moderately Complex	Moderately Complex	Moderately Complex	Moderately Complex	Simple Market and Non-Market Damage Functions	
MIT	Very Complex	Very Complex	Very Complex	Very Complex	Very Complex	Not Yet Determined
NEW EARTH 21	Simple	Moderately Complex	Simple	Simple	Simple Damage Function	
PAGE	Simple	Not Explicitly Included	Simple	Simple	Simple Damage Function	
PEF	Simple	Simple	Simple	Simple	Moderately Complex	Moderately Complex
TARGETS	Simple	Moderately Complex	Moderately Complex	Moderately Complex	Moderately Complex	Simple

Table 4
MODULE INTERACTIONS AND FEEDBACKS IN INTEGRATED ASSESSMENT MODELS

Model	Module Interactions and Feedbacks
AIM	Some Interactions and Feedbacks Included, More Under Consideration
CETA	Straight Pass Through From One Module to Next
CSERGE	Straight Pass Through From One Module to Next
DICE	Straight Pass Through From One Module to Next
GCAM	Many Interactions and Feedbacks Under Consideration
ICAM-2	Straight Pass Through From One Module to Next in ICAM-1, Many Interactions and Feedbacks Under Consideration in ICAM-2
IMAGE 2.0	Many Feedbacks and Interactions Considered
ISM	Straight Pass Through From One Module to Next
MAGICC	Straight Pass Through From One Module to Next
MERGE	Straight Pass Through From One Module to Next
MiniCAM	Straight Pass Through From One Module to the Next
MIT	Many Interactions and Feedbacks Under Consideration
NEW EARTH 21	Straight Pass Through From One Module to Next
PAGE	Straight Pass Through From One Module to Next
PEF	Straight Pass Through From One Module to Next, More Complex Interactions Under Consideration
TARGETS	Many Feedbacks and Interactions, Only Model with Links to Other Global Change Issues

Table 5
GENERAL DESIGN FEATURES OF INTEGRATED ASSESSMENT MODELS

Model	Purpose	Treatment of Uncertainty	Regions	Key Inputs	Key Outputs
AIM	Policy Impacts Focusing on Asia-Pacific Region	Not Explicitly Considered	19 Economic 5' Square for Impacts	Potential GNP En. Tech. Costs Elas. Subs. Land-Use Trans. Climate Sens.	CO ₂ Emissions CO ₂ Concen. Temp. Change Sea Level Impacts
CETA	Compute Optimal Emissions Trajectories	Not Explicitly Considered	Global or North/South	Population Labor Prod. Ener. Resources Damage Fcn. Climate Sens.	CO ₂ Emissions CO ₂ Concen. Temp. Change Control Costs Damage Costs
CSERGE	Compute Optimal Emissions Trajectories	Two Point Probability Distributions on Key Inputs	Global	Population Labor Prod. Control Cost Fcn Damage Fcn. Climate Sens.	CO ₂ Emissions CO ₂ Concen. Temp. Change Control Costs Damage Costs
DICE	Compute Optimal Emissions Trajectories	Not Explicitly Considered	Global	Population Labor Prod. Control Cost Fcn Damage Fcn. Climate Sens.	CO ₂ Emissions CO ₂ Concen. Temp. Change Control Costs Damage Costs
GCAM	Policy Impacts Initially, Then Opt. Trajectories	Model Designed to Facilitate Uncertainty Analysis	9 Regions	Population Labor Prod.	CO ₂ Emissions CO ₂ Concen. Temp. Change Sea Level Precipitation
ICAM	Policy Impacts	Explicitly Incorporated in Design of Model	2 Regions North/South	Potential GNP Control Cost Fcn Damage Fcn. Climate Sens.	CO ₂ Emissions CO ₂ Concen. Temp. Change Control Costs Damage Costs

Table 6
Key Results From Deterministic Cost Benefit Analyses

Model	Control Rate (percent reduction relative to baseline emissions)		Carbon Tax (1990\$/tonne)	
	1990-2000	2090-2100	1990-2000	2090-2100
CETA Linear Damages Cubic Damages	5% 7%	5% 33%	\$8 \$12	\$12 \$165
DICE	9%	14%	\$5	\$18
GCAM				
MERGE				

Table 7
Key Sensitivities From Deterministic Cost-Benefit Analyses

Model Sensitivity Cases	Control Rate (percent)		Carbon Tax (1990\$/tonne)	
	1990- 2000	2090- 2100	1990- 2000	2090- 2100
CETA				
Warming per 2XCO ₂				
Low - 1°	0%	2%	\$2	\$9
Baseline - 3°	5%	9%	\$10	\$60
High - 5°	11%	82%	\$29	\$198
Damage Function Power				
Low - 1	2%	3%	\$6	\$18
Baseline - 2	5%	9%	\$10	\$60
High - 3	7%	47%	\$16	\$162
Utility Discount Rate				
Low - 2%	8%	10%	\$6	\$38
Baseline - 3%	5%	5%	\$10	\$60
High - 4%	1%	29%	\$22	\$136
DICE				
Rate of Time Preference				
3% Baseline	9%	15%	\$5	\$21
1% Low	19%	28%	\$24	\$78
GCAM				
MERGE				

Table 8
Alternative Policies to Mitigate Uncertainty

Category	Source of Uncertainty	Policy
1. Traditional Insurance	1. Diversifiable (individual) risk	1.a) Private insurance b) Social Insurance (against terms-of-trade or income losses)
2. Consumption smoothing over time	2. Risk of large or catastrophic loss	2. Investment (for a rainy day)
3. Precautionary investments	3. Uncertain scope of damage or abatement costs	3.a) Precautionary abatement (higher carbon tax) b) Precautionary adaptation (retreat from coastline) c) Investment in knowledge (geophysical and social-science research)

Source: Nordhaus (1994).

Figure 1. Basic Building Blocks of Integrated Assessment Models

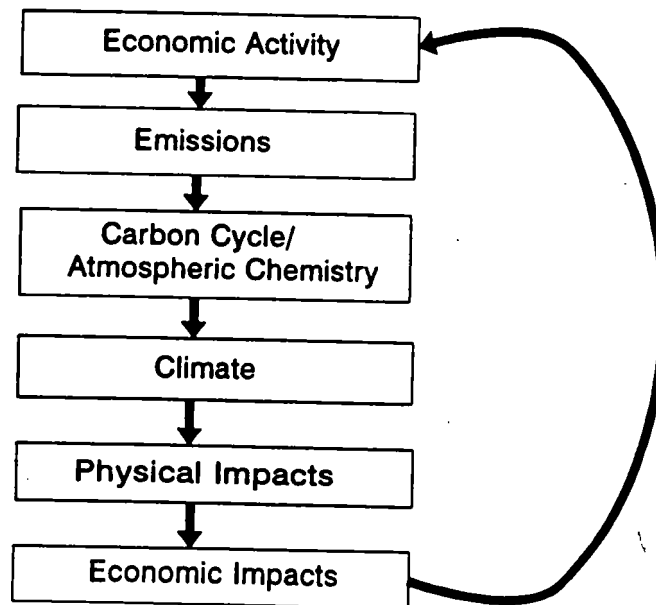


Figure 2. Basic Building Blocks of Integrated Assessment Models With Interactions and Feedbacks

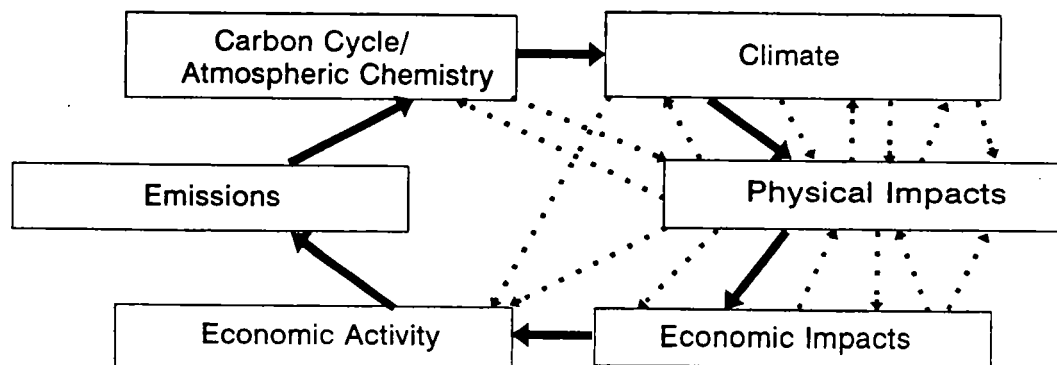


Figure 3. Tradeoff Between Natural and Economic System Complexity in Integrated Assessment Models

	Model (Date Operational)	
	Simpler Models of Natural Systems	More Complex Models of Natural Systems
More Complex Models of Economic Systems	PAGE (6/92) CSERGE (5/94) PEF (9/94)	MAGICC (10/93) ISM (1/94) Image-2 (6/94) ICAM-2 (9/94) TARGETS (9,94)
	CETA (1/92) DICE (10/92) MERGE (10/93) MiniCAM (9,94) New Earth 21 (1/95)	AIM (9/93) GCAM (6/95) MIT (12/95)

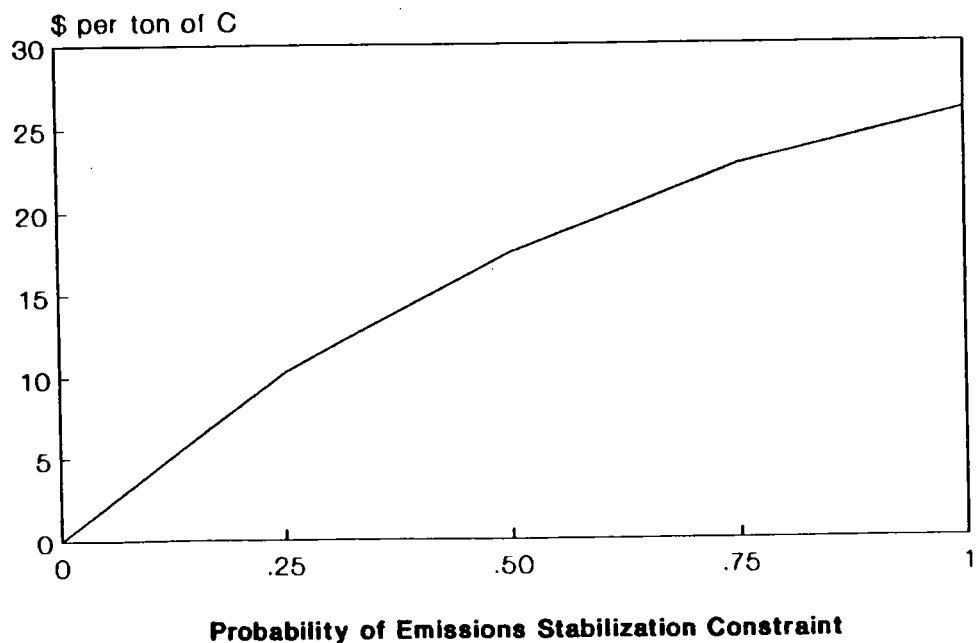
Figure 4. Natural Systems Complexity Versus Uncertainty in IA Models

	Model (Date Operational)	
	Simpler Models of Natural Systems	More Complex Models of Natural Systems
Deterministic	CETA (1/92) DICE (10/92) MERGE (10/93) MiniCAM (9,94) New Earth 21 (1/95)	AIM (9/93) MAGICC (10/93) ISM (1/94) Image-2 (6/94) GCAM (6/95)
Uncertainty Focused	PAGE (6/92) CSERGE (5/94) PEF (9/94)	ICAM-2 (9/94) TARGETS (9,94) MIT (12/95)

Figure 5. Economic Complexity Versus Uncertainty in IA Models

Model (Date Operational)	
Uncertainty Focused	Simpler Models of Economic Systems
	More Complex Models of Economic Systems
Deterministic	MAGICC (10/93) ISM (1/94) Image-2 (6/94)
Uncertainty Focused	CETA (1/92) DICE (10/92) AIM (9/93) MERGE (10/93) MiniCAM (9,94) New Earth 21 (1/95) GCAM (6/95)
	PAGE (6/92) CSERGE (5/94) ICAM-2 (9/94) PEF (9/94) TARGETS (9,94)
	MIT (12/95)

Figure 6. Implicit Tax on Carbon in 2000



CHAPTER 11

An assessment of economic policy instruments to combat the enhanced greenhouse effect

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Summary

1. A clear distinction needs to be drawn between the costs and benefits of actions taken to reduce the impacts of climate change itself and the costs and benefits of actions taken to reduce emissions. The first involves a consideration of adaptation policies such as developing new drought resistant plant cultivars while the second involves a consideration of policies designed to mitigate climate change.
2. Policy instruments designed to mitigate global climate change must be identified at two different levels: those that might be used by a coalition of countries and those that might be used by individual nations unilaterally or to achieve compliance with a multilateral agreement on greenhouse targets.
3. Governments may have different sets of criteria for assessing international as well as domestic greenhouse policy instruments. Among these criteria are efficiency/cost effectiveness, distributional (including intergenerational) equity, flexibility in the face of new knowledge, understandability to the general public and consistency with national institutions and traditions. The choice of domestic instruments may also partly reflect a desire on the part of governments to achieve non-climate change related objectives such as meeting fiscal targets or influencing pollution levels which are indirectly related to greenhouse gas emissions.
4. A coalition of nations may choose one or a mix of policy instruments including tradable quotas, feasible forms of joint implementation, harmonised domestic carbon taxes, international carbon taxes, non-tradable quotas and various international standards. At both the international and national levels, market-based approaches are likely to be more cost effective than other instruments. At the international level, all of the potentially efficient tax or quota solutions should be available to facilitate future negotiations. Under a harmonised carbon tax, incentives exist for countries to alter related policies so as to reduce the domestic welfare effects of the tax (for example by introducing offsetting production subsidies). This would make harmonised carbon taxes less effective than tradable quotas in reducing emissions. For a global treaty, a tradable quota system is the only potentially efficient arrangement where an agreed level of emissions is attained with certainty (subject to enforcement).
5. In principle, individual countries can choose from among a large set of available instruments, including carbon taxes, tradable permits and deposit refund systems as well as technology standards, performance standards and product bans. A choice of tradable quotas at the international level would provide maximum flexibility for instrument choice at the domestic level.
6. A tradable quota or permit system has the disadvantage of making the marginal cost of emission reductions uncertain while a carbon tax has the disadvantage of leaving the effect on the level at which emissions are controlled uncertain. The weight given to the importance of reducing these different types of uncertainty will be crucial in determining the final choice between competing market-based instruments.
7. The consequences of climate change policy will be determined by the choice of policy instrument as well as the design and implementation of those policies.

An assessment of economic policy instruments to combat the enhanced greenhouse effect

11.1 Introduction

11.1.1 Guidelines from the FCCC

The aim in this chapter is to provide an economic assessment of possible policy instruments to manage greenhouse gas emissions under the Framework Convention on Climate Change (FCCC). The Framework Convention contains several key guidelines for policy implementation. First is the emphasis given to developed countries demonstrating that they are taking the leading role in policies to control greenhouse emissions. In essence, developed country signatories (as listed in Annex 1) have accepted the goal, but not necessarily the requirement, of stabilising greenhouse gas emissions at 1990 levels by 2000 (Article 4.2). In ratifying the Convention, Annex 1 countries have effectively accepted a quantitative emissions target although the level of that target remains uncertain. Developing country signatories (non-Annex countries) are under no such obligation. Rather, the economic needs and special circumstances of developing countries (Articles 4.8 and 4.10), and of countries that are highly dependent on incomes from fossil fuels (Article 4.10), will be taken into account in determining specific commitments to control emissions.

To achieve greenhouse emission reductions, Annex 1 countries have the option to implement greenhouse policy measures jointly with other Parties to the Convention (Article 4.2). This provision is consistent with another guiding principle in the Convention that all greenhouse policy measures should be cost effective — that is, achieve policy goals at least cost (Article 3). Other key principles in Article 3 include that Parties should promote sustainable development, that precautionary measures are taken to minimise the costs of greenhouse uncertainties and risks (noting that where there are risks of serious or irreversible damage, lack of scientific certainty should not be used to justify policy deferral), and that measures taken to combat climate change should not amount to unfair trade restrictions.

Prior to the development of the FCCC the most closely related international conventions were the Vienna Convention for Protection of the Ozone Layer (concluded in 1985) and the 1987 Protocol on Substances that Deplete the Ozone Layer (the text of which was revised in 1990 and again in 1992). The experience of the parties to that Protocol provides valuable information about implementation of policy approaches within the FCCC.¹

In this chapter, the factors affecting the policy mix for the control of greenhouse gas emissions are reviewed using these guiding principles and taking account of the general international legal framework in which the Convention must operate.

11.1.2 The Greenhouse Policy Problem

Two characteristics of the greenhouse problem are central to the design of policy responses. The first key feature is that it is a global problem. It is the total accumulation of greenhouse gases in the atmosphere which could cause global warming over the next century (IPCC 1990; 1992), regardless of the geographic source of emissions. Added to this, there is a long time lag, up to 50 years, between emission reductions and their impact on atmospheric concentrations. Thus the greenhouse problem is a pollution problem over space and time. Any benefits from controlling concentrations depend on

¹ For a comprehensive legal review of the Convention see Bodansky (1993).

long term global cooperation, and the costs of collective control will be incurred long before any potential benefits are realised.²

The second key feature of the greenhouse problem is that both the extent of any climate change and the nature of its effects are uncertain. This means that potential greenhouse policies must be assessed using a decision-making framework which explicitly incorporates risk, uncertainty and the capacity to learn about evolving climatic and economic conditions around the world.

A basic principle in public policy (as for any financial decision) is to time the introduction of the policy to maximise the expected discounted value of the stream of net benefits from the initiative. In this context, there may be significant gains from waiting to reduce uncertainties before implementing greenhouse policies³. The value of the information gained from waiting could allow greenhouse policy to be properly tailored to the most likely damage scenario in order to avoid excessive control costs (Peck and Teisberg 1993; Leary and Scheraga 1994; Richels and Edmonds 1994). Conversely, there could be significant costs in waiting if waiting precludes greenhouse policy from being properly tailored to avoid excessive damage costs (Chichilnisky and Heal 1993) or if waiting results in the need for urgent action at some future time, with associated disproportionate adjustment costs.

Greenhouse policy assessment must therefore take into account the existence of opposing risks. Indeed, one important avenue for policy assessment is to examine the extent to which policy can be directed to reduce the costs of uncertainty and the costs of risk from natural damage caused by the enhanced greenhouse effect and from mitigation measures in response to climate change concerns. An immediate response to the greenhouse problem is to invest in research and development to reduce greenhouse uncertainties.

An efficient greenhouse policy will ensure that the costs of greenhouse uncertainties, and of associated risks, and the costs of emission reductions and adaptation strategies are balanced, at the margin, with the benefits from avoiding damage from global warming. One implication of this efficiency criterion is that optimal policy is least cost in achieving a global greenhouse target in the face of risk, uncertainty and learning about the causes and effects of climate change.

11.1.3 A Guide to the Chapter

The remainder of this chapter is organised as follows. In Section 11.2 the policy instruments under review are briefly described and criteria for their assessment outlined. This is done first in the domestic policy context and then in the international domain. The question of the need for comprehensive targets covering all greenhouse gases is also addressed.

In Section 11.3 changes in background policy settings which may have a positive impact on the efficiency of fossil fuel use, and therefore emissions, as well as be of benefit to the economy more generally are outlined. These approaches are important in that they constitute part of a number of countries' stated official policies on mitigating the effects of climate change. It is also noted that some policies may hinder the rate of adaptation to climate change.

² However, it is worth noting that there may be side benefits, such as health-related benefits, as a consequence of any reductions in pollution associated with reductions in greenhouse gas emissions.

³ For a general review of the literature on investment under uncertainty see Pindyck (1991).

In Sections 11.4 and 11.5 reviews of both conventional regulatory instruments and market-based policy instruments are provided, while issues of policy implementation are outlined in Section 11.6. This material is brought together in an assessment of greenhouse instruments in Section 11.7. Some concluding remarks are made in Section 11.8.

11.2 Greenhouse Policy Instruments and Criteria for Policy Assessment

The variety of instruments that are available to policy makers to control greenhouse gas emissions is outlined here. Such instruments include conventional regulatory instruments, market-based instruments such as taxes, subsidies and tradable quotas and permits, and other complementary policies. In this chapter the term 'tradable quota' is used to describe internationally traded emissions allowances. The term 'permit' is more commonly used in the literature to describe domestic trading schemes and that convention is adopted here. Existing global climate change research that has analysed a broad range of policy instruments includes Mintzer (1988); US Congress, Office of Technology Assessment (1991); IPCC (1992); National Academy of Sciences (1992); and McCann and Moss (1993).

11.2.1 Domestic Policy Instruments

11.2.1.1 Conventional Regulatory Instruments

One way of controlling activities which both directly and indirectly lead to greenhouse gas emissions is to set standards and to regulate the activities of firms or individuals. By mandating standards governments attempt to ban or alter the use of materials and equipment that is considered to be damaging. Standards are typically applied in areas such as buildings (energy efficiency, for example), fuel use by motor vehicles, energy efficiency of household durables and the content of fuels. Standards may be voluntary or mandatory. They may be fixed or set as targets, or 'rolling standards' might be adopted (Grubb 1991, p. 128).

11.2.1.2 Market-Based Instruments

In using market-based instruments governments attempt to alter price signals to ensure that emitters face direct cost incentives to control emissions. The primary market-based instruments for greenhouse management are emissions taxes and tradable emissions permits.

11.2.1.2.1 Taxes and Subsidies

Under an emissions tax, those who produce emissions face a tax per unit of emissions. The tax on each fossil fuel should be imposed at the same rate per unit of its long term global warming potential. A tax on energy content measured in British thermal units, the so called BTU tax, would not satisfy this criterion as it relates to energy use per se rather than with any externalities associated with end-products of combustion (see Poterba, 1993). A tax on carbon content of fossil fuels on the other hand would approximate this criterion. Implementing such taxes at a uniform rate per ton of carbon content of fossil fuels to curtail carbon emissions assumes that existing excises on energy products are levied at the optimal level based on minimising the excess burden of taxation and internalisation of environmental externalities. If such an assumption does not hold in practice, it complicates the design of carbon taxes.

Subsidies might be offered for adopting particular technologies or practices. Such subsidies might be directed at fostering emissions abatement or the creation of additional sinks by, for example, subsidising tree planting.

11.2.1.2.2 Tradable Permits

Under an emissions trading scheme emitters are given permits to emit (the total allocation is the aggregate emissions cap for the country) and have the option of buying or selling permits in the marketplace. While there are important and often subtle

differences between taxes and tradable permits, under some restrictive circumstances, the outcome can be the same. Both may target full user cost pricing of the atmosphere to dispose of net greenhouse gas emissions from human activity. When traded on a national market, permit prices are established that show the costs of marginal emissions, just as an emissions tax does. The difference is that the tax is exogenous (in this case, set by the government) and its effects on emissions endogenous, while emissions are exogenously determined in the case of a permit system and hence, permit prices are endogenous.

A tradable permit system could be used in combination with either an international tradable quota system or an international carbon tax. In the former case, the domestic permit system could either be integrated with an international quota system, where the permit-holding parties (say, a limited set of wholesale fossil fuel dealers) trade directly on the international quota market (see Grubb and Sebenius 1991; Sander et al. 1994) or be run as a separate subsystem providing the national government with a net excess demand for (supply of) emission quotas at the ruling international quota price. In the case where governments paid an international tax on carbon emissions, it would be up to each government to determine beforehand the volume of domestic permits available per period. Ideally, this volume should be such that the resulting permit price equalled the tax rate. If not, nationally as well as internationally too little or too much abatement would take place.

11.2.1.3 Other Complementary Policies

A range of other complementary instruments exist which might be adopted to moderate greenhouse gas emissions or to promote adaptation to climate change. Education and provision of new information, for example by promoting research, may be valuable in changing consumer behaviour with respect to energy consumption and the development and adoption of new technology. Family planning may play an indirect role in reducing total energy demand in the future as might more general education directed specifically at women in developing countries. Modifications of trade policy and reductions in energy production and consumption subsidies (and other market distortions) may also have indirect consequences for greenhouse gas emissions. Changes in migration policies in some countries may allow more flexibility for developing countries to adapt to regional population pressures that may arise as a consequence of changes in the incidence of occurrences such as severe drought.

11.2.2 International Policy Instruments

The use of the available policy instruments will only lead to a cost-effective global outcome if certain conditions are met. First, unless individual countries undertake cost effective domestic greenhouse policy measures compatible with global efficiency, the policy instruments adopted internationally will not lead to global efficiency. Each individual country is free to choose its own instrument or combination of instruments to meet its international obligations but the choice of international instruments will, to some extent, dictate the choice of policy instrument at the domestic level. This is clearly so in the case of the harmonised carbon/energy tax proposed by the European Commission for member states of the European Union. Under this regime, every member of the Union would impose the same tax rate, although states would be free to decide for themselves what to do with the revenues from the tax. If nations themselves were taxed by an international agency, then it would not necessarily follow that nations would choose to impose the same tax domestically. For example, they might instead choose to reduce emissions domestically by means of a tradable permit scheme. Similarly, in the case of a system of internationally tradable quotas, individual countries might choose to implement their obligations by means of a domestic tradable permit scheme or through a domestic emissions tax.

Second, given that information is not perfect and that distortions already exist in both international and domestic markets, the actual market outcomes from the

implementation of particular greenhouse policies will not necessarily be efficient. The importance of the policy environment is discussed in section 11.3 and implementation issues surrounding the adoption of market-based instruments are outlined in section 11.6. For purposes of discussion, it will be assumed that a given ceiling on emissions as a target has been identified, and that governments seek to minimise the costs of meeting this target. The main concern here is thus with cost-effectiveness rather than efficiency as such.

11.2.2.1 Regulatory Instruments

Standards uniform among countries participating in an international emissions reduction agreement are conceivable. But it is likely to be difficult to achieve wide agreement about any large set of specific instruments of this type. For example, while individual countries may adopt standards on housing insulation it is most unlikely that the same standards would be applicable in both temperate and tropical countries. Moreover, such an approach would limit individual countries' domestic policy choices and hence their flexibility in adjusting their emissions under an international greenhouse gas reduction agreement. What amounts to another regulatory approach is where countries agree on fixed national emission levels (a 'non-tradable emissions quota' system), essentially in the tradition of the European Union's Large Combustion Plants Directive. This agreement specifies reductions in the emissions of sulphur dioxide and oxides of nitrogen from plants with a thermal rating of 50MW or larger. Such an approach would mean that marginal emissions abatement costs among participating countries would tend to be different and, hence, total abatement costs, globally speaking, would be unnecessarily high.

11.2.2.2 International Taxes and Harmonised Domestic Taxes

If countries agreed to apply the same level of domestic greenhouse or carbon taxes (harmonised domestic taxes), marginal abatement costs would tend to be equalised among countries. Such an agreement may have to include side payments from rich to poor countries if the latter are to be encouraged to participate.

An alternative type of international policy to reduce emissions could be an agreement to levy a uniform international tax on greenhouse or carbon emissions in each of the participating countries. The total international tax revenue would be shared among the participating countries according to rules established in the agreement.

If an international tax agreement did not cover all countries, world fossil fuel prices would decrease and fossil fuel use increase in non-participating countries (so-called carbon leakage). In addition, since carbon-intensive products would be less expensive in such countries, exports of them to the participating countries are likely to rise. A policy instrument might then be introduced by the latter countries to control carbon leakage (see section 11.6.5 for further discussion). For example, a carbon tariff might be imposed at a rate corresponding to the tax rate on imported products on the basis of their estimated carbon contents.

In the case of a domestic carbon tax imposed by international agreement, national commitment to impose the tax will also vary across countries because perspectives on global warming vary among countries. If a country has signed such an agreement under international pressure, that country could make the carbon tax an ineffective instrument by reducing existing energy taxes, by taxing close substitutes to fossil fuels (for example hydroelectricity) or providing subsidies to complements or products that are fossil fuel energy intensive, and by lax enforcement of the agreed on carbon tax (see Hoel, 1991). Thus by following a suitable strategy, a free ride becomes possible. A global carbon tax imposed by an international agency, on the other hand, would impinge on national sovereignty and would therefore be difficult to negotiate.

If global carbon taxes were levied as producer taxes instead of consumer taxes, tax revenue would be collected in fossil-fuel producer countries instead of consumer

countries and hence, shift the burden between the two types of countries (Whalley and Wigle 1991). The distributional effects of such a 'producer cartel' solution may be unacceptable to a great many countries and, if used, give rise to retaliatory trade policy measures. It is worth noting that under an incomplete agreement (that is and agreement which does not include all countries) the distributional consequences of taxes imposed on producers of fossil fuels as opposed to fuel consuming countries will be quite different. (Neither carbon producer taxes⁴ nor producer quota systems are further discussed in detail in this chapter.)

11.2.2.3 Tradable Quotas

Another potentially cost effective international solution would be one where countries agree to an allocation of carbon emission quotas, perhaps reflecting an overall emissions target. In a practical sense signatories to the FCCC have implicitly accepted such a quantitative target. International quota trade (Sandor et al. 1994) would establish a quota price — an implicit international tax rate — which would tend to equalise marginal abatement costs among countries. A carbon-leakage problem similar to that mentioned above would arise to the extent that such an agreement was not global.

In the case of an international tradable quota scheme, participating countries may use whatever domestic policies they prefer in order to stay within their ex-post-quota-trade quotas. For example, they might employ tradable permits, domestic taxes or regulations. If a domestic carbon tax is used, the efficient tax rate for the coming period would be the (unknown) quota price level for that period.

11.2.2.4 Other Complementary Policies

Technology transfer from industrialised to developing countries potentially has a large part to play in reducing future emissions. One mechanism to facilitate such transfers is through joint implementation, to the extent that joint implementation proves practically feasible. Joint implementation aims at minimising the joint costs of emissions reductions for a group of emitters. In the context of emitters who are committed to targets it could lead to the development of a tradable quota scheme.

11.2.3 Criteria for Policy Assessment

In this chapter a range of criteria is used to assess policy instruments to manage the greenhouse problem. Two important criteria are economic efficiency and distributive justice. The efficiency objective or benefit-cost principle is to maximise the global net benefits from the use of resources. Both the global greenhouse emissions target and the policy instrument to achieve it are choice variables in satisfying this criterion. However, there is considerable uncertainty regarding the causes and effects of unconstrained greenhouse gas emissions at this time. Hence, there is uncertainty regarding the benefit and cost functions, and as a consequence of this, there is considerable uncertainty regarding the optimal (economically efficient) level of control. One practical response is to employ a cost effectiveness objective — that is, to minimise the costs of achieving a given global greenhouse emissions target.

The cost effectiveness of achieving a given but potentially time varying target is a criterion that is employed in much of this chapter. Policies potentially differ in their ability to achieve an emissions target under changing conditions. A policy which consistently 'hits the target' (achieves environmental effectiveness) and remains cost effective is desirable.

As a practical matter it is also important to distinguish static from dynamic cost effectiveness. Static efficiency refers to a short term operating environment in which technology options and aggregate primary resource availabilities are fixed, while

⁴ A related suggestion is that for a 'tradable abatement (adsorption) obligation'. For details see Read (1994).

dynamic efficiency pertains to a long term operating environment in which technology options and primary resource availabilities change. A policy which is cost effective in the short run may not be cost effective in the long run.

As well as applying the global least cost principle to policies for emissions control, the other main criterion for policy assessment is the objective of distributive justice. This requires that the total net benefits (costs) generated by the policy should be 'equitably' shared.

Central to the analysis of the performance of any greenhouse policy is the recognition that the real world operating environment involves major sources of greenhouse uncertainty and associated risk regarding future economic and ecological conditions. Decision makers will face the costs of uncertainty and risk from making incorrect decisions. But it is possible to reduce these costs by ensuring that policy is flexible and reversible in response to new information about the most cost effective future strategy. The ability to modify policy settings and introduce new policies without generating major costs of adjustment are key criteria for greenhouse management.

Potential net benefits from a policy initiative must also take into account the administrative costs of the program. Whether an efficiency criterion (maximising net benefits) or a cost-effectiveness criterion (minimising aggregate costs) is being employed, it is essential that the full measure of costs include both implementation costs (typically borne by governments) and transaction costs (typically borne by the private sector).

Costs need to be measured correctly. A taxonomy of the costs of environmental regulation, beginning with the most obvious and moving towards the least direct, is provided in Table 11.1.⁵ First, many policy makers, and much of the general public, would identify the on-budget costs to government of administering (monitoring and enforcing) environmental laws and regulations as the cost of environmental regulation. However, most analysts would identify the capital and operating expenditures associated with regulatory compliance as the fundamental part of the overall costs of regulation, although a substantial share of compliance costs for some environmental regulations fall on government rather than private firms — one example being regulations of contaminants in drinking water. Additional direct costs include legal and other transaction costs, the effects of refocused management attention, and the possibility of disrupted production.

Next, the potential 'negative costs' (in other words, non-environmental benefits) of environmental regulation, including the productivity impacts of a cleaner environment and the potential effects on innovations of regulation should also be considered. General equilibrium effects associated with product substitution, discouraged investment⁶, and retarded innovation constitute another important layer of costs, as do the transition costs of real-world economies responding over time to regulatory changes. Finally, there are a set of potential social impacts that are given substantial weight in political forums, including those on jobs and economic security.⁷

⁵ For a very useful decomposition and analysis of the full costs of environmental regulations, see Schmalensee (1994). Conceptually, the cost of an environmental regulation is equal to the change in consumer and producer surpluses associated with the regulations and with any price and/or income changes that may result' (Cropper and Oates 1992, p. 721).

⁶ For example, if a firm chooses to close a plant because of a new regulation (rather than installing expensive control equipment), this would be counted as zero cost in typical compliance-cost estimates.

⁷ For a fuller explanation of these different categories of the costs of environmental protection, see Jaffe, Peterson, Portney and Stavins (1995).

This discussion of some of the special difficulties of assessing the cost effectiveness of alternative policy instruments should not be taken to mean that this single criterion is of exclusive or paramount importance. On the contrary, individual nations will inevitably choose their own criteria to distinguish between competing policy instruments. The specific criteria chosen will always be a function of the individual socioeconomic and cultural context, but in many cases the following set of criteria will be among those considered: (a) probability that the environmental goal will be achieved; (b) efficiency or cost-effectiveness; (c) dynamic incentives for innovation and the diffusion of improved technologies; (d) flexibility and adaptability to exogenous changes in technology, resource use and consumer tastes; (e) distributional equity; and (f) feasibility in terms of political implementation and administration.

Finally, in assessing policy options in this chapter both spatial and temporal aspects of emissions coverage are considered. General design features of economic instruments are categorised by the coverage of net greenhouse gas emissions, the scope and level of participation and the point of application. That is, for example, an emissions control objective could involve a target on all or a subset of all human sources and sinks and all or a subset of all greenhouse gases. In addition, the scope of a policy instrument could involve all or a subset of countries. The level of participation in a scheme refers to the economic unit responsible for meeting a target. Options range from the level of the country to that of individuals or companies. The point of application of the policy simply refers to the point in the production or consumption chain of a good or service at which greenhouse gas emissions are to be counted or proxied.

11.2.4 Coverage of Greenhouse Gases

11.2.4.1 The Need for Comprehensive Targets

Should an initial international program include all greenhouse gases or focus on CO₂ alone? This question has received considerable debate in the literature (see, for example, Cristofaro and Scheraga 1990; Victor 1991; Stewart and Wiener 1992). The advantage of the more comprehensive approach is the additional flexibility it introduces into the system, and hence the potential it creates for even greater cost effectiveness. However, the sources and sinks of methane and nitrous oxide emissions are as yet poorly understood. Currently, important anthropogenic sources of emissions of methane appear to include domesticated ruminant animals, rice cultivation, landfills and mining; and for nitrous oxide appear to include legume crops and nitrogen fertilisers (Howden and Munro 1994; Pearce and Warford 1993). Clearly, countries with a comparative advantage in agricultural industries could be significantly affected by either the exclusion or use of a multiple gas scheme. While CO₂ is the main source of past and present greenhouse concerns, methane and nitrous oxide are also significant in radiative forcing.

By including all the major greenhouse gases (sources and sinks) in setting global and any national greenhouse management targets policy makers would avoid throwing away valuable knowledge (Schmalensee 1993). Given a set of weights relating the radiative forcing potential of each greenhouse gas to a numeraire (say CO₂), a multiple gas market policy would only need to involve one quota market or one emissions tax scheme and one permit market or domestic tax scheme as well as one control obligation for each country. At this stage these weights are uncertain and may vary with both environmental and economic conditions (Hoel and Isaksen 1993).

If the administrative burden is deemed to be too great initially for the incorporation of (net) greenhouse gas emissions other than CO₂ in an international greenhouse management program, the program needs to be flexible enough to do so when implementation costs fall, and indeed could provide incentives to generate such an outcome. Care must be taken not to worsen problems for future greenhouse management. This means that the international target must be comprehensive as must targets for countries within the coalition which adopts any international market based

policy regime. Coalition governments must manage those emissions outside the international market based policy regime.

11.2.4.2 Initial Coverage of CO₂ Sources and Sinks

The coverage issue in the case of CO₂ has been widely discussed (see, for example, UNCTAD 1992; OECD 1992a,b). Should consideration be limited to only changes in emissions of CO₂ or also include changes in CO₂ sinks, such as expanding forests? One question is whether and how an international agreement might help retard deforestation and promote reforestation (Dudek and LeBlanc 1992). Deforestation could be treated as equivalent to emissions, while afforestation activities could be a source of emissions abatement credits. A good deal of care is needed in establishing the accounting methodology to ensure that the net effects of land clearing and revegetation with alternative species are measured and that domestic consumption and exports of wood products are separated.

Whether one is considering net CO₂ emissions from fossil fuel burning or net deforestation, it is necessary to have a net emissions target (baseline which applies in the absence of policy) from which to assess the effectiveness of the greenhouse policy in place. This baseline has yet to be determined for the forestry sectors of the world's economies, and cost effective monitoring techniques have not yet been proven. One of the major difficulties is that many trees exist outside forests as such and measuring their contribution to carbon sequestration with remote sensing devices is extremely difficult. A further and more pervasive issue is associated with specifying ex ante a 'status quo' time path, against which 'improvements' can be measured.

The coverage of the scheme may have a major impact on the incentive of different countries to participate. With an international market program for CO₂, countries like Brazil and Indonesia might find it economically attractive, as well as environmentally sound, to retard the depletion of their forests or to implement reforestation programs. Under an international tradable quota regime, CO₂ emissions credits would amount to a valuable export commodity from the seller's viewpoint and would be an equally valuable import from the buyer's viewpoint (a country which would otherwise be in CO₂ emissions deficit). Under an international CO₂ emissions tax, net emissions would also be treated symmetrically.

Currently, there are significant difficulties in measuring the carbon stored in trees and how it varies over time (Houghton 1992). Current estimates of the costs of carbon sequestration through tree planting vary widely (ranging from US\$1 to US\$50 per ton of carbon abated), reflecting the opportunity costs of alternative land use (Stavins 1994b) as well as uncertainty (see Sedjo 1994 and the references cited there). However, estimates at the low end of the range refer to developing countries and, aside from uncertainty, appear promising in terms of shifting any long term need for high cost carbon free backstops further into the future. According to current estimates such backstops become economic when the marginal cost of emissions is around US\$250 per ton of carbon (Manne and Richels 1991).

Satellite imagery is a critical tool in monitoring forestry systems. Given the potential stimulus of global net CO₂ emissions trading, this tool could be tailored to ensure that coverage is complete and backed by verification (OECD 1992b). Further, such a price stimulus for reduced deforestation (and increased afforestation) could yield complementary gains in terms of sustainable land management practices and global gains in biodiversity values. Indeed, the global nature of biodiversity values has prompted one suggestion for an international tradable quota system in global forestry management (see Sedjo 1994).

Hence, an important option value would be preserved by including in any international agreement to control CO₂ sources that the adoption of sinks would be reviewed, at fixed

points in time, by all Parties. However, it would be important to ensure that the integrity of the existing policy regime was preserved as new sinks were included.

11.3 The Domestic Policy Context

From the basic theorems of welfare economics it can be deduced that if an economy is perfectly competitive, there is a full set of markets and information is perfect, then the resulting equilibrium (if it exists) is efficient in the sense that no one could be made better off without making someone else worse off. The real world does not satisfy these conditions. There exist many externalities, of which climate change is only one. Competition is not perfect; increasing returns to scale characterise some industries. Information is often not perfect and markets are not complete. Moral hazard and adverse selection partly explain why a full set of insurance markets does not exist. What is more, even if all the conditions of perfect competition were satisfied, the resulting Pareto efficient outcome may not accord with society's view of a distribution of resources that is equitable or 'fair'. If certain other conditions hold, then an alternative, feasible, Pareto efficient allocation can be sustained as a competitive equilibrium with appropriate lump-sum taxes and transfers, and so the objectives of efficiency and equity need not necessarily clash. But lump-sum taxes and transfers are typically infeasible, and, as a consequence, distorting taxes and transfers are employed virtually everywhere.⁸

The above observations about distortions are important because many analyses of climate change policy assume that the externality of climate change is the only distortion which exists. In fact, climate change policy must be considered in the context of real economics, already rife with distortions. A market economy can function effectively only if governments define property rights and provide for the enforcement of contracts. In some countries even these basic requirements are not met. The extent to which government can provide these basic requirements and correct market failures will in part determine GNP. The importance of GNP in determining future emissions is highlighted in Chapter X.

Further, it is necessary to take into account the distortions introduced by governments. Government interventions can undermine net national income and cause environmental damage (see Binswanger 1989). Another important determinant of future emissions, as discussed in Chapter X, is population. Here, too, both market and government failures play a role. For example, high rates of fertility have been linked to the absence of effective capital markets, which make it difficult or impossible for people to obtain social security (see Dasgupta 1993).

One purpose in this Section is to draw attention to the importance of this policy context in evaluating climate change policy proposals. The merits of any given proposal depend on this context. Equally, changes in the context have implications for emissions. Sometimes these two different observations are confused, and another purpose here is to clarify the distinction between them. Obviously, the types of policies that might warrant discussion here are many. However, the discussion is restricted to a few areas that seem particularly important and on which some research has already been done.

11.3.1 Pre-existing Market Distortions

11.3.1.1 Energy Subsidies

The emissions abated by a climate change policy will depend not only on the policy itself but also on whether the consumption of energy is subsidised, and the magnitude of

⁸ Although lump sum taxes and transfers are typically infeasible in a single economy, market based instruments such as a tradable quota scheme or a carbon tax can be designed to achieve transfers of goods and services between countries to implement the equity criteria described in Section 11.2.3.

such subsidies. It is the combination of the climate change policy and these subsidies (and indeed other policies) which will determine relative prices and hence the incentives for substituting away from the carbon-intensive fuels.

In some regions such subsidies are significant (Larsen and Shah 1994a). Using border prices as a benchmark, Larsen and Shah (1992) calculated that primary fossil fuel subsidies worldwide are equivalent to a negative carbon tax of US\$40 a ton. Larsen and Shah (1994a) estimate that global CO₂ emissions would be reduced by between 4 and 5 per cent if all energy subsidies were removed.⁹ At the same time, eliminating such subsidies would increase real incomes by improving efficiency. The reason is that the subsidies distort prices; users pay less for fossil fuels than it actually costs to supply them.

An OECD study using the GREEN model arrives at a similar result. The OECD estimates that the removal of energy subsidies would reduce global emissions by 18 per cent compared with the level that would otherwise be attained by 2050 (Burniaux, Martin and Oliveira-Matins 1992a). Elimination of subsidies could increase global real incomes by 0.7 per cent annually and real incomes in non-OECD countries could rise by 1.6 per cent annually.

Fossil fuels may also receive indirect subsidies from electricity generation. Electricity is typically subsidised in both developed and developing countries. In the United States, for example, government regulation frequently restricts electricity prices from privately owned utilities to equal long run average costs, which are often below marginal costs. Power is sold by the federal government at approximately 25 per cent below even these levels, because of interest and tax subsidies (DCEIA 1992). In developing countries, electricity prices declined in real terms by 25 per cent over the 1980s, and by 1988 were at an average level just over half as large as the average level in OECD countries, even though long run marginal costs in real terms were higher in developing countries (Schramm 1992). In 80 per cent of developing countries, electricity prices are below long run marginal costs — on average 30 per cent below (World Bank 1990, 1992a). Such distortions lead to excessive expenditure on new capacity, failure to generate sufficient internal funds to maintain or expand service, excessive energy consumption and excessive environmental impacts from power generation.

11.3.1.2 The 'Local' Environmental Benefits of Climate Change Policy

So far, the effect that the removal of energy subsidies can have on income, as conventionally measured by GNP, has been stressed. But the effects are likely to be felt more widely. One consequence of actions to reduce CO₂ emissions will be a reduction in other pollution. For example, Bye, Bye and Lorentsen (1989) estimate that a policy which reduced CO₂ emissions in Norway by 20 per cent would have the incidental effect of reducing SO₂ emissions by 21 per cent and NO_x emissions by 14 per cent. Larsen and Shah (1994b) calculate that, for Pakistan, a carbon tax could be justified taking only the benefits of reductions in local pollutants into account, despite the fact that Pakistan already has high energy-related taxes.

11.3.1.3 Information and Energy Conservation

There has long been concern that apparently cost-effective energy conservation technologies were being adopted and diffused only very gradually and that market penetration rates for such technologies were not as high as engineering based models predict. This may be due partly to imperfect capital markets. Another possible reason may be the failure of the market to supply appropriate and credible information about these technologies (Hassett and Metcalf 1992; Jaffe and Stavins 1994a).

⁹ They estimate that a carbon tax of US\$60-70 per tonne of carbon would be required in OECD countries to achieve an equivalent reduction in global emissions.

Empirical work dating back to Hausman (1979) shows that purchases of energy-saving technologies often reflect high rates of discount (see Treadwell, Thorpe and Fisher 1994).¹⁰ In other words, purchasers of such technologies may insist on earning a higher rate of return on this investment than on alternative investments. In an econometric analysis, Hassett and Metcalf (1992) show that future uncertainty regarding energy prices, due to past volatility in those prices, can attribute a large option value to waiting before investing in energy-conserving capital. On the other hand it could be argued that uncertainty about future energy prices creates an incentive to invest in energy efficient equipment to minimise the share of energy costs in total costs. This would reduce risk exposure if energy prices were more uncertain than other input prices.

One means of avoiding this dilemma is for the company manufacturing the technology to offer a warranty on the product's performance. But there is a problem in that the performance of the good may depend on how it is used by the consumer, as well as its intrinsic qualities (the moral hazard problem). A full warranty would therefore create an incentive for the consumer to misuse the good. Another problem is that there may be a tendency for the users most likely to purchase a more expensive good with a full warranty also to be those most likely to misuse the good (the adverse selection problem). For both these reasons, warranties may not be able to convey the information that would benefit both consumers and the firms manufacturing the technology.

Empirical evidence in the United States (Horowitz and Haeri 1990; Sutherland 1991) indicates that when information on energy efficiency is widely available, the real estate market functions efficiently — consumers show a willingness to pay more for houses with energy-saving features, all else being equal. However, Jaffe and Stavins (1994a,c) demonstrate that information problems can directly inhibit the diffusion of energy efficient technologies in new housing. They also show that decisions on such investments depend on expectations about the future. If the price of such technologies is expected to fall, or the availability of information about the performance of such technologies is expected to increase, then consumers may delay making such purchases. Though individually rational, such behaviour can lead to less investment than is socially desirable, depending on whether true market failures are involved (Jaffe and Stavins 1994b). This creates a potential role for public policy.

A number of projects designed to convey information to rural people exist in developing countries. One such project is the Mount Elgon Conservation and Development Project in Uganda which is designed to provide new information to local people to enhance the cost effective use of local fuel resources and minimise damage to forest reserves.

11.3.1.4 Transport

A large and growing fraction of CO₂ emissions arise from transport fuel use. Full social (user cost) pricing can promote greater efficiency in transport while reducing these emissions substantially. Most countries tax gasoline (petrol) to finance highways and other public automotive transport services. However, few countries collect enough from drivers to pay the full social costs of automotive travel.

Appropriately designed road user charges should also reflect the peak-period costs of using congested road capacity (Cameron 1994). Congestion costs, in the form of time delays, accidents, excess fuel costs and pollution, are an increasingly serious urban problem in developed and developing countries. In the United States, the cost of time delays alone has been estimated to be \$50 billion a year (Repetto, Dower, Jenkins and Geoghegan 1992). User charges set at an appropriate level could lead to a change in the allocation of resources to the transport task and, coincidentally, may also lead to a

reduction in greenhouse gas emissions assuming that such charges could be collected cost effectively.

11.3.1.5 Agriculture and Forestry

Distortions in agriculture and forestry are common. As already noted, government subsidies and tax policies have encouraged deforestation in the Amazon (see Binswanger 1989; Mahar 1988). But the distortions in agriculture go further than this. The external environmental costs of wood harvesting, including loss of soil cover and fertility, are substantial (Newcombe 1989), and yet user charges for rights to harvest timber on public lands typically do not even cover the replacement costs of the wood. In many countries, land must be cleared to gain land rights (Pearce and Warford 1993). In sub-Saharan Africa, farmers and nomads carry extra cattle as an insurance against droughts and as an asset. Herd size may also be taken as a measure of status. Herds are therefore larger than they would be if capital and insurance markets were fully developed (Dasgupta and Mäler 1994).

Underpricing of water in agriculture leads to inefficiency in water use, excessive expenditure on irrigation, and a variety of local environmental and social costs, including soil waterlogging and salinisation and the degradation of riverine and estuarine environments. Irrigation charges in a sample of six developing countries covered only 1–23 per cent of storage and conveyance costs during the 1980s. Charges for federally supplied irrigation water in the United States cover only 5–20 per cent of these costs (Repetto 1986). These charges fail to reflect the marginal opportunity cost of water in alternative urban and industrial uses, which is typically an order of magnitude higher than its value in agriculture (Stavins 1983). When irrigation water is underpriced, farmers grow more rice than they otherwise would, even in the semi-arid areas of Egypt, India, Pakistan, China and the United States. These practices increase methane emissions (Ranganathan, Neue and Pingali 1994). Proper pricing for water could well generate global benefits as well as significant domestic gains.

11.3.1.6 Policies affecting Adaptation

The net adverse effects of climate change will depend not only on the extent of climate change, but also on the extent to which economies successfully adapt to any change. Some existing policies may mitigate against adaptation or increase the vulnerability of some sectors of the economy to climate change. For example, subsidised drought or flood insurance may encourage investment in high risk areas and reduce incentives for self-reliance. Similarly, some agricultural support policies might discourage farmers from shifting to enterprises and production systems better suited to an altered climate.

11.3.2 Revenue Recycling

The abatement achieved by a carbon tax, and the effect of the tax on an economy, will depend on what is done with the tax revenue. Likewise, a tradable permit scheme can raise the same government revenue as a carbon tax if the government auctions the permits and the impact of such a scheme on the economy will depend to some extent on what is done with the revenue. The direct impact on government revenue of the two policies can be made equivalent across a variety of cases. No direct impact on government revenue would occur if permits were grandfathered (that is, allocated on the basis of some historical record) or tax revenue redistributed to emitters. Intermediate cases would be represented by partial grandfathering or partial redistribution of revenue to emitters. Thus, in principle, the same revenue recycling issues apply regardless of whether a tax or tradable permit scheme is used (Bohm 1994b), although taxes have been studied in more detail in the literature.

There is widespread agreement that revenue recycling can significantly lower the costs of a carbon tax (Koopmans, Mors, and Scherp 1992; Schackleton et al. 1992; Goulder 1992, 1993, 1995; Bovenberg and de Mooij 1994; European Commission 1994; Jorgenson and Wilcoxon 1994). Some researchers have suggested, further, that all of the

¹⁰ For a comprehensive coverage of discount and social time preference rates see chapter 4 of this report.

abatement costs associated with a carbon tax can be eliminated through revenue recycling in the form of cuts in income taxes or taxes on payrolls. However, at least in the case of cuts in income taxes, research by Goulder (1992, 1993, 1995) and related theoretical work by Bovenberg and de Mooij (1994) rejects this stronger claim. Their work indicates that recycling revenues through income tax cuts only partly offsets the total general equilibrium abatement costs implied by a carbon tax (also see chapters 8 and 9 of this report).

None of the above research denies the possibility that a carbon tax or revenue from a permit scheme may increase national income when combined with reductions in a particularly burdensome existing tax. In any event, such a result is an argument for reform of the taxation system rather than for the introduction of a carbon tax or permit scheme. It may be that some tax other than a carbon tax could result in a greater efficiency gain in raising public revenue. If there are efficiency arguments for a carbon tax or tradable permit scheme and reform of the tax system, then both changes should be introduced.

11.3.3 The Broad Context for Climate Change Policies

11.3.3.1 'No Regrets' Policies

Policies or policy reforms which improve the efficiency of an economy while also reducing greenhouse gas emissions have sometimes been described as 'no regrets' policies because their adoption could not be 'regretted' even if climate change were later shown not to be detrimental (also see chapters 8 and 9 of this report).

Of course, the reduction of virtually any distortion is to be encouraged, provided equity concerns can be safeguarded. Policy reforms which help in this regard are therefore also to be welcomed, whatever the consequences for climate change. If greenhouse gas emissions are reduced in addition then extra potential gains exist. But even where this is not so, the removal of distortions can lead to greater economic welfare. In general, such policies should not be linked directly to climate change policy. However, their significance for climate change policy needs to be recognised and the prospects of 'double dividends' from carbon taxes or tradable permit systems can give the extra political impetus needed to reduce existing distortions. These policies will influence both the 'business-as-usual' emissions scenario and the effectiveness of any climate change policy.

While there may be political advantages (particularly in terms of providing impetus for reform) in linking so-called 'no regrets' policies to climate change policy, such linkage may serve to confuse the policy debate. For example, the observation that a carbon tax (or auctioned tradable permits) may increase national income when combined with a tax reform is really an observation that the structure of taxation could be improved. A carbon tax is not the only device available for improving public finance, and indeed it may not be the best device available; it is possible that a different tax could improve the efficiency of raising public finance by more than a carbon tax. What this means is that the merits of a carbon tax will depend on whether the tax is evaluated taking all other existing policies as given, or whether it is instead evaluated against the background of a (second-best) efficient tax regime. Put differently, estimates of the full consequences of a carbon tax must take account of how the revenues are to be employed.

It is not, however, obvious how a carbon tax should be evaluated. If the tax is evaluated against the background of a (second-best) efficient tax regime, and yet the actual tax regime is different, then the evaluation could lead to inappropriate public policy. A better approach would be to demonstrate how the performance of a carbon tax (reflecting both the emissions and level of economic activity associated with the tax) depends on the policy context, including the regime for raising public finance and the presence of distortions in energy pricing.

11.3.3.2 Adaptation Policies

It is important to draw a clear distinction between the costs and benefits of actions taken to reduce the impacts of climate change itself and the costs and benefits of actions taken to reduce emissions. The first reduces the potential damage caused by climate change directly while the second has the effect of reducing emissions of greenhouse gases now, which, in turn, will have an impact on future climate. Examples of adaptation include such actions as increasing irrigation water availability in regions where the climate has become drier, improving refrigeration to offset the effects of a warmer climate and relocating economic activities away from the coast where sea levels have risen. Measuring the cost of adaptation is somewhat problematic given that both ecosystems and economic systems are changing all the time and will adapt autonomously, to some extent, to climate change.

The term 'adaptation' may be confusing because actions falling into this category can be counted as a cost of climate change. To see why adaptation can yield a net benefit, consider the problem of estimating the costs of climate change. An estimate might be obtained assuming that there will be no adaptation—that is, if sea level rises by one meter, all shoreline property less than a meter above sea level will be lost. Alternatively, it might be assumed that there will be some adaptation—that dykes might be built for example. The latter response is indeed a cost of climate change; it would not need to be taken in the absence of climate change. However, the response may reduce the damage associated with climate change. If the reduction in such damage exceeds the costs of adapting, then adaptation should be undertaken (Fankhauser 1993).

Unlike the case of abatement of greenhouse gases, adaptation typically involves private goods. If the climate were to become drier, a demand would be created for drought-resistant crop varieties, and the firms that developed these would be rewarded by the market. If climate were to become more variable, then individuals would seek to insure themselves against such changes. Such responses belong in the realm of the private sector. However, even when dealing with strictly private goods there may be a role for the state. Dasgupta (1993), for example, argues that some assistance should be given to the assetless in developing countries who are not able to command sufficient purchasing power to convert their potential labour power into actual labour power. Such assistance, perhaps in the form of agrarian reform, not only redistributes income but results in an increase in the rate of growth of aggregate incomes. Although such policies are already needed in some countries, the need for them may be increased in the event of climate change.

However, the principal role for government in the context of adaptation is in supplying public goods. Public infrastructure projects such as building dykes or funding resettlement programs are cases in point as is the funding of public research and development of carbon free technologies where there would otherwise be strong free riding incentives. Furthermore, if there are risks of increased environmental hazards (drought, flood, fire, famine, pests) then greater hazards insurance is an appropriate defensive action. Another type of 'insurance' could be purchased by increasing public research expenditure. For example, increasing efforts in plant breeding in order to develop plant cultivars better adapted to new climatic conditions is one possible response.

Any adaptation policies should be designed in concert with mitigation policies. Both types of policies are aimed at minimising the expected damage from climate change. Adaptation will be undertaken up to the point where the damage avoided by an incremental increase in adaptation equals the associated incremental cost. Abatement will be undertaken up to the point where the reduction in damage effected by an incremental unit of abatement equals the incremental cost. However, the two types of policies are not entirely equivalent. First, the benefits of adaptation are likely to be felt much more quickly than the benefits of mitigation and second, some types of adaptation policies will not be subject to the same problems of free-riding (see section 11.6.5) as

abatement. For example, if a country defends its shoreline by building seawalls, its own population, in most cases, will receive all of the benefits. This is not true of unilateral abatement.

11.4 Regulations, Voluntary Agreements and other Non-Market-Based Instruments

The conventional approach to environmental policy in many countries has employed policy instruments in the form of uniform standards (based on technology or performance) and direct government expenditures on projects that are designed to improve the environment (Baumol and Oates 1979; OECD 1989; Hahn and Stavins 1991). As with market-based incentives, the first of these strategies requires that polluters undertake pollution abatement activities, while under the second strategy the government itself expends resources on environmental quality. Both of these strategies figure prominently in current and proposed policy measures to address global climate change.¹¹ For the reasons already mentioned in section 11.2.2.1 the discussion of regulations is confined to their application in a domestic policy context.

11.4.1 Uniform Technology and Performance Standards

Uniform regulatory standards (often described as 'command-and-control' regulations) can be loosely categorised as being either *technology-based* or *performance-based*, although the distinction between these two categories of instruments is often unclear. Technology-based (or design) standards typically require the use of specified equipment, processes or procedures. In the context of climate change policy, there could be requirements that particular types of energy efficient motors, combustion processes, or landfill gas collection technologies be utilised by firms.

Performance-based standards are relatively more flexible than technology-based standards, specifying allowable levels of pollutant emissions or polluting activities, but leaving the specific methods of achieving those levels up to the regulated entities. Examples of performance standards for greenhouse gas abatement include minimum levels of energy efficiency for appliances, maximum allowable levels of carbon dioxide emissions from combustion, or maximum levels of methane emissions from landfills.

Uniform standards can also take the form of outright bans of certain products or processes, such as the banning of aerosol sprays containing ozone-depleting substances. Although bans may appear to be the strictest form of regulation, if low-cost substitutes for targeted products are available, bans may actually be a relatively cost-effective policy instrument. Moreover, bans or other more proactive design standards may make economies of scale in the production of substitutes materialise faster than through market mechanisms by themselves (Bohm and Russell 1985).

Although uniform technology and performance standards may be effective in achieving established environmental goals and standards, they typically tend to lead to economically inefficient outcomes in which firms use unduly expensive means to control pollution (Tietenberg 1985; Hahn 1989; Hahn and Stavins 1991). Because the costs of controlling pollution vary greatly among and even within firms, any given aggregate pollution control level can be met at minimum aggregate control cost only if pollution sources control at the same *marginal cost*, as opposed to the same *emission level*. Indeed, depending on the age and location of emission sources and available technologies, the cost of controlling a unit of a given pollutant may vary by a factor of a 100 or more among sources (Crandall 1984). Nonetheless, because performance standards give economic agents additional flexibility to make choices based on economic criteria, performance-based standards will generally be more cost effective

¹¹ In the case of the United States, for example, see: US Environmental Protection Agency (1989); National Academy of Sciences (1992); Clinton and Gore (1993).

than technology-based standards. On the other hand, if there is essentially only a single means of achieving a particular performance standard, a technology-based standard may conserve on information and administration costs.

In theory, the government could achieve a cost-effective allocation of pollution control responsibility among sources if it assigned source-specific control levels that equated the marginal costs of control across sources. This approach would, however, require detailed information on the pollution control cost functions of individual firms and sources — data that governments usually lack and could obtain only at great cost, if at all. Although they are not typically designed to address the cost-effectiveness issue, source-specific or firm-specific permit programs are one approach traditionally taken to adjust regulatory standards to individual circumstances. If pollutants exhibit highly localised effects, such an approach may have distinct advantages over a tax or permit system. Global climate change is not, however, a localised problem; a unit of greenhouse gas emission will have roughly the same impacts regardless of where it is emitted.

Even if the government were able to use conventional technology and uniform performance standards to achieve a cost-effective allocation of pollution control at present, such standards would not necessarily provide continuous *dynamic* incentives for the development, adoption and diffusion of environmentally and economically superior control technologies (Bohm and Russell 1985; Jaffe and Stavins 1994d).

All forms of intervention have the potential for inducing or forcing some amount of technological change, because, by their very nature, they induce or require firms to do things they would not otherwise do. Performance and technology standards can be explicitly designed to be 'technology forcing', mandating performance levels that are not currently viewed as technologically feasible or mandating technologies that are not fully developed (Jochem and Gruber 1990). The problem with this approach, however, is that while regulators can typically assume that *some* amount of improvement over existing technology will always be feasible, it is impossible to know just how much. Standards must either be made unambitious, or else run the risk of being ultimately unachievable, leading to political and economic disruption (Freeman and Haveman 1971). Another difficulty with a regulatory approach to environmental protection is that the regulatory agency may, over time, develop such a close working relationship with the regulated industry that it relaxes its enforcement standards in the interests of the industry itself. This phenomenon is sometimes referred to as 'regulatory capture'.

Once a performance standard has been satisfied, there is little benefit to the individual firm from developing and/or adopting even cleaner technology. In addition, regulated firms may fear that if they do develop a cleaner technology, the performance standard will be tightened. Technology standards are even worse than performance standards in inhibiting innovation, since, by their very nature, they constrain the technological choices available, and may thereby remove all incentives to develop new technologies that are environmentally beneficial (Magat 1979). As an example, when vehicle emissions standards requiring the use of catalytic converters were adopted by the European Union,¹² incentives to develop lean burn engines were reduced. This disincentive occurred because these technologies are presently incompatible, at least in the sense that a lean burn engine cannot be fitted with a 3-way catalytic converter.¹³ Lean burn technology (with 2-way converters) is now available which is capable of meeting Japanese and European standards. However, this technology is not presently able to meet the United States' emissions standards or the stricter standards expected to

¹² This is no longer the case even in Europe which now has performance based standards as in the United States and Japan.

¹³ These technologies remain incompatible because of the stringent requirements with respect to NO_x control.

emerge in the near future.¹⁴ However, lean burn remains an important and developing approach. Not only does it have the potential advantage of reducing CO₂ emissions significantly,¹⁵ but also offers the prospect of reducing other emissions more effectively over the lifetime of the automobile.¹⁶

Under some circumstances, however, a performance standard may provide greater incentives for technological adoption than a marketable permit system (Malueg 1990). There are better and worse ways of establishing performance standards. To take an example, the Corporate Average Fuel Economy (CAFE) standards in the United States are applied to the fleet average of every manufacturer and importer. CAFE may thus be binding on a manufacturer which sells many larger cars as well as some small cars, but not on a manufacturer which sells only small cars. The problem here is that the former manufacturer may sell small cars which are more energy efficient than the latter manufacturer. In other words, the innovation and manufacture of more efficient automobiles may not be rewarded by these standards. If CAFE differentiated the standards according to the market segment of each vehicle (sub-compact, compact, mid-size, etc), then firms which sold vehicles which were more efficient for their class than required by the standard would be rewarded by not having to pay the penalty for which the manufacturers of less efficient cars were liable. Better still, if manufacturers were allowed to trade in energy efficiency credits, then even the manufacturer of the most efficient cars would have a continuous incentive to develop even more energy efficient cars. Finally, a tax on petrol/gasoline would not only provide incentives for the manufacture of more fuel-efficient cars, but would also provide incentives for vehicle owners to reduce their fuel consumption.

As with virtually all policy instruments, the administration of uniform standards typically includes programs for compliance monitoring and enforcement. Although

¹⁴ Currently there are 'lean burn' Japanese made vehicles, which can meet current Japanese standards and are also available on the European market (Watson Melb. Univ. pers. com. 1994). Lower temperatures obtainable in lean burn combustion reduce NO_x production but imply less complete combustion of hydrocarbons forcing a continued reliance on at least 2-way catalytic converters. These vehicles therefore also incorporate 2-way catalysts (that control hydrocarbons and carbon monoxide) with NO_x control being left to careful engine management and exhaust gas recirculation. However, no production vehicles using lean burn technology are able to meet the current US (Californian) emissions standards over the useful life of the vehicle (80 000 km). Furthermore, while the Californian standards are currently the most stringent, future standards in OECD countries are expected to tighten compared with current levels.

¹⁵ Lean burn engines are potentially more fuel efficient since by definition they use less fuel in the air/fuel mix. A recently cited case is a 10 per cent improvement in fuel efficiency due to Toyota's particular lean burn control system with 2-way converter (Watson 1994). Such an improvement in fuel efficiency would require incomplete offset by other effects of lean burn such as lower temperatures of operation and less smooth running in the absence of more sophisticated engine control technologies. Any disincentive to the technological development of lean burn engines is of particular concern in the context of reducing carbon dioxide emissions from conventionally fuelled cars since vehicle-based, 'engineering' advances in this respect depend essentially on improving fuel efficiencies.

¹⁶ Further, lean burn technologies have the potential to reduce toxic emissions more effectively over the lifetime of the automobile in that they are a durable technology compared with currently available catalytic converters which are constructed with an expected lifetime which is that of the US car (50 000 miles or 80 000 km.). However, many cars in fact have lifetimes well in excess of this—for example, the Australian experience is 240 000 km. The resulting number of older cars with malfunctioning converters is a concern since even a relatively few such cars may be major sources of toxic emissions.

technology-based standards may seem to be the least cost-effective of the policy instruments, if monitoring costs are high in some particular circumstances they may have an advantage because they are relatively easy to monitor and enforce. An inspector can simply check whether a particular piece of equipment has been installed, rather than continuously monitoring information on emission levels. Performance standards, in general, and pollution charges and marketable permits for non-carbon greenhouse gas emissions all require more detailed monitoring systems, which can suffer from the following problems: (a) once emissions leave the source they are usually lost to measurement; (b) emissions may be random, rather than fixed values, and may vary depending on equipment breakdowns, shifts in product mix and input quality, or changes in production levels; (c) monitoring instruments may be imprecise; and (d) unless monitoring is continuous, polluters may adjust emissions up or down according to the likelihood of inspections (Beavis and Walker 1983).¹⁷

11.4.2 Government Investment

Direct government expenditures also play a major role in both current and prospective environmental programs in many countries. Such government activities include projects to: (a) prevent, mitigate, or adapt to changes in environmental quality; (b) disseminate information; (c) conduct research; and (d) educate specialists and the general public (Baumol and Oates 1975). Government purchasing policies may also be used in some instances to attempt to achieve secondary goals such as influencing environmental quality. Many environmental ends that could be achieved through incentive-based policy instruments or uniform standards can also be met directly through government-funded projects or programs.

The two primary economic rationales for the inclusion of direct government investment in an effective overall government policy are the public good character of many environmental services and the possibility of economies of scale. Public goods arguments for direct government expenditure to disseminate information, conduct research and sponsor education programs are common in debates about climate change policy. Indeed, the potential role for government research and information provision regarding energy efficient technologies is particularly prominent in the climate change context (Jaffe and Stavins 1994d). Proposed methods for addressing climate change through climatic engineering or 'geoengineering' options are also likely to require direct government involvement but at this stage far more research needs to be conducted before such options could be contemplated. For details of some suggested approaches see Nordhaus (1991), National Academy of Sciences (1992), US Environmental Protection Agency (1992), National Academy of Sciences (1992) and Clinton and Gore (1993).

Government or institutional investment at the international level also has a part to play in mitigating climate change. For example, the Global Environment Fund's portfolio on renewable energy includes support for promising backstop technologies such as gasification of woody and crop residue coupled with advanced gas turbines in Brazil and anaerobic digestion of organic residues from agriculture and urban households in India and Pakistan (World Bank 1993).

11.4.3 Voluntary Agreements

Beyond mandatory policy instruments, voluntary agreements can also play a role in an overall greenhouse gas reduction strategy. The threat of mandatory government intervention may be enough to encourage voluntary agreements. Forward-looking firms may undertake some, albeit limited, steps in controlling greenhouse gas emissions if they fear more costly mandatory controls in the absence of these voluntary reductions.

¹⁷ For discussions of relevant enforcement issues see, for example: Harford (1978); Shibata and Winrich (1983); Polinsky and Shavell (1979).

This could explain why voluntary agreements have arisen in some cases in domestic energy management.¹⁸ The vast majority of greenhouse gas reductions from the actions announced or expanded through the US *Climate Change Action Plan* (Clinton and Gore 1993) come from voluntary initiatives aimed at increasing the energy efficiency of the industrial, commercial, residential and transport sectors.

11.4.4 Demand Side Management

Demand side management may be defined as an attempt by an electricity utility to alter the characteristics of its demand profile for energy services. Demand side management may alter the quantity of electricity supplied, the timing of the use and the quality of supply (voltage variability and the interruptibility of supply). There is an extensive literature on demand management (Katz 1992; Kahn 1992; Hirst 1993; Joskow and Marron 1993) as a means of reducing capital costs for utilities. The impact of demand side management on operating costs and emissions has not been studied as closely. The most widely recognised form of demand side management is where utilities attempt to limit the growth in demand for electricity.

It is difficult to offer an economic rationale for why electricity utilities would want to limit the growth in demand without taking account of the regulatory environment in many countries. It would be in the self-interest of a utility to slow the growth in demand if, at the margin, the cost of reducing demand by an additional kilowatt (a so-called 'negawatt') was less than the net profit from selling an additional kilowatt. It is clear that such a relationship could hold only if the net profit from selling an additional kilowatt were negative. The simplest and most efficient way to reduce the growth in demand is likely to be to raise price but this may be difficult because of regulatory or political obstacles. An economic rationale for involvement of utilities in the types of programs regarded as demand side management can be made only if price is regulated to a level below marginal cost. Some of the regulatory pressures applied to utilities to adopt such programs can also be regarded as disguised environmental impact taxes (Sioshansi 1992).

The types of programs regarded as demand side management include provision of information about energy efficiency and subsidies for the adoption of energy efficient equipment. Thus, utilities sometimes attempt to promote the types of policies that might be regarded as no regrets as discussed earlier in the chapter. It was also noted earlier that electricity prices in some countries are regulated at levels below long run marginal costs. It may be more cost-effective to increase electricity prices up to long run marginal cost than have utilities involved in demand side management programs. Higher electricity prices would increase the incentive for consumers to search for and adopt more energy efficient technologies, perhaps reducing the scope for apparent no regrets options.

Load smoothing is also usually defined by utilities as demand side management. It is well known that there are distinct daily and seasonal peaks and troughs in the pattern of electricity demand. Time varying prices are used by utilities to attempt to shift demand to clip peaks and fill troughs. Such time varying prices are a straightforward application of marginal cost pricing since marginal generating and distribution costs increase with load. Transactions costs mainly in the form of metering and billing costs limit the extent to which time varying prices can be applied to residential consumers. Since load smoothing improves utilisation of generating capacity, load smoothing reduces emissions required to produce a given electricity output over a day.

¹⁸ See, for example, the experience of the Netherlands cited in Lenstra and Bonney (1994).

11.4.5 Distributional Impacts

Any greenhouse policy will have distributional effects on firms and households. Regulations impose quantity limits on the use of particular inputs or outputs in production and consumption activities. The direct cost of regulation is the reduction in profits and consumer welfare due to the regulatory constraint on choice. The distribution of this cost is often hidden, but that does not make it unimportant. For example, poorer households tend to own appliances which are cheaper to purchase but more costly to run. That is, poorer households tend to make appliance purchasing decisions reflecting higher effective individual discount rates (Hausman, 1979). A regulation which required that all households purchase more efficient appliances would thus fall disproportionately on the poor, even though by outward appearances it might seem not to. To the extent that regulation is not a least cost option to control greenhouse emissions, the excess burden it implies must also be distributed. Notably, though, in contrast with a system that taxes all emissions, with quantity limits—whether in the form of conventional regulations or tradable permits systems—individual emitters do not face an environmental cost for emissions which are less than the limit.

While the initial incidence of a greenhouse regulation will fall on greenhouse-intensive energy users, the final incidence will depend on the ability of firms to pass the costs of the regulation to others through higher prices for goods and services, and these distributive impacts are likely to differ over time. For example, the long run incidence of greenhouse pollution controls applied progressively to newer cars might be regressive as low income earners face substantial increases in used car costs, although in the short run low income earners might gain a relatively larger capital reward on selling their cars (Tietenberg 1992). Where the costs of regulation are regressive (costs fall disproportionately on the poor), compensatory transfers may be used, funded from a specific tax or general government finances, or the regulation might be modified, exempting some individuals from the regulatory net.

To date, most applied economics research on potential greenhouse policy responses has concentrated on analysing the overall costs and incidence of market-based instruments. Multicountry and national studies on the economic impacts of regulatory measures are needed. Researchers may need to give more emphasis to incorporating real world conditions in these models, such as uncertainty and asymmetric information in energy markets. This would allow for any differences in the informational role of price and quantity controls (and policy mixes) in determining the size and distribution of greenhouse control costs.

11.5 Market-Based Policy Instruments

Because of the considerable potential costs of meeting greenhouse gas emission targets, one of the central issues for Parties to the Framework Convention is to identify least cost measures, that is, policies which minimise the costs of achieving a given greenhouse gas emissions target. In this section attention is focused on emissions taxes and tradable quotas and permits, the two core market-based instruments which directly target least cost measures to meet greenhouse gas emissions targets. Mention is also made of joint implementation, an instrument which can facilitate technology transfer and amounts to bilateral 'trades' in emissions.

There is an extensive literature on the principles underlying the use of market-based policy instruments for greenhouse management—for example, see Bohm and Russell (1985); Baumol and Oates (1988); Stavins (1988); OECD (1989, 1993); Tietenberg (1990); Epstein and Gupta (1990); Dornbush and Poterba (1991); Stavins (1991); Bureau of Industry Economics (1992); Cropper and Oates (1992); IIASA (1992a,b); Pillet, Hediger, Kyrcas and Corbaz (1993); Hahn and Stavins (1993). For a summary and assessment of the cost and environmental effectiveness of emissions taxes and tradable quotas in national applications see Howe (1994).

In a perfectly competitive market place, under an emissions tax or tradable quota scheme emitters would reduce emissions up to the point where the marginal cost of control equals the emissions tax rate or the equilibrium price of an emissions quota. Both instruments would promote dynamic efficiency (cost minimisation over the long term when factors of production are variable and technological change may be stimulated) as each provides a continuous incentive for research and development in emissions abatement technologies to avoid the tax or quota purchases. Under competitive markets and certainty, an emissions tax is identical to a tradable emissions quota scheme in which quota rights are auctioned and revenues are redistributed in the same way (Rajah and Smith 1993).

11.5.1 Domestic Carbon Taxes

With market-based policies, there can be incentives to reduce greenhouse emissions through the development and use of new technologies and by making changes to existing production and consumption practises. The aim in using an emissions tax (a tax per unit of emissions) is to minimise the total economic costs of achieving a given emissions target. In principle, both static and dynamic efficiency gains can be fostered under an emissions tax. Static (dynamic) efficiency gains arise where emitters face different opportunities for emission control (have different marginal abatement cost curves) in the short (long) run when factors of production and technological opportunities are largely fixed (vary endogenously).

Most research has focused on a tax on the carbon content of primary fossil fuels consumed as the most practicable base for greenhouse emissions (Pearce 1991; Boco, Clark and Winters 1991; Jorgenson and Wilcoxon 1992; Repetto, Dower, Jenkins and Geoghegan 1992; Dower and Zimmerman 1992; OECD 1992a, 1993; Jones and Tobler 1993; Pillet et al. 1993; Boyd, Krutilla and Viscusi 1994). A carbon tax is a tax on the carbon content of fossil fuels consumed. A carbon tax is not a perfect proxy for a tax on CO₂ emissions. For example, a carbon tax on fossil fuels provides an incentive to reduce the use of carbon based fuels, but not to reduce CO₂ emissions by such means as capture (fixation) and disposal of the emissions at source (on carbon removal see Section 11.5.1.1). There may also be, due to leakage or incomplete combustion, emissions of other carbon compounds which differ from CO₂ in their greenhouse effects (notably methane). In addition, consistent accounting would need to apply to domestic emissions resulting from the processing of fuels from one energy form to another (such as in electricity generation).

There is a variety of points in the 'product cycle' for fossil fuels at which a carbon tax could be applied from production of fuels to their end use. End use is obviously the point at which emissions occur; but monitoring points covered under the policy would be fewest, and hence implementation costs lowest, if carbon contents were measured and policy applied to wholesale use.

A carbon tax is a more efficient instrument for reducing energy sector CO₂ emissions than taxes levied on some other basis, such as energy content of fuels or the value of energy products (ad valorem energy tax). For example, model simulations of the US economy indicate that an energy tax could be between 20 and 40 per cent more costly, and an *ad valorem* tax two to three-times more costly, than a carbon tax for equivalent reductions in emissions (Scheraga and Leary 1992; Jorgenson and Wilcoxon 1992). The reason for this is that an energy tax raises the price of all forms of energy, whether or not they contribute to CO₂ emissions, and would make it more costly to substitute lower emitting or non-emitting energy sources for high emitting energy sources. As a corollary, a combined carbon/energy tax would be less efficient and more costly than a pure carbon tax, due to its energy tax component.

11.5.1.1 Related Instruments – Deposit Refund Systems for Carbon Removal

A deposit refund system can take one of several forms: a tax (deposit) on a commodity followed by a subsidy of the socially least-cost disposal option (a refund); mandated deposits requiring private sellers of a commodity to add to the price a deposit that will be refunded under certain conditions; or a performance bond requiring an agent that engages in certain (production) activities to avoid certain negative consequences of these activities. For surveys of current use of deposit refund systems and descriptions of potential new areas of applications, see: Bohm (1981); Hahn (1988); Russell (1988); Stavins (1988); OECD (1989); Anderson, Hofmann and Rusin (1990); Hahn and Stavins (1991); Sigman (1991); Stavins (1991); US Environmental Protection Agency (1991).

For a deposit refund system to be a feasible means of encouraging carbon fixation, there must exist alternative actions that decision makers can take to avoid creating the environmental externality in question. This could be a choice between controlling emissions at source and 'end of pipe' emissions removal.

Currently, potential emitters of CO₂ — purchasers of fossil fuels for combustion, for example — do not have available to them the option of choosing to remove the carbon from emissions.¹⁹ On the other hand, new techniques for carbon removal (from stack gases, in particular) may eventually become economically feasible. (In 1993 Japan's Ministry of Trade and Industry launched a project on CO₂ fixation — see MITI 1993.) When and if this happens, incentives will exist to choose carbon removal when this is less expensive than reducing fossil fuel combustion through improvements in energy generation or use efficiency. This would open up the possibility of applying the deposit refund concept to CO₂ emission reduction.

This suggests that it is important, in the meantime, to maintain appropriate incentives for research and development of technologies that can eventually provide cost effective options for carbon removal. The appropriate incentive will exist if (future) carbon removal is known to be subsidised at a level equal to the (tax, tradable quota, or shadow) cost of carbon emissions.²⁰

Thus, it may be possible to introduce clauses into a future climate change protocol that would validate subtractions of carbon removal from emissions. This would, in effect, be equivalent to creating an international deposit refund system — a tax/subsidy scheme — where nations would be credited for certified carbon removal (estimated carbon emission avoided) by equally large additions to their emission quotas. These quotas would be measured by the carbon contents of fossil fuel use, equal to production plus imports minus exports. Moreover, if fossil fuel use is taxed domestically (directly or indirectly through a tradable permit system), and carbon removed is subsidised (credited by a refund of the deposit, equal to the tax), the resulting policy package will be an international deposit refund system.²¹

¹⁹ It is precisely for this reason that a carbon tax (with relatively low monitoring costs) is feasible, by contrast with a true CO₂ emissions tax, which would obviously be extremely costly to monitor and enforce. (Compare this with the case of sulphur dioxide (SO₂), for which a sulphur content tax on coal would be problematic, since it would fail to provide incentives for flue gas desulphurisation (scrubbing) even when this would be the cost effective route to reducing SO₂ emissions.)

²⁰ An option of this kind was used to some extent in the Montreal Protocol (Article 1.5). For an analysis of the cost-effective attributes of the Protocol see Bohm (1990).

²¹ In addition, uses of fossil fuels for purposes other than combustion, for example as chemical feedstocks, could be subjected to similar deposit refund treatment to 'keep the prices right'. Likewise, products such as lubrication oil could be subjected to the carbon tax while waste lubrication oil would be entitled to a tax refund if returned for oil recovery or disposal other than by incineration (Bohm 1981).

Other greenhouse gases, such as CFCs, that could be recovered when servicing cooling equipment such as refrigerators or air conditioners, could be made subject to a system with general deposits (taxes) on CFCs and a refund when and if CFCs are recovered, provided that the transactions costs of such a system are not prohibitively high (Stavins 1988; Miller and Mintzer 1986). Obviously, if CFCs are successfully phased out in the near future, the role of policy instruments such as deposit refund systems to control CFC emissions will be very limited. Still, the problem mentioned above concerning CFC contents in discarded cooling equipment, which may be present for some twenty years after the phase-out of new production using CFCs, may be significant enough to justify the use of a CFC deposit refund system (Bohm 1981, 1990). Note, however, that for products containing CFCs that already have been purchased by final users, the deposit refund system will be one with zero deposits and a positive subsidy. In other words, it will collapse into a pure subsidy system. Then, one of the advantages of deposit refund systems, that ordinary taxes are not required for financing the refund/subsidy incentive, would no longer hold.

11.5.2 Tradable Permits

A powerful theoretical feature of a perfectly competitive tradable domestic permit scheme is that, no matter what the initial permit allocation, equilibrium permit prices will be the same and the final allocation after domestic trade will be the one that minimises the cost of reducing emissions. Firms will want to buy permits if abatement costs exceed the permit price and sell permits in the opposite case. In this way, trade will continue until all firms are indifferent between buying and selling permits — that is, between marginal abatement and additional fossil fuel use. When this state is reached, an ex post allocation of permits that minimises the costs of reducing emissions has also been reached.²²

An international tradable quota scheme could coexist with domestic permit schemes within each country or particular countries may choose to meet their emission targets by some other means, such as using taxes or regulatory systems. In the case of a domestic tradable permit scheme, a national government would issue (time-limited) emissions permits to wholesale dealers in fossil fuel or producers and importers of fossil fuel and allow them to trade on a domestic permit market. The government could also allow permit holders to trade directly on an existing international market. Alternatively, to the extent that both international quota and domestic permit markets existed for a particular country, the government could trade on the international market and set a definite or preliminary domestic limit on the volume of domestic permits for some period ahead.

A government may choose one of two main ways to distribute permits to individual firms. In the first case firms would be given shares of the total permit volume based on some historical record ('grandfathering') such as their recent fossil fuel sales. The second alternative would be for the government to auction permits. Some combination of these two approaches may also be feasible.

The two approaches differ primarily in two respects. First, grandfathering implies a 'transfer' of wealth, equal to the value of the permits, to existing firms, whereas, in the latter case, it is this wealth that is transferred to the government. The government would then collect revenue similar to that from a domestic tax producing the same volume of

²² In a static model with fixed prices and neglecting the public goods aspect of abatement, transfers have purely distributional effects. However, this is not the case where economies are growing and production technology differs across countries in the sense that different quantities of capital and emissions are required to produce a given output of consumption or capital goods. In this case transfers make it possible to raise the growth rate of an economy above the maximum determined by its original productive capacity. This is illustrated by Hinchy and Hanslow (1994) using an *n*-country generalisation of a model studied by Tahvonen and Kuuluvainen (1993).

emissions. As with tax receipts, auction revenues could be used to reduce pre-existing distorting taxes as outlined in Section 11.3. In addition, grandfathering improves the wealth of incumbent firms and, given uncertainty, may keep them in business longer than otherwise. If so grandfathering may reduce the rate of entry of new firms and slow technological change (Bohm 1994b).

By contrast with international tradable quota systems which have so far been applied on a small scale only (for example, under the Montreal Protocol for international CFC production quota trade and for CFC consumption quota trade within the European Union), there is considerable experience with the use of tradable permit schemes within countries (see OECD 1992b; UNCTAD 1992). In most of these applications, permits have been allocated by grandfathering. Many of these applications have been designed to deal with local air pollution problems and, as a consequence, the permit markets have often been relatively small and far from perfect. This contrasts with the case of a tradable carbon permit system which would be nationwide. The contrast would be even more stark for an international scheme involving many governments and possibly large firms as well.

11.5.3 International Carbon Taxes

International action would be required to meet a global emissions target. One possibility is that a carbon tax could be imposed on nation states themselves by an international agency. In this case, the agreement would not only specify tax rate(s) but also a formula for reallocating the revenues from the tax. Cost-effectiveness would demand that the tax rate be uniform across all countries (assuming full participation), but the reallocation of revenues would not have a direct bearing on cost-effectiveness. As an alternative, the agreement could stipulate that all countries should levy the same domestic carbon tax, so-called harmonised domestic carbon taxes. In both cases, some experimentation would be required with the tax rate because it would only be by trial and error that the tax rate that achieved the coalition's emissions target was struck. The tax rate would also need to be adjusted over time as economic conditions changed and as more scientific information became available.

Requiring that tax rates be uniform is required for reasons of cost-effectiveness. But the resulting distribution of costs may not conform to principles of equity and justice. For this reason, transfers of resources may be required. In principle, the two versions of an international tax agreement could involve the same actual financial transfers, although the transfer principles may differ. Under the harmonised tax system, the agreement could involve fixed lump-sum payments from rich to poor countries, whereas under the first-mentioned international tax system, the agreement could specify what shares of the total international tax revenues would go to each participating country (Hoel 1993). (In a tradable quota system, the financial transfers could again, in principle, be the same, but would then be represented by sales of time-limited quotas by poor countries and quota purchases by rich countries.)

11.5.4 Tradable Quotas

Under an international tradable emissions quota scheme all coalition countries would be allocated a quota for emissions (for whatever emission is being controlled). A quota could define a right to either repeated emissions (for example, one tonne of carbon per year over the indefinite future) or a right to emit a given volume once only. Thus a quota system could comprise either 'eternal' quotas of the first type or a series of 'non-eternal' quotas (for example, quotas for five-year periods) or some combination of both. In the case of either type of quota, emission rights could be 'banked'. In other words, any unused right to emit during a given year could be banked and used at a later time.

In each period, countries would be free to buy and sell quotas on an international exchange (on the spot or forward market) in order that neither buyer or seller need be

identified. Time limiting the quotas would probably be necessary not only to account for uncertainty about the extent of the enhanced greenhouse problem but also to give credibility to the system and, specifically, to avoid a situation where some present government sells quotas, that is, part of the nation's wealth, to an extent that would not be honoured by future governments in the country. Time-limited quotas would also reduce the risk of large countries gaining market power on the quota trade market or the need for measures to ensure that such market imperfections were avoided (such as limits to quota holdings).

An efficient international tradable quota system presupposes a market organisation for quota trade (see Sandor et al. 1994). In the case of a system for the control of emissions of CO₂, quotas would have to be denominated according to the carbon content of the fossil fuel used. If quotas were to be established for the full suite of greenhouse gases, it would be necessary to weight gases according to their estimated (and agreed) global warming potential. For any such scheme to be effective in controlling emissions, it is clear that there must be a reasonable probability of detecting and penalising those responsible for unauthorised emissions. This, however, does not distinguish a tradable quota system from any other international agreement on emission reductions. In what follows, the focus is on quota systems for carbon emissions only.

Negotiations on initial quota allocation are likely to be facilitated by reference to some criteria such as, GNP, real GNP, total population, adult population, land area, 'basic needs' defined by industry structure and/or local climate, dependence on fossil fuel production, etc. (for an overview, see UNCTAD 1992; also see Grubb and Sebenius 1991; Bertram 1992; Bohm and Larsen 1993; Hinchy, Thorpe and Fisher 1993). There are numerous other possibilities. Evaluations of proposed rules would need to take account of their international trade repercussions.

Each of the criteria will have adherents, largely those with larger allocations under that criterion.²³ Several criteria may need to be blended to create international consensus on emission allocations.²⁴ For example, it is clear that the developing countries have relatively little incentive to participate unless they see clear economic benefits from an agreement. At the same time, the wealthy countries will want to make sure their burdens are divided in ways that are perceived as equitable. Whatever the initial allocation, subsequent trading can lead to a cost-effective outcome.²⁵ This potential for pursuing distributional objectives while assuring cost-effectiveness is an important attribute of the tradable quota approach.²⁶

As compared to an international tax agreement, where the effect on emissions is uncertain while transfer payments (if lump sum) are known, the tradable quota system has a known effect on emissions but uncertain quota prices and, hence, uncertain distributional effects through quota trade. (This is true for fully global agreements; if

²³ For example, under an allocation system related to population levels, the big players in the market would likely be India and China, as permit sellers, and the United States and perhaps the former Soviet Union, as buyers. (See Epstein and Gupta 1990.)

²⁴ For example, the Canadians proposed using population and GNP combined as allocation criteria when CFC reduction obligations were being considered in the development of the Montreal Protocol.

²⁵ This is abstracting from the potential consequences of significant transactions costs.

²⁶ For a general discussion see Bohm (1992). 'Appropriate' initial allocations can serve as an effective device to draw countries — particularly, developing countries — into an international agreement. On this, see: Barrett (1992c); Hinchy, Hanslow and Fisher (1994a,b). Most proposals for allocating control obligations among nations call for proportionately higher rates of reduction in emissions by the industrialised countries (and, among the industrialised countries, by the United States) and substantial reductions in the predicted rates of increase in CO₂ emissions by most developing countries. See, for example: Krause (1989); Flavin (1989); Wirth and Lashof (1990).

only a limited set of countries is involved, carbon leakage must be taken into account in both cases.) This means that the benefits of known effects on emissions in a tradable quota system must be bought at the price of some distributional uncertainty. Thus, if a decision is taken that a poor country should be offered some minimum compensation, then initial quota allocations to that country would have to be increased as compared with the case under certainty. Alternatively, the agreement would have to include some co-insurance system.

Countries allocated quotas surplus to their emission requirements would be able to use the revenue from the sale of these surplus quotas to increase their imports relative to their exports (Chichilnisky, Heal and Starrett 1993). Countries allocated quotas less than their requirements would have to reduce imports relative to exports to pay for additional quotas. In this way a tradable quota scheme would tend to reallocate world production. The allocation of tax revenue from an international carbon tax scheme would have similar effects.

Providing large initial quotas to poor countries for compensatory reasons implies that they would be selling quotas primarily to rich countries. Since quota permit prices represent an implicit or explicit tax on all participating countries, the terms of trade within the coalition for countries with the same carbon intensities in production would remain unaffected. Given some tariff or other protection from competition from non-participating countries, when the agreement does not involve all countries, means that industrialisation in poor countries would not have been made more difficult, relatively speaking, aside from the inevitable consequences of reduced global fossil fuel use. In addition, reducing fossil fuel use would emerge as a potentially important 'export industry' for the poor countries. From a distributional point of view, the end result would be that poor countries would be perhaps fully compensated, whereas rich countries would have to pay, first, for their own emission reductions as called for by the quota price and, second, for carbon reductions imported through quota purchases from abroad.

11.5.5 Joint Implementation

Joint implementation, provided for by Article 4.2 (a) of the FCCC, involves cooperation between two countries, with one funding emission reduction in the other to help the first meet its reduction commitments.²⁷ The potential economic merits and demerits of joint implementation proposals have been widely discussed (Hanisch 1991; Hanisch, Pachauri, Schmitt and Vellinga 1992; Hanisch, Selrod, Torvanger and Aaheim 1993; Anderson 1993; Barrett 1993a, 1994d; Jones 1993; Johnson 1993; Parikh 1994a,b; Reddy 1993; Bohm 1993a, 1994a; Loske and Oberthür 1994; Jepma 1995). In essence, there are three potential roles for joint implementation: (a) as the first step toward establishing an international tradable quota system for greenhouse management among Parties that have made a firm commitment to limit their emissions; (b) as a cost-effective option for Annex-I Parties to fund emission reductions projects in non-Annex-I Parties (developing countries) that have made no such commitments; and (c) as an activity for exploring when it is cost effective to bring new emissions sources or sinks into an existing international greenhouse management scheme.

A system of joint implementation trades in carbon reduction projects could develop automatically into an international tradable carbon quota system for countries which have carbon targets (Bohm 1994a). Where aggregate targets exist, the joint level of aggregate carbon emissions reported is a sufficient monitoring statistic for the actual aggregate abatement levels undertaken by each country under a joint carbon reduction policy. Cost incentives are such that emission reductions below the target in one country, when less costly than in another country, would be purchased by, and credited

²⁷ For a comprehensive review of the legal and practical aspects of joint implementation see Kuik, Peters and Schrijver (1994).

to, the latter. In particular, when several countries committed to carbon targets trade in this fashion, the incremental costs of emissions reductions will tend to be equalised across economies. As a result, an international tradable quota scheme could be established once countries commit to binding targets, which would in effect then become their tradable quotas.

The literature on joint implementation has focused mainly on low-cost emission reduction projects in developing countries. Bohm (1994a) also considers the case of joint implementation between developed and developing countries, where only the former commit to binding targets while the latter do not. In the absence of binding targets in developing countries it would be difficult to determine the net emission reduction effects due to a specific joint implementation project, since nationwide indirect and direct effects on emissions must be counted (see Tietenberg and Victor 1994). The net emission reduction effects of low-cost abatement projects are particularly uncertain since such projects may be close to being profitable and hence may be carried out by the market itself in the near future. In addition to these systematic risks, there are incentives to misrepresent the effectiveness of projects. Parties to a joint implementation project may exaggerate the project's nationwide net emission reduction effects. A clearinghouse version of joint implementation trades between developed and developing countries would eliminate these incentives on the part of the buyer countries. The role of the clearinghouse would be to screen and aggregate all projects from potential sellers before they are offered as anonymous carbon credits to buyers at a market clearing price.

Another potential role for joint implementation is as a complementary exploratory tool for information gathering to expand an existing international regime which initially involves only international carbon trading resulting from fossil fuel emissions. Participating nations could agree to revisit the coverage issue at fixed intervals, modifying strategies to accord with the underlying science and economics of climate change. Successful joint implementation programs are those which provide the necessary information to incorporate a truly cost effective new emissions source or sink into an international market base policy. However, this application of joint implementation raises problems of project emissions baseline estimation similar to those mentioned in the preceding case, and hence difficulties in ascertaining the nationwide net emission reduction effects of individual non-carbon projects. Current and future joint implementation demonstration projects could provide additional insight into these estimation problems provided that there are sufficient incentives for developed countries to finance such projects.

The potential driving force behind joint implementation is that both buyer and seller countries, developed as well as developing, would benefit from this particular trade as they do from other forms of voluntary transactions. So far, monitoring problems seem to stand in the way of using joint implementation as an instrument for significant cost-effective operations, except for the limited case where Parties to the FCCC have committed themselves to emissions targets, primarily for carbon emissions. This type of joint implementation amounts to an international tradable quota system, the cost-effectiveness properties of which is determined by the number of countries that have made such commitments and want to engage in operations under such a system.

11.5.6 Distributional Impacts of Market-Based Measures

The literature on industrialised countries typically portrays carbon taxes and other market-based instruments such as emissions taxes, gasoline or BTU taxes as regressive because outlays on fossil fuel consumption as a proportion of current annual income tend to fall as incomes rise. But recent studies (see table 11.2) using US and European data show that carbon taxes are considerably less regressive relative to life-time income or annual consumption expenditures than to annual income (see Poterba 1991, 1993; Jorgenson, Slesnick and Wilcoxon 1992; Smith 1992a,b).

Jorgenson et al. (1992) provide the most detailed assessment to date for the United States. They decompose the simulated equity and efficiency impacts of a carbon tax using an explicit national social welfare function. In this decomposition, when the carbon tax revenue is rebated lump sum, the negative efficiency effect dominates and the much smaller equity effect is either mildly progressive or regressive depending on assumptions regarding the nation's aversion to income inequality and the measure of progressivity used.

There is evidence that the same holds true for the rest of the world, although for quite a different reason. In developing countries institutional factors play an important role (see Shah and Larsen 1992). In the developing world, progressivity, or at least low regressivity, could be fostered by: (a) a significant tax burden could be passed on to foreign treasuries, producers and consumer where there is a significant degree of foreign direct investment from countries where investors are allowed foreign tax credits against domestic liabilities; (b) if price controls apply, producers often cannot pass the tax on to consumers in terms of higher prices; and (c) with binding import quotas or rationed foreign exchange, a tax would reduce the excess profits made by the privileged class.

The existence of factors such as market power are likely to lead to regressivity. In this situation, producers could increase product prices in order to pass on a carbon tax to consumers. As it turns out, in most developing countries, there is some combination of the above elements, creating a situation where taxes can be only partially shifted to consumers. This means that a carbon tax would either be progressive or much less regressive than often suggested (see table 11.3). Further, it is likely to be regressive only for the lowest income groups, which could be protected through direct subsidies or alternative measures. In addition, the overall tax structure could be made even less regressive by using a carbon tax to reduce other more regressive taxes.

In principle, if a policy is introduced in order to achieve a particular outcome and it is found to be regressive then the theoretically appropriate policy instrument to deal with the equity issue is a lump sum transfer to the affected parties. This rests on the assumption that there are no non-greenhouse market distortions. If such distortions exist then non-lump sum transfers can improve welfare (Jorgenson et al. 1992). As Schillo et al. (1992) explain, if carbon tax revenue is used to reduce labour, or a blend of labour and capital, taxes then simulated household welfare improves as the adverse efficiency effect is reversed by the rebate, but at the cost of reducing the equality of wealth. A capital rebate is shown to neutralise the efficiency effect but has uneven distributional effects.

11.6 Policy Implementation Issues

In assessing any of the wide range of instruments as potential devices for addressing global climate change, it is imperative to give due consideration to the implementation issues that can so severely affect real world outcomes. Such issues need to be considered in the design of practical policies, whether at the national, multinational or global level.

In the case of tradable permit systems, as applied to local air pollution problems in the United States, the claims made for their cost-effectiveness have in some cases exceeded what can reasonably be anticipated. Tietenberg (1980) assimilated the results from ten analyses of the costs of air pollution control, and in a frequently cited table, indicated the ratio of cost of actual regulatory programs to least-cost benchmarks. Unfortunately, the resulting ratios (which ranged from 22.0 to 1.1) have sometimes been taken by others to be directly indicative of the potential gains from adopting specific ('cost effective') mechanisms such as tradable emission permits. A more realistic and appropriate comparison would be between actual regulatory policies and either actual

trading programs or *reasonably constrained* theoretical permit programs (Hahn and Stavins 1992).

A number of factors can adversely affect the performance of tradable permit systems: concentration in the permit market (Hahn 1984; Misiolek and Elder 1989); concentration in the output market (Malueg 1990); transaction costs (Stavins 1994); non-profit-maximising behaviour, such as sales or staff maximisation (Tschirhart 1984); the pre-existing regulatory environment (Bohi and Burtraw 1992); and the degree of monitoring and enforcement (Keeler 1991). In the case of taxes, research on implementation issues has focused on: administrative costs (Polinsky and Shavell 1982), monitoring (Russell 1990), and enforcement (Harford 1978; Russell, Harrington and Vaughan 1986).

In the following sections a review is undertaken of what is known about some prominent issues regarding the implementation of (carbon) taxes and/or tradable permit systems. Where appropriate, reference is also made to regulatory systems. It is important to note that most of the research on tradable permit schemes is based on experience in the United States where such schemes were superimposed on regulatory policies. These schemes typically involve a limited number of participants, eternal permits and initial allocation by grandfathering. To control global emissions, tradable permit schemes might operate where there was no former regulation, they would involve a larger number of participants, permits may be time limited and initial allocation eventually may be by auction. Thus, experience in the United States may not generalise to such schemes with rather different characteristics.

11.6.1 The 'Currency' of Regulation

Due to the monitoring and enforcement burden associated with regulating actual carbon dioxide emissions, the most practical 'currency' for a tax or tradable permit system would presumably be the carbon content of fossil fuels. Given the proportional relationship between carbon content and CO₂ emissions and the lack of practical means at present of sequestering these stack gases, this is a highly appropriate approach. Monitoring could rely partly on self-reporting supplemented by international access to national fossil fuel inventories. Under an international carbon tax or tradable permit scheme, implementation costs may be least where incentives to comply are self-enforcing. An effective enforcement system makes ultimate sanctions credible so that penalties would rarely need to be imposed. However, even monitoring fossil fuel consumption in many countries is not a trivial problem.²⁸

11.6.2 Market Power

There are two aspects of the market power problem for tradable permit systems (Bureau of Industry Economics 1992). The first is the potential for some economic agents to influence the permit price. The second is the potential for some economic agents to use permits to exercise market power in the output market for the product that 'generates' emissions. Market power in the permit market is sufficient but not necessary for market power in the output market (BIE 1992). Malueg (1990) argues that market power in the output market may reduce economic welfare under a tradable permit scheme even if tradable permits are fully cost effective.

The degree of competition in the tradable permit market will affect the extent to which potential control cost savings are likely to be realised. Hahn (1984) considers the case of a monopsonist (a price setting buyer) who forces down the real permit price below the competitive level. This behaviour is not cost effective since the monopsonist buys too few permits (spends too much on abatement) while the competitive agents will buy too many (spend too little on abatement). Misiolek and Elder (1989) consider the

²⁸ Monitoring and enforcement are discussed in detail by Tietenberg and Victor (1994).

converse case of a monopolist (a price setting seller) who forces up the real permit price above the competitive level. That is, the monopolist spends too little on abatement while competitive agents spend too much. To the extent that market power derives from the initial allocation of permits, one solution may be to limit the amount of permit held by any player (Tietenberg 1985). This may be achieved by widening the market to many players, including by limiting the temporal duration of permits.

An emissions tax designed to make emitters face the full costs of production will tend to result in a cost-effective allocation of the control burden, provided that emitters are cost minimising/price takers. But this outcome does not necessarily occur where emitters have some degree of monopoly power in emission-intensive output markets (Buchanan 1969). In principle, a monopolist in an output market for an emissions-intensive commodity will tend to reduce output below the competitive level in order to raise its profits. Hence, the welfare gains from reduced emissions must more than offset the losses from reduced output of the monopolist for an emissions tax to be worthwhile (Cropper and Oates 1992). Which effect dominates is an empirical issue.²⁹ For example, Oates and Strassman (1984) find that monopoly power in the output market is unlikely to be a key concern in their select study of US industries.

In the case of a scheme to reduce global emissions, there typically will be many more participants than under the schemes operating in the United States. This would reduce the problem of market power. In an international scheme, firms that are large domestic emitters may be required to hold permits as a means of broadening the market. In domestic schemes, if market power posed a problem, government intervention may be required or a tax scheme may be a preferable option.

The issue of market power warrants further consideration in the context of either tax or permit schemes. Whether or not OPEC is involved in a scheme, the potential oligopolistic response of oil producers could interfere with the effectiveness of attempts to control global emissions (Sinclair 1992).

11.6.3 Transaction Costs

Transaction costs can potentially be of importance in the performance of tradable permit markets (Baumol and Oates 1988; Tripp and Dudek 1989; Hahn and Hester 1989a). Stavins (1994a) identifies three potential sources of transaction costs in tradable permit markets: (a) search and information; (b) bargaining and decision; and (c) monitoring and enforcement. The first source, search and information, may be the most obvious. Due to the public-good nature of some information, it can be under-provided by markets. Brokers step in, provide information about firms' pollution-control options and potential trading partners, and thus reduce transaction costs, while absorbing some as fees. Although less obvious, the second source of transaction costs, bargaining and decision, is potentially as important. There are real resource costs to a firm involved in entering into negotiations (Kohn 1991), including time and/or fees for brokerage, legal, and insurance services (Hahn and Noll 1982). The third source of transactions costs — monitoring and enforcement — can also be significant, but these costs are typically borne by the responsible government authority and not by trading partners, and hence do not fall within the notion of transaction costs incurred by firms as defined here.

There is abundant anecdotal evidence indicating the prevalence of significant transaction costs in tradable permit markets. Atkinson and Tietenberg (1991) survey six empirical studies that found trading levels — and hence cost savings — in permit

²⁹ Although there is no cutoff point, it is unlikely that firms or nations could engage in price-setting behaviour if they controlled less than 10 per cent of the market (see Scherer 1980). Ultimately, the question is whether other firms present credible threats of entry to the market — that is, whether the market is 'contestable'. If so, it is less likely that anti-competitive behaviour can thrive (see Baumol, Panzar and Willig 1982).

markets to be lower than anticipated by theoretical models. Liroff (1989, p.2) suggests that this experience with permit systems 'demonstrates the need for ... recognition of the administrative and related transaction costs associated with transfer systems.'³⁰ For example, under the US Environmental Protection Agency's emissions trading program for 'criteria air pollutants', there is no ready means for buyers and sellers to identify one another, and — as a result — buyers frequently pay substantial fees to consultants who assist in the search for available permits (Hahn 1989). At the other extreme, the high level of trading that took place under the program of lead rights trading among refineries as part of the USEPA's leaded gasoline phasedown has been attributed to the program's minimal administrative requirements and the fact that the potential trading partners (refineries) were already experienced at striking deals with one another (Hahn and Hester 1989a). Hence, transaction costs were kept to a minimum and there was little need for intermediaries.

Another source of indirect evidence of the prevalence of transaction costs in permit markets comes from the well-known bias in actual trading toward 'internal trading' within firms, as opposed to 'external trading' among firms. It has been hypothesised that the crucial difference favouring the internal trades and discouraging the external trades is the existence of significant transaction costs that arise once trades are between one firm and another (Hahn and Hester 1989b). Finally, the existence of commercial brokers charging significant fees to facilitate transactions is another body of evidence.

Stavins (1994a) considers a market for emission permits in which costs are associated with the exchange of permits, and models several alternative types of transaction cost functions. He finds that transaction costs reduce trading levels and increase abatement costs and, most importantly, that in some cases, equilibrium permit allocations and hence aggregate control costs are sensitive to initial permit distributions. Thus, in the presence of transaction costs, the initial distribution of permits can matter in terms of efficiency, not only in terms of equity.

The effects of transaction costs should be ameliorated in markets with relatively large numbers of potential trading sources or where formal international or domestic trading exchanges have been established. As the pool of potential trading partners increases, it should be easier for sources to identify potential trading partners even in the absence of formal exchanges, thereby lowering transaction costs. A larger number of firms can also mean more frequent transactions, generating more information, and thereby reducing uncertainty.

Economists have tended to give greater emphasis to the symmetry between tradable permits and pollution charges, than to their differences, although the two approaches are not symmetric under conditions of uncertainty (Weitzman 1974), in the presence of transaction costs (Stavins 1994a), or under a number of other conditions (Stavins and Whitehead 1992). Analyses that have compared taxes and permits have assumed zero transaction costs. Systems of pollution taxes, of course, can also involve substantial administrative costs, both fixed (per firm) and variable (Polinsky and Shavell 1982).

11.6.4 Free-Riding and Emissions Leakage Problems

Can a unilateral policy by one country alone or by a group of cooperating countries prove effective in abating global greenhouse gas emissions? This is an important

³⁰ Alternative explanations of low observed trading levels have also been advanced: lumpy investment in pollution-control technology; concentration in permit or product markets; the sequential and bilateral nature of the trading process (in the context of a non-uniformly mixed pollutant) leading to some initial trades that then preclude better trades from being carried out subsequently (Atkinson and Tietenberg 1991); and the regulatory environment. Some of these 'alternative explanations' of low trading levels can be viewed as special cases of transaction costs, broadly defined.

question, for it is total emissions, and not individual country emissions by themselves, that determine global concentrations of greenhouse gases, and yet some countries seem more willing to adopt abatement policies than others.³¹ The answer depends on how the other ('non-cooperating') countries respond to the unilateral policies adopted by the 'cooperating countries'. These responses in turn reflect two phenomena: 'leakage' and 'free-riding'.

As Barrett (1994a) explains, free-riding and leakage can undermine any international greenhouse management initiatives, whether they be market-based or rely on regulatory measures. Free-riding arises when countries which benefit from global abatement do not contribute toward its provision. Leakage arises when abatement by the cooperating countries alters world relative prices (including shadow prices) in a way which leads to non-cooperating countries increasing their emissions.

11.6.4.1 Policies to Reduce Free-Riding

As long as participation in an international greenhouse management policy is voluntary, countries will have incentives to free ride, sharing in the benefits from such a policy without sharing in the costs. Even if there were no leakage, free-riding would result in abatement being less than would be globally optimal, in the sense that the benefit of a small increase in global abatement would exceed the associated cost. This issue has been examined in a number of studies including Barrett (1992a); Hoel (1992); and Parson and Zeckhauser (1992). None of the existing empirical models have been used to estimate the magnitude of potential free-riding, although some insights into the gains from full cooperation are provided by Barrett (1992a,b,c), Bohm and Larsen (1993), Hinchey et al. (1994a,b) and Hoel (1992).

As Hoel (1992), Carraro and Siniscalco (1993), and Barrett (1994c) have shown, in spite of free-rider incentives, a stable coalition of cooperating countries may exist. The size of this coalition will depend on the ability of the cooperating countries to punish countries which might withdraw from the coalition, and to reward countries which might accede to the coalition. However, to be effective, such punishments/rewards must be both substantial and credible, and these requirements often clash. As a result, the size of the stable coalition may be quite small. In fact, these analyses do not consider international trade, and where there is trade, free-riding will be exacerbated by leakage. On the other hand, trade may also provide a vehicle for deterring free-riding.

For example, Barrett (1994a,b) explains how the threat of a complete ban on trade between cooperating and non-cooperating countries in carbon-based fuels and products could work to support full participation in a greenhouse management scheme. The key to this agreement, as with the Montreal Protocol on Substances that Deplete the Ozone Layer, is that the threatened trade ban would come into effect once a threshold level of countries agreed to participate in the scheme; but the threshold is determined such that all countries would gain from participation once it is reached. In other words, it is not necessary that trade be restricted, but rather that the threat to impose trade restrictions be credible.

An actual ban on trade introduces a distortion in the global economy, and is in this sense undesirable. However, free-riding is itself a distortion, and if trade restrictions reduce free-riding, they may be beneficial overall. The implication for climate change policy is that trade restrictions should not be prohibited. Whether they should ever be allowed, and under what circumstances, is a different matter, and one requiring additional research.

³¹ This problem may exist within groups of countries as well as more generally. For a discussion of issues surrounding the attempted introduction of a harmonised carbon tax in the European Union and a possible alternative policy see Bergesen et al. (1994).

Finally, Heal (1992) argues that the free-riding problem can be exaggerated. He notes that in repeated games it is more likely that players will cooperate than in one-shot games. There may be reinforcing effects that strengthen the chances of forming a stable coalition. An example would be if countries share in the costs of developing abatement technology. Developing countries may benefit from abatement technology created in developed countries and this may increase their incentive to abate.

11.6.4.2 The Severity of Emissions Leakage

There are two main channels through which emissions leakage may be transmitted. First, a carbon abatement policy by cooperating countries would shift comparative advantage in carbon-intensive goods toward non-cooperating countries. As a result, production of such goods, and emissions, would rise outside the coalition. Second, the unilateral policy would have the effect of lowering world demand for carbon-intensive fuels, and thereby reduce the world price for such fuels traded in international markets. As a result (and ignoring income effects), demand for such fuels, and emissions, are likely to rise outside of the coalition. It should be emphasised that these two responses by non-cooperating countries do not result from any deliberate policy to increase emissions, but rather result from the absence of a policy to reduce emissions.

Barrett (1994a) surveys several global simulation studies which provide positive leakage estimates, including GREEN, 12RT, Global 2100 and the Whalley-Wigle model. The leakage rate is defined as the increase in emissions by non-cooperating countries divided by the reduction in emissions by cooperating countries. The evidence of positive emissions leakage varies widely and is strongly dependent on the model used. For example, positive leakage rates are low in GREEN (Oliveira-Martins, Burniaux and Martin 1992) and high in the Whalley-Wigle model (Pezzey 1992).

In particular, Pezzey estimates that a 20 per cent reduction in carbon emissions within the European Union alone (relative to a baseline trend in emissions) would be associated with a leakage rate of 80 per cent. In other words, for every 10 tonnes of carbon abated by the EU, global emissions would fall by only 2 tonnes. Pezzey also calculates that a 20 per cent reduction in OECD emissions would be associated with a leakage rate of 70 per cent. These leakage rates suggest that unilateral policy would be largely ineffective. On the other hand, Oliveira-Martins et al. estimate much lower leakage rates for policies aimed at stabilising carbon emissions at their 1990 levels. They estimate leakage rates for a unilateral EU policy of 11.9 per cent in 1995 and 2.2 per cent in 2050, and for a unilateral OECD policy of 3.5 per cent in 1995 and 1.4 per cent in 2050. These leakage rates suggest that leakage does not render unilateral policy ineffective. These rates are more in accord with those reported by Hanslow, Hinchey, Small, Fisher and Gunasekera (1994, p. 16) who estimate that a policy induced 20 per cent reduction in CO₂ in Annex 1 countries would be associated with a leakage rate of 3.8 per cent.

One reason for the difference in these leakage estimates is that emissions leakage is greater where a country's fossil-fuel-intensive products and fossil fuels have close substitutes. Trade flows in GREEN (Oliveira-Martins, Burniaux and Martin, 1992) are based on the Armington assumption that goods produced from different countries are imperfect substitutes (implying an exporter has some degree of market power). By contrast, in the Whalley-Wigle model goods from different countries are assumed to be perfect substitutes, thus making trade flows more sensitive to relative price changes. In MEGABARE, the model reported in Hanslow et al. (1994), imported goods from different sources are imperfect substitutes. An important distinguishing feature of the model is the way in which technology in the energy intensive industries is modelled.

As already noted, other studies estimate leakage rates somewhere between these two sets of estimates. As well, Oliveira-Martins et al. estimate negative leakage rates for some regions in some years, and Horton, Rollo and Ulph (1992) argue that leakage may exceed 100 per cent in some cases. Currently, there is no consensus among economists

about the magnitude of leakage. More research is needed, and it would be particularly helpful if leakage rates were calculated for identical simulations employing a consistent set of assumptions, as has already been done in estimating the costs of climate change policies (see Dean and Hoeller 1992). What can now be said is that leakage is a potentially serious problem for unilateral policies.

The above studies ignore a possible third channel for leakage transmission. Under certain assumptions, non-cooperating countries will abate their emissions up to the point where their own, national marginal benefit of abatement equals their own marginal cost of abatement (see Barrett, 1994c). In the extreme, this optimisation rule will mean that non-cooperating countries will not abate their emissions at all. However, more generally this rule implies that non-cooperating countries will abate their emissions by less than they would if they cooperated. To take an example, although the United States is not a signatory to the 1979 Sulphur Protocol under the Convention on Long-Range Transboundary Air Pollution, it has undertaken to abate its sulphur emissions unilaterally; it has been in its self-interest to do so. Where non-cooperating countries do undertake positive unilateral abatement, and where the marginal benefit of abatement to non-cooperating countries decreases with the level of global abatement, an increase in abatement by cooperating countries will create an incentive for non-cooperating countries to reduce their abatement. Hence, leakage may occur even in the absence of trade.

11.6.4.3 Policies to Reduce Leakage

What can be done to reduce emissions leakage? What is currently known stems from the basic general equilibrium model of trade so commonly used. As background, take the somewhat simpler case of the international incidence of a global carbon tax. Most of the results from greenhouse modelling studies to date are based on the simplifying assumption that the global cost-effectiveness of a common carbon tax (tradable quota system) does not depend on the distribution of incomes between or within countries, that is, only relative prices matter for this cost effectiveness result. (This is not to say that the international distribution of the impacts from these policies does not depend critically on what is done with tax revenues or initial quota allocations.)

Hence, consistent with basic trade theory, a uniform global production tax (quota) on greenhouse emissions is equivalent to a uniform global consumption tax (quota) on these emissions. Both minimise the cost to global economic welfare of achieving a given global emissions target where there is perfect foresight. There are terms of trade gains (losses) to net fossil fuel exporters (importers) under a production tax, and the converse holds for a consumption tax. That is, fossil fuel exporters are less worse off under a production than a consumption tax on emissions, and the converse is true for net importers. Precisely such results are illustrated in the Whalley-Wigle model (Dean and Hoeller 1992).

What happens in this standard framework when coalition membership is less than global? This issue has been examined by Markusen (1975); Krutilla (1991); Bohm (1993b); Hoel (1994, 1995); and Barrett (1994a). Treating the coalition as a single entity, and the rest of the world similarly, if the coalition is a net importer (exporter) of carbon intensive products in the absence of the carbon tax then a tariff (subsidy) which reduces positive emissions leakage through the terms of trade should be imposed on these net imports (exports). This response minimises the coalition cost of meeting the greenhouse constraint. Precisely the same argument holds for leakage through trade in carbon based fossil fuels. In addition, instead of using an import tariff (export subsidy) the equivalent production subsidy (tax) and consumption tax (subsidy) could be applied in the coalition. Hoel (1995) shows that if an optimal tariff (subsidy) or its equivalent can be employed, then the carbon tax should be uniform across all sectors in all coalition countries, but if not then differential tax rates and exemptions may be required.

In summary, all the results from basic trade theory hold in analysing emissions leakage from a carbon tax or quota (see, for example, Woodland 1982; Voudsen 1990). However, as with a customs union, determining the optimal tariff (subsidy) to reduce positive emissions leakage from the carbon tax will be a complicated calculation given the extensive but differential use of carbon based fuels in all economies and the differential ability of some countries to exercise market power. Trade compliance with GATT rules will also need to be considered. In addition, further research on the leakage problem is warranted to consider strategic interactions between greenhouse policies in coalition and non-coalition countries.

11.6.5 Compliance

Free-rider deterrence is concerned with securing broad participation in an agreement, and leakage reduction is concerned with making abatement by cooperating countries more effective. A related concern is compliance, or the incentives which countries have to fulfil their pledges under an international agreement. Some international agreements contain explicit compliance measures such as trade sanctions. However, it is more usual for agreements to seek alternative means for securing compliance (see Chayes and Chayes, 1993).

Indeed, it is a fundamental norm of international law that treaties are to be obeyed, and as a rule countries do not negotiate, sign, and ratify agreements with the intention that they will not comply fully with all relevant provisions. Hence, compliance is not as great a problem as it is sometimes taken to be. More difficult are the problems of negotiating an agreement that requires real sacrifices by the parties and of getting countries to sign the agreement in the first place.

Where compliance is a problem, the reasons are usually innocent. For example, four years after the Montreal Protocol was signed, only about half of the parties to the agreement had complied fully with the reporting requirements of the treaty. This was not because these countries hoped to get away with non-compliance but rather because they did not have the resources and technical know-how needed to carry out their obligations. On the other hand, compliance with certain oil pollution treaties once proved more worrying because non-compliance was linked to the difficulty of monitoring and verifying the amount of oil discharged by tankers at sea. However, once an equipment standard was established requiring all new tankers to have separate ballast tanks, monitoring became easy and problems of non-compliance subsided. Indeed, monitoring of international agreements may be the more important problem (US General Accounting Office, 1992). The lessons seem to be that treaties should be designed to facilitate easy monitoring, and that they should also ensure that all parties have the means to comply with the requirements of the agreements, given the will to do so.

11.6.6 Information Issues, the Role of Brokers and Risk Management

Policy instruments should be designed to provide needed information. In the case of tradable permit systems there are three ways this can be done: (a) government can take actions that directly reduce regulatory uncertainty; (b) barriers to private brokerage services can be reduced; and (c) allowance can be made for the development of futures markets. In the first case, at a minimum, government authorities can avoid creating regulatory barriers (such as requirements for government pre-approval of trades) that drive up transaction costs and discourage trading.

Private provision of brokerage services can also play an important role in information provision. Thus, although commercial brokers can certainly be recipients of transaction costs, their activities reduce transaction costs below what they would otherwise be (Stavins 1994a). Intermediaries, in general, can contribute to social welfare by helping parties economise on transaction costs. Brokers can play the role of consultants, adding value by understanding the regulatory process and by maintaining information about prospective suppliers and demanders of permits. Under the more conventional function

of bringing together buyers and sellers ('brokering deals' by matching buy orders and sell orders), these firms both absorb and reduce transaction costs. Finally, brokers may assume risk by buying, holding, and selling permits.

An important merit of an international tradable quota system (compared with any scheme including an emissions tax scheme) is that it can be used as a risk management tool to reduce the costs of greenhouse risks. An optimal international tradable quota system will not contain eternal quotas as this would fail to preserve the full worth of the option value to modify policy with future knowledge. Indeed, the costs to nations, and therefore to the world as a whole, of the uncertainties and of the risks attached to greenhouse management may be reduced if nations can adopt an optimal portfolio of tradable quotas.³²

A forward market for quotas could develop if there are a sufficient number of hedgers and speculators none of whom can significantly congest price signals. The latter requirement could be met by a rule fixing the maximum share of total net emissions entitlements held by any one country. By reducing the costs of risk and uncertainty, time limited quotas would tend to reduce any nation's incentive to pursue strategic behaviour (such as through quota hoarding) and could also reduce validity-forecasting problems.

Once the parties to the agreement know the basis on which quotas will be allocated over time, a futures market could develop. Provided contracts are standardised, one of the main difference between the above forward contracts market and a futures market is that the latter offers greater liquidity if contracts can be settled by the monetary equivalent of quota transactions as opposed to the delivery of the quota itself. As a consequence, more transactions are likely in the futures market and this should lead to greater information flows, reducing uncertainty and risk and transactions costs. As a consequence, spikes in the quota price would tend to be rapidly smoothed out as market players took up speculative and hedging positions.

Hence a major factor favouring a tradable quota scheme is that a forward and or futures market based on (net) emissions quota contracts would provide a way of efficiently reducing greenhouse costs of uncertainty and of risk. This would reduce the costs of control and stimulate investment in the research, development and use of least cost net emissions control mechanisms. For example, suppose a country invests in a risky technology transfer project as part of a strategy to meet its national greenhouse target. It could hedge against the risk of project failure by buying futures. Any profit on the futures market transaction could partly compensate for any rise in the spot price if it needs to buy quotas.

An auction system for forward sales in emissions quotas exists in the United States as part of provisions, controlling domestic sulphur dioxide (SO₂) emissions from fossil fuel fired power plants, in the 1990 amendment to the Clean Air Act. As Howe (1994) notes, under the amended legislation, by the year 2000, total SO₂ emissions from the United States electricity power sector are required to be around 50 per cent below the

³² One proposal is to time limit quotas to say ten years with one year overlapping for banking and for practical 'end of period' reasons (see Bertram 1992; OECD 1992b). In particular, one-tenth of quotas could expire each year and could be replaced by a new issue according to a procedure which could be modified say every five years. This would reduce the costs of uncertainty by providing flexibility to adapt to new information including the entry of new sources and sinks into the system. It also establishes a market in forward contracts to reduce the costs of greenhouse risks. Quotas of different duration would co-exist in the market to cover both short and long term risks, and the quota price would reflect the costs of risk.

1 1980 level. By January 1, 1995, of the 111 power plants directly affected in the first
2 phase of measures, each must hold tradable quotas covering its total annual emissions
3 target (its quota allocation), capped at about 50 per cent of the 1980 level. Currently,
4 allowances may be traded to any party or credited ('banked') for future use. In the
5 second phase, most electric power utilities will be brought within the system, beginning
6 January 1, 2000. In addition to receiving an annual target allowance, quotas for excess
7 emissions may be bought directly from other plants or through auctions held by the
8 Chicago Board of Trade for the United States Environmental Protection Agency.

10 The temporal component of any pollution problem can be important, but this is
11 particularly so in the case of 'stock pollutants' which tend to accumulate in the
12 environment at a rate which significantly exceeds their natural rate of decay.
13 Accumulations of greenhouse gases are of this nature and thus raise a set of time-related
14 issues. If the overall goal of some public policy were to limit the rate or degree of
15 climate change, then significant tradeoffs would exist with regard to the timing of any
16 proposed reductions in greenhouse gas emissions. Earlier reductions would have the
17 effect of slowing the potential onset of climate change.

19 Within the context of a tradable permit system, these temporal considerations can be
20 addressed, to some degree, through provisions for (or restrictions on) 'banking', a
21 mechanism that enables firms or nations to make early emission reductions in exchange
22 for the right to emit a comparable amount at some later date. This notion could be
23 extended to sinks as well as sources. It could be advantageous to allow nations to
24 engage in banking of greenhouse gas allowances, since this would allow for inter-
25 temporally efficient market exchanges and could tend to delay the onset of global
26 climate change.

28 11.6.7 Implementation Issues for Economies in Transition

30 Nations with economies in transition from centrally-planned to market-based systems
31 are likely to exhibit certain characteristics that are relevant to the choice, design and
32 implementation of greenhouse policy instruments. A small, but rapidly growing
33 literature has begun to investigate issues of particular concern for implementation of
34 environmental policy in transition economies, including matters such as: the adaptation
35 of existing environmental tax systems to changing conditions (OECD 1994; Semenienc
36 and Kundrotas 1994; Markandya 1994); historical, institutional, and fiscal factors
37 (Zylicz 1994a; 1994b); the use of economic instruments to raise revenue for highly
38 constrained government budgets (Zylicz 1994c, OECD 1994); the environmental
39 impacts and cost-effectiveness of instruments for air pollution control in specific
40 regions (London Economics 1993; Csermely, Kaderjak, and Lehoczki 1994; Dudek,
41 Kulczynski and Zyliz 1993); and environmental liability (Bell and Kolaja 1993).

43 High rates of economic growth and price inflation could affect the attractiveness of
44 alternative policy instruments over time, due, for example, to the rapid inflation of
45 relative permit prices or the erosion of unit-based taxes (Stavins and Whitchhead 1992).
46 Situations in which a large portion of the economy is state-owned or the private sector
47 is in its infancy suggest the need to validate the usual assumption that emission sources
48 (firms and individuals) are cost-minimisers and that markets are relatively complete
49 (Stavins and Zyliz 1994). Enterprises may be protected from bankruptcy, facing only
50 'soft budget constraints' or have the ability to avoid environmental requirements
51 through negotiation (OECD 1994).

53 Concentration of product or emission permit markets due to inherited industry mixes
54 and possible barriers to entry (for example, imperfect capital markets) may also impede
55 the efficient operation of a tradable permit system (Hahn 1984). Significant structural
56 adjustment, including privatisation, shifts in industrial sector shares in the economy,
57 and disruptions in international trading relationships could also affect the stability and
58 predictability of greenhouse gas emissions resulting from alternative policy instruments.

1 Effective taxes may, for example, increase enterprise bankruptcies in a period of severe
2 economic problems (OECD 1994). Even after privatisation, many enterprises may lack
3 information on technological options for pollution control and their cost-effectiveness,
4 hindering efficient responses to policy (OECD 1994).

6 Other non-economic characteristics of transition economies may also be relevant to the
7 implementation of policy instruments to manage greenhouse gas emissions. Problems
8 may arise from the legal and administrative constraints inherited from central planning,
9 making monitoring and enforcement difficult. A relatively undeveloped sense of
10 corporate responsibility and a lack of public awareness of environmental issues and a
11 lack of pressure from non-government organisations could further impede effective
12 implementation. Government personnel may lack the necessary administrative skills
13 due to a shortage of economic, financial, and accounting skills and an inability of
14 government agencies to offer competitive salaries (OECD 1994). Finally, high *ex ante*
15 levels of pollution, high levels of desired reduction, and a concentrated pattern of
16 pollution exposure may present environmental conditions that are more extreme than in
17 many advanced industrialised countries, but may also provide abundant opportunities
18 for low-cost abatement.

20 11.7 Comparative Assessment of Greenhouse Policy Instruments

22 In this section an attempt is made to outline the issues that need to be considered in
23 determining any greenhouse policy mix. Countries differ in their institutional structures,
24 their resource endowments and their levels of industrialisation. Differences in economic
25 and technical capacities among countries offer the potential for emissions abatement
26 cost saving under a harmonised international greenhouse management scheme but, at
27 the same time, add complexities in terms of reaching final agreement about appropriate
28 policy approaches and burden sharing.

30 Economic instruments are considered by policy makers in a political environment. This
31 has several important implications for the nature of the instruments finally adopted, as
32 well as for the potential for reaching an international agreement on climate change.

34 First, to some extent the choice of instrument will be dictated by existing institutional
35 infrastructure and experience. For example, market-based instruments are likely to be
36 seen as less appropriate in an economy with a high level of central planning than in one
37 with a long history of free enterprise.

39 Second, the ability to enforce the different instruments is likely to vary across nations.
40 In addition, nations are unlikely to grant significant authority to a supranational body
41 that would allow for consistent enforcement across countries.

43 Third, to the extent that domestic policy is affected, the choice of policy instruments at
44 the international level could itself affect the likelihood that an agreement will be
45 reached.³³ For example, some countries may be unwilling to accept an agreement
46 involving the use of international taxes or harmonised domestic taxes. On the other
47 hand, as pointed out earlier, a tradable quota scheme leaves open the choice of domestic
48 instruments.

50 Fourth, any approach that is implemented to control greenhouse gases may vary from
51 the textbook application of these concepts. There are many reasons why both market-
52 based and regulatory approaches deviate from their ideal. Departure of actual
53 instruments from their theoretical ideal, however, is not sufficient cause for rejection of
54 an approach.

³³The likelihood of reaching an international environmental agreement will be affected
by several factors. See: Sebenius (1991); and Hahn and Richards (1989).

Fifth, the adoption of any international (domestic) instruments will have some impact on the distribution of wealth between (within) countries. Negotiations about distributional issues are likely to be crucial in determining the final policy mix that is chosen. In the case of domestic taxes and tradable permits some of the government revenue may be returned to the affected parties. Thus, for example, many charging systems in Europe designed to limit pollution recycle revenues to the participants or earmark the revenue for specific tasks. Similarly, in the United States, tradable permits for protecting the environment are distributed based on the historical pattern of emissions (grandfathering). While the precise nature of the distribution will be the subject of vigorous political discussions, countries and special interest groups (including environmental groups) are unlikely to accept an agreement that substantially shifts the distribution of wealth or political power. Since all instruments probably will have to, and also can, be connected with compensatory measures — side payments or specific quota/permit allocations — no difference between them would arise in this regard. For example, an international tax or tradable quota scheme might be designed in such a way as to encourage developing countries to join a coalition in order that they benefit from international transfers of income.

Sixth, governments are likely to attach more stringent monitoring and enforcement requirements to a market-based approach for limiting non-carbon greenhouse gas emissions than to a regulatory system. For example, environmentalists bargained successfully for the installation of continuous emission monitors as a condition for allowing a tradable allowance system for reducing SO₂ emissions in the United States. A similar strategy is likely to be applied if market-based approaches are implemented for limiting non-carbon greenhouse gases or for controlling carbon sequestration. One notable difference between the two control problems is that technology for accurately monitoring many sources and sinks of greenhouse gases has not yet been developed.

And finally, there are several reasons why politicians have traditionally taken a 'regulatory' approach, rather than an economic incentive-based approach to environmental policy (Bohm and Russell 1985; Hahn and Stavins 1991). First, industry tends to favour direct regulation over incentive mechanisms because: (a) if a tax instrument is used, the polluter must pay fees in addition to control costs, although the acceptance of this will be influenced by any revenue recycling as mentioned above; and (b) firms may have greater influence over the specifics of uniform standards. Second, the effects of quantity regulation are likely to be perceived to be more certain than pollution charges, whose effect will depend on abatement cost functions which are typically unknown. Third, economic efficiency arguments often rely on a relatively sophisticated understanding of market operation and price effects which seem 'indirect' compared with direct 'regulation' of the polluting activity. Finally, in many countries, economists play a minor role in the development of environmental policy, compared with the number of decision makers with backgrounds in law, natural science, or engineering.

11.7.1 Comparing Regulatory Systems and Market-Based Instruments

Regulatory policies may be defined as those where the authorities determine the level of permissible emissions from an emission source. Market-based policies may be defined as those where firms are free to determine their level of emissions but must pay some penalty (such as a tax or buy an emission permit) determined by the authorities for their level of emissions. For given output and input prices, to minimise the total costs of abatement, the level of abatement at each source needs to be chosen to equalise the marginal costs of abatement. If the authorities had complete information about the marginal costs of abatement at each source, regulatory policies could be determined to minimise the total costs of abatement. Given that the authorities will not have such complete information and typically cannot acquire it at a reasonable cost, regulatory approaches tend not to be cost minimising.

On the other hand, it is necessary to consider the public as well as the private costs of control (Stavins 1994a). In other words, the total costs to be minimised by a truly cost-effective environmental policy instrument include both the costs of abatement (typically borne by private industry, and including transaction costs) and the costs of administration (typically borne by government in the form of monitoring and enforcement costs). When monitoring and enforcement needs are particularly burdensome, performance-based standards in general may not be cost effective. On the other hand, certain forms of technology standards, which are typically relatively high cost in terms of abatement, can involve only relatively minimal needs for adequate monitoring and enforcement. Finally, in addition to such concerns about static or allocative cost-effectiveness, it is important to consider the relative effects of alternative policy instruments on the invention, innovation and diffusion of new technologies. That is, in the long term, it is the dynamic efficiency properties of environmental policy instruments that are likely to be most important.

In the international context, monitoring and enforcement requirements would hardly differ with respect to fossil fuel use, since fossil fuel output plus imports minus exports would have to be reported for each participating country under all systems.

Tradable permits (for emissions during a given time period) and taxes are the two major domestic market-based policies. With tradable permits a national permit exchange would develop among permit-liable fossil fuel producers and importers (or wholesale dealers in fossil fuels) after the initial allocation of permits through recurring government permit auctions or (temporary) grandfathering. In this connection transaction costs would arise. Under a tax scheme administrative costs would be incurred in payment and collection of the tax. The issue of how enforcement costs would differ between policies to detect violation with a given probability has not been studied and there does not appear to be any empirical evidence.

There have been a number of empirical studies that suggest significant potential cost savings from the adoption of truly cost-effective instruments compared with regulatory approaches (Tietenberg 1985), although most of these studies have contrasted actual regulatory instrument costs with a theoretical cost-minimising alternative, not an actual market-based policy instrument (Hahn and Stavins 1992).

In economies without well-developed market systems, there may be net efficiency gains from applying regulatory approaches over a wider range of emission sources. On the other hand, the adoption of a market-based approach may speed the development of the market system. Net efficiency gains may favour the development of market-based systems at an earlier date than otherwise would be the case.

At the international level, there is little scope for using direct regulation of emissions over and above using non-tradable emission quotas. Such a quota system would clearly entail extra costs to the extent that marginal abatement costs will differ among countries. Cost effective candidates for an international agreement are tradable quotas and international or harmonised domestic carbon taxes.

11.7.2 Comparing Domestic Tradable Permits and Domestic Tax Systems

Both taxes and tradable permits impose costs on industry and consumers.³⁴ Both taxes and tradable permits force firms to internalise the costs of their pollution. Practically speaking, this means that firms will experience financial outlays, either through expenditures on pollution controls or through cash payments (buying permits or paying taxes). Taxes and permit prices (especially when permits are auctioned by the government) tend to make these costs more visible to industry and the public. This may

³⁴ Compared to conventional command-and-control regulations, both taxes and permits provide an explicit price signal about the marginal cost of limiting emissions.

be problematic for political reasons, although in the long run it may have the advantage of clearly signalling and educating the public about the costs and tradeoffs associated with various levels of environmental control.

In principle, there need be no difference between domestic carbon taxes and tradable carbon permits from a distributional point of view. Moreover, tax recycling and a 'double dividend' for carbon taxes can exist to the same extent for a permit system. Tradable permits may be grandfathered, in the short run, to (partly) compensate existing firms that may have not been sufficiently forewarned about the new policy. This choice corresponds to a tax scheme where, in a period of transition, all carbon tax revenues are redistributed to the firms that would have received free permits under a permit scheme. Alternatively, or after a period of transition is over, no compensation at all would be paid. This would amount to a tax system where the government kept the tax revenue (and used it for unrelated purposes) or a permit scheme where all permits were auctioned and the government retained the sales revenue. Partial matching versions of each type of scheme might also be imagined.

The lack of control over emission levels with taxes could be a distinct disadvantage in terms of an international agreement. Taxes would have to be varied frequently given the inadequate information base of the authorities to determine the appropriate tax level and the need for adjustments in response to changes in the level of economic activity and changes in relative and absolute price levels. The need for frequent changes in tax levels would add to business uncertainty and would add to the practical difficulty in a political sense in implementing such a policy.

Tradable permit systems may be more susceptible to 'strategic' behaviour than tax systems. In order for a tradable permit system to work effectively, relatively competitive conditions must exist in the permit (and product) market. The degree of competition will help determine the amount of trading that occurs and the cost savings that will be realised. Should any one firm control a significant share of the total number of permits, their activities may influence permit prices. Firms might attempt to manipulate permit prices to improve their positions in the permit market (say, by withholding permits and forcing others to cut production or keeping new entrants out). These risks would be reduced by: (a) using time-limited permits — that is, permits for emissions for a period of say five years, which might be in line with the design of an existing international tradable quota scheme;³⁵ and (b) the government auctioning permits.³⁶

Tradable permits have an advantage over taxes when time and uncertainty are introduced into the analysis. Under a tax scheme, there would be a high level of uncertainty about investment in emission intensive activities with long payback periods such as coal fired power stations and research and development in technologies to reduce emissions. Such uncertainty would arise from uncertainty about the future nominal level of the tax and the impact of that tax given possible changes in relative prices, the absolute level of prices and the level of economic activity.

A tradable permit scheme can be designed to reduce uncertainty about the future in a number of ways. One approach would be to issue permits with different durations (Bertram 1992) or for a set of future (for example, five-year) periods. Firms undertaking emission intensive investments with long payback periods would be able to reduce

³⁵ Granting permits for moving periods of say five years as compared to eternal permits would reduce the possibility of a monopolist hoarding permits and 'forever' exposing future buyers to leasing permits at monopoly prices.

³⁶ Auctioning could be used to help avoid a situation under grandfathering where one large firm was allocated a significantly large share of permits. On the other hand it could be argued that grandfathering would provide an asset which may be sold by a firm wishing to leave an industry and thus facilitate adjustment.

uncertainty about future costs by buying permits for the desired number of periods. The development of a forward or futures market for permits (that could be coupled with permits of different duration) would provide an even better mechanism to spread the risks associated with uncertainty about future policy toward emissions. Firms undertaking research and development into technologies to reduce emissions would be able to hedge the risks associated with the payoff from such technologies through operations in the futures market (Epstein and Gupta 1990). Similarly, firms investing in emission intensive activities would be able to hedge against the risks of future policy changes through futures markets operations.

To summarise, permits are more effective than taxes in achieving given emission targets. The lack of control over emissions with taxes could be a disadvantage. The frequent changes in taxes that may be required would add to business uncertainty. Permits may be more susceptible to strategic manipulation than taxes but this problem can be reduced, as explained above. Permits appear to have a distinct advantage in creating the basis for a futures market that could enable a more efficient spreading of the risks about future policy uncertainty.

11.7.3 Comparing International Tradable Quotas and Tax Systems

As outlined above, in many situations economic-incentive policies can lead to lower total pollution control costs and spur greater technological innovation than conventional regulatory approaches. Which incentive-based instrument is most effective, however, will depend on a number of specific factors. The broadest set of possible international applications is considered below.

A system of harmonised domestic carbon taxes would involve an agreement about compensatory international financial transfers as well as the pre-carbon-tax net tax rates on fossil fuels. These taxes would represent (at least) what amounts to an estimate of the domestic environmental effects of fossil fuel combustion. Internationally acceptable estimates of these basic tax levels, which would tend to differ between countries, would be difficult to establish. Moreover, no design seems feasible and generally acceptable where participants are not allowed to undertake policies on their own which indirectly affect fossil fuel use, such as levying a tax on substitutes to carbon and subsidising complements to carbon (Hoel 1993). Thus, there are significant risks that a tax harmonisation agreement would either never be adopted or fail after implementation (Bohm 1993a).

A system of international taxes, where all participating countries were liable to pay a given carbon tax, could include an agreement on how tax receipts would be shared among the participants. Under such a system countries might retain all or part of the taxes raised domestically and some participants (low income countries) might receive a transfer (Hoel 1993). Each country would have a good knowledge of the amount of tax revenue likely to be raised internally. However, less information would be available about other countries' tax revenues and hence there would be uncertainty about the size of the net transfers to and from each country.

A tradable quota scheme leaves each participant to decide what domestic policy to use. Such a scheme does not require any ongoing side payments. Here, the initial allocation of quota entitlements among countries reflects distributional considerations. A disadvantage of a tradable quota scheme is that the (endogenous) future prices in international quota trade are unknown when an agreement on the quota allocation is reached. Hence, the exact distributional implications cannot be known beforehand. This is the price paid for the main advantage of such a scheme, namely that the resulting global emissions will be known with certainty for a global agreement and, net of carbon leakage, for a non-global agreement.

11.8 Summary

The following main points can be drawn from the above analysis:

1. A clear distinction needs to be drawn between the costs and benefits of actions taken to reduce the impacts of climate change itself and the costs and benefits of actions taken to reduce emissions. The first involves a consideration of adaptation policies such as developing new drought resistant plant cultivars while the second involves a consideration of policies designed to mitigate climate change.
2. Policy instruments designed to mitigate global climate change must be identified at two different levels: those that might be used by a coalition of countries and those that might be used by individual nations unilaterally or to achieve compliance with a multilateral agreement on greenhouse targets.
3. Governments may have different sets of criteria for assessing international as well as domestic greenhouse policy instruments. Among these criteria are efficiency/cost effectiveness, distributional (including intergenerational) equity, flexibility in the face of new knowledge, understandability to the general public and consistency with national institutions and traditions. The choice of domestic instruments may also partly reflect a desire on the part of governments to achieve non-climate change related objectives such as meeting fiscal targets or influencing pollution levels which are indirectly related to greenhouse gas emissions.
4. A coalition of nations may choose one or a mix of policy instruments including tradable quotas, feasible forms of joint implementation, harmonised domestic carbon taxes, international carbon taxes, non-tradable quotas and various international standards. At both the international and national levels, market-based approaches are likely to be more cost effective than other instruments. At the international level, all of the potentially efficient tax or quota solutions should be available to facilitate future negotiations. Under a harmonised carbon tax, incentives exist for countries to alter related policies so as to reduce the domestic welfare effects of the tax (for example by introducing offsetting production subsidies). This would make harmonised carbon taxes less effective than tradable quotas in reducing emissions. For a global treaty, a tradable quota system is the only potentially efficient arrangement where an agreed level of emissions is attained with certainty (subject to enforcement).
5. In principle, individual countries can choose from among a large set of available instruments, including carbon taxes, tradable permits and deposit refund systems as well as technology standards, performance standards and product bans. A choice of tradable quotas at the international level would provide maximum flexibility for instrument choice at the domestic level.
6. A tradable quota or permit system has the disadvantage of making the marginal cost of emission reductions uncertain while a carbon tax has the disadvantage of leaving the effect on the level at which emissions are controlled uncertain. The weight given to the importance of reducing these different types of uncertainty will be crucial in determining the final choice between competing market-based instruments.
7. The consequences of climate change policy will be determined by the choice of policy instrument as well as the design and implementation of those policies.

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Table 11.1: A Taxonomy of Costs of Environmental Regulation

Government Administration of Environmental Statutes and Regulations
Monitoring Enforcement
Private Sector Compliance Expenditures
Capital
Operating
Other Direct Costs
Legal and Other Transactional
Shifted Management Focus
Disrupted Production
Negative Costs
Natural Resource Inputs
Worker Health
Innovation Stimulation
General Equilibrium Effects
Product Substitution
Discouraged Investment
Retarded Innovation
Transition Costs
Unemployment
Obsolete Capital
Social Impacts
Loss of Middle-Class Jobs
Economic Security Impacts

Source: Jaffe, Peterson, Portney and Stavins (1995).

Table 11.2: A Summary of Empirical Evidence on the Redistributive Impact of Economic Instruments

Instrument	Author	Country	Model	Results
Carbon tax	Bull, Hassett & Metcalf (1993)	United States	Computable dynamic general equilibrium model; spending behaviour may adjust	Tax burden is nearly proportional with respect to lifetime income
Carbon tax	DeWitt, Dowlatabadi & Kopp (1991)	United States	Partial equilibrium model; spending behaviour may adjust; expenditure data; no recycling of tax revenues	Distributional impact is regressive and varies across regions
Carbon tax	Jorgenson, Slesnick & Wilcoxon (1992)	United States	Computable general equilibrium model; three stages intertemporal optimization for household consumption	Carbon tax is either mildly progressive or regressive depending on the welfare function used
Carbon tax	Poterba (1991)	United States	Partial equilibrium model; expenditure and income data	Carbon tax is regressive, but the impact is smaller if expenditure data are used
Carbon tax	Schillo, Giannarelli, Kelly, Swanson & Wilcoxon (1992)	United States	DECO aggregate macroeconomic model; expenditure data; three	Depending on the compensation system adopted, the carbon tax is regressive to compensation systems: neutral
Carbon tax	Schillo, Giannarelli, Kelly, Swanson & Wilcoxon (1992)	United States	Urban Institute's TRIM2 microsimulation model; two compensation systems	Carbon tax is regressive w.r.t. pre-tax income in both scenarios, but it becomes regressive to neutral relative to post-tax income
Carbon tax	Pearson (1992)	Europe	Partial equilibrium model; spending behaviour may/ may not adjust (2 models); Eurostat data	Both models indicate that tax on domestic fuels is regressive, while tax on motor fuels is mildly progressive
Carbon tax	Pearson & Smith (1991)	Europe	IFS model of consumer expenditures; compensation system; spending behaviour may adjust	Ireland and UK show a regressive impact. For other countries, the burden is weakly related to income
Carbon tax	Shah & Larsen (1992)	Pakistan	Partial equilibrium model; income and expenditure data; three scenarios	Carbon tax incidence is either proportional or progressive in a developing country context
BTU tax	Bull, Hassett & Metcalf (1993)	United States	Computable dynamic general equilibrium model; spending behaviour may adjust	Tax burden is nearly proportional with respect to lifetime income

Instrument	Author	Country	Model	Results
Gasoline tax	Greening, Schipper & Jeng (1993)	United States	Partial equilibrium model; expenditure data	Gasoline tax affects negatively mainly older married couples with dependent children. Income distributional results not reported
Gasoline tax	Krupnick, Walls & Hood (1993)	United States	Partial equilibrium econometric model; limited adjusting behaviour	Gasoline taxes are regressive, much more than previous studies since income data are used
Gasoline tax	Poterba (1990)	United States	Partial equilibrium model; expenditure data	Gasoline tax is broadly regressive if the lowest income class is ignored. The latter class devotes a smaller share of their budget to gasoline than the lower-middle income class
Tax on GHG emissions	International Energy Agency (1993)	Europe	Partial equilibrium model; expenditure data	Regressive effect on households if no compensatory measures with respect to domestic heating. Less clear result for motor fuels
Tax on direct fuel expenditure	Smith (1992a,b)	Europe	Partial equilibrium model; expenditure data; spending behaviour may/may not adjust; two compensatory systems	Carbon tax is regressive, but if spending behaviour adjusts its impact is smaller; only lump-sum transfers make the impact progressive
Tax on industrial energy use	Smith (1992b)	United Kingdom	Input-output tables + consumer spending simulation program	Modest effect of changes in prices on consumers spending, but negative especially for low income households

Table 11.3: Carbon Tax Incidence in Developing Countries

Tax incidence with respect to				
Institutional considerations	Implications for tax shifting	Income	Expenditure	Life time income
(a) Foreign ownership and control	Rome by foreign treasury through foreign tax credits	Nil	Nil	Nil
(b) Full market power	Full forward shifting (100% on final consumption)	Regressive (pro-rich)	Less regressive	Less regressive
	Perfectly inelastic demand or perfectly elastic supply			
(c) Price controls and legal pass-forward of the tax disallowed	Zero forward shifting (100% on capital income)	Progressive (pro-poor)	Progressive	Progressive
	Completely inelastic supply		-	-
	Import quotas and rationed foreign exchange		-	-
	Reduced rents			
	No effect on prices (100% on capital income)			
(d) An intermediate case of (a) and (b) above	Partial forward shifting (31% to capital income, 69% to final consumption)	Proportional	Progressive	Progressive

An Evaluation of the IPCC IS92 Emission Scenarios

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NOTE: This is the Technical Summary of Chapter 6: *An Evaluation of the IPCC IS92 Emission Scenarios* of the 1994 IPCC Special Report.

Technical Summary¹

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 a policy perspective they provide information about the consequences of action or inaction to reduce greenhouse gas emissions. Recognising the pivotal role of these scenarios, the IPCC undertook the development of a comprehensive and international set of emission scenarios as part of its First Assessment (1990). In 1992 the original reference scenario, SA90, was updated with new information and six new reference scenarios were developed: IS92 a-f (reported in IPCC (1992)).

This report presents an evaluation of the six IS92 Scenarios. Other published scenarios are also taken into account, but only by way of comparison with the IS92 Scenarios. It is emphasised 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 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 limited time available for this evaluation, it focuses exclusively on CO₂, CH₄, N₂O and S emission scenarios from energy and land-use activities. Other sources of greenhouse gases and sinks are not discussed.

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 industrialised and the developing world.

It is also important to note that no other scenarios other than the IS92 Scenarios were evaluated. Therefore the reader should be aware that any shortcomings identified for the IS92 Scenarios in this evaluation may or may not apply to other scenarios.

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

Because there are no generally accepted procedures for evaluating these or other kinds of scenarios, a new approach is proposed. The approach consists of a set of purposes of scenarios, together with criteria to satisfy those 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 purpose can include setting emission reduction targets and developing scenarios to reach these targets. It can also include examining the driving forces of emissions and sinks to identify which of these forces can be influenced by policies.
- Purpose 4. As input for negotiating possible emission reductions for different countries and geographic regions.

Because the IS92 Scenarios were only designed for Purpose 1, this evaluation centres on the suitability of the scenarios for this purpose.

The mixed scientific/policy nature of the scenarios makes it difficult to separate scientific from policy objectives. Indeed, Purposes 1 and 2 have both scientific and policy goals. From the scientific side, they explore future states of the global climate system, and from the policy side, they assess the consequences on climate and society of different emission levels.

No accepted methods exist for evaluating whether the IS92 Scenarios are satisfactory for Purpose 1 above, or any of the other purposes.² Scenarios deal with the future, so they cannot be compared with observations. The "reasonableness" of a scenario can be evaluated by its assumptions and methodology, but this is best done by comparing several models in an organised exercise. However, this approach 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. Although this comparison does not answer all questions about the scenarios, it provides information about their position 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 emissions are more detailed and advanced than those for land-use emissions. In addition, existing energy models could easily be adapted to compute CO₂ emissions. As a result, much of the scenario comparison focuses on energy-related emissions with the following results:

²The Terms of Reference referred to in the Work Plan require that the evaluation of the IS92 Scenarios by Working Group III should result in a report on the "validity, appropriateness and utility" of "a range of internally consistent scenarios for future emissions based on reasonable economic, demographic and technological projections, and taking account of gaps and uncertainties in available knowledge, especially concerning the evolution of socio-economic development and technology; where possible, policy assumptions should reflect their economic and social consequences." This chapter evaluates the IS92 Scenarios in the light of most of the specific factors outlined in Part III, "Emissions Scenarios", Chapter 5, "Consideration of Consistent Scenarios," of the approved WG III Work Plan, but does not evaluate the IS92 Scenarios according to all the above factors because of the great difficulty in doing so in the time available.

¹This Summary was accepted as a Technical Summary by the IPCC Working Group III Plenary.

- Energy-related emissions currently dominate other types of CO₂ emissions and will continue to do so in the future under all scenarios considered.
- Almost all published non-intervention scenarios (including the IS92 Scenarios) show an increase in energy-related CO₂ emissions over the next century. Only one of the 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 GtC/yr in 2100. (1 GtC stands for one gigatonne (10⁹ tonnes) of carbon. A gigatonne is equal to a petagram.) The IS92 Scenarios bracket a large part of this range, spanning the range 4.6 to 34.9 GtC/yr.
- 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, but by 2100 it is nearly a factor of 8. The highest and lowest non-IPCC scenarios reviewed here vary by a factor of 3 in 2025 and a factor of 50 in 2100.
- This wide range can be explained mostly by differences in the input assumptions for the scenarios, particularly assumptions regarding economic and population growth, and 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 from 1990 to 2100 range from 492 to 3447 GtC (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 GtC).
- The cumulative emissions of energy-related CO₂ from 1860 to 1990 were about 215 GtC. This amount is exceeded by even the IS92c Scenario (the lowest IPCC scenario) which would result in energy-related emissions of 700 GtC from 1990 to 2100.
- Cumulative emissions are important for climate analysis because CO₂ and other direct greenhouse gases can affect climate for decades to centuries after they are emitted because of the integrative nature of the atmosphere-ocean system.
- Whether or not CO₂ emissions will accumulate in the atmosphere depends on many factors that 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 ppmv³ by 2100. Hence, even the lowest IPCC Scenario (which would result in lower CO₂ emissions in 2100 than at present) could lead to a build-up of CO₂ in the atmosphere.

Compared with CO₂, far fewer scenarios are available for CH₄, N₂O and other greenhouse gas emissions. For these scenarios an additional source of uncertainty is important, namely, the uncertainty of *baseline* emission estimates. Thus, 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 the IS92 Scenarios for non-CO₂ emissions overlap with the few other published scenarios of this type.

Global scenarios of sulphur emissions are virtually unknown outside of the IS92 Scenarios. Baseline emission estimates are quite good for the OECD regions but less reliable elsewhere. In the IS92 Scenarios, estimates of energy-related sulphur emissions in the year 2100 range by somewhat less than a factor of 5.

Regional Results

There are many regional and country estimates of energy-related CO₂ emissions, but the estimates do not correspond to the IS92 regions, so comparison was not possible. The following comments can be made about the few scenarios available for comparison:

- The range of results is about the same as that of the 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 decline in economic activity in this region.
- The range of IS92 Scenarios is in the lower half of the range of non-intervention estimates for the USA.

Energy-Related Scenarios — How Do Their Components Compare?

Both the IS92 Scenarios and other scenarios examined in this report rely on large numbers of input assumptions. It was not possible in this evaluation to assess the differences between all these assumptions. Rather, in this evaluation the projections of energy-related CO₂ emissions were broken down into four components, and these components were compared across the scenarios. The four components 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 components are specified as model inputs, and some are derived from model calculations.
- Nearly all scenarios show a downward trend in energy intensity. The energy intensities of the IS92 Scenarios have a narrower range than those of other scenarios.
- The carbon intensity of all IS92 Scenarios shows a downward trend, whereas the carbon intensity of some non-IPCC scenarios shows an upward trend.
- Assumed changes in energy and carbon intensities have an important influence on estimates of emissions, especially in the second half of the next century.
- The range of economic growth assumptions for the IS92 Scenarios is representative of the range in other global scenarios (this statement applies to scenarios of both energy-related and land-use emissions). The economic growth rates used for the IS92 Scenarios are generally lower than historical rates, but would nevertheless lead to large increases in *per capita* GDP in all regions.
- 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 population growth rates of all the 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.

³ 1 ppmv = 1 part per million by volume.

- It is outside the scope of this report to evaluate the various critical issues related to population projections, such as population ageing, the 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 range found in 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 regarding future emission projections can be attributed to the different methods and models used to compute emissions. However, the evidence from model comparisons indicates that model differences explain only a small part of the wide range of emission estimates found in the literature. Most of this range arises from differences in the input assumptions of the scenarios. The input assumptions that have the most effect on the range of emission estimates are those concerning population growth, economic growth and the amount of carbon-based fuel in use in the economy.

The IS92 Scenarios are also sensitive to assumptions about labour productivity, the growth of demand for energy in developing countries as incomes rise, and the rate of improvement in end-use energy efficiency not related to fuel prices.

Land-use-Related Scenarios — How Different Are Their Results?

Global Results

Far fewer scenarios are available for land-use emissions than for energy emissions, and global estimates are more common in the literature than regional estimates. The following comments can be made about global CO₂ scenarios related to land-use:

- Net deforestation accounts for about 18% of current total CO₂ emissions, and most scenarios assume that this percentage will decline in the future.
- Projected emissions of CO₂ resulting from deforestation differ widely. Unlike energy-related emissions which diverge with time, land-use emissions have their widest range (0.2 to 4.8 GtC/yr) before the middle of the 21st century. Most scenarios converge to zero by the end of the century because they project that either the forces causing deforestation equilibrate or forests are depleted.
- The IS92 Scenarios fall within the lower half of the range of other global land-use CO₂ scenarios.
- The range of cumulative emissions over the period 1990 to 2100 is 30 to 320 GtC. Cumulative emissions have an upper bound set by the maximum available amount of terrestrial biomass that could be oxidised (about 600 GtC neglecting afforestation). No similar upper limit is foreseen for energy-related emissions in the next century.

Regional Results

The few published regional land-use scenarios for CO₂ and other greenhouse gases exhibit considerable differences. The IS92 Scenarios sometimes fall inside and sometimes fall outside the range of other scenarios. The range of emission estimates is about the same for regional scenarios as it is for global scenarios, and the regional and global scenarios converge in a similar way by the year 2100.

Land-use-Related Scenarios — How Do Their Inputs Compare and To What Are Their Emission Estimates Sensitive?

- The assumed rate of deforestation is the most important factor influencing emissions of CO₂ related to deforestation. Most scenarios make simple assumptions about the causes of deforestation, although some use models to simulate land conversion. The different ways of representing deforestation lead to different estimates of deforestation rates: the scenarios examined agree that forest clearing will diminish by 2100 for the reasons cited above.
- Assumptions about the carbon content of vegetation also strongly influence estimates of CO₂ emissions.
- The scenarios examined take a wide variety of approaches to estimating future emissions. This variety reflects lack of knowledge or agreement on how best to represent emission-generating processes related to land-use.
- Not only are these processes poorly understood, but baseline estimates differ between scenarios. Differences in baseline estimates lead to even greater differences in future emission estimates. Results from studies of current emission inventories are needed to improve these baseline estimates.
- The IS92 Scenarios do not account for the feedback of climate to land-use emissions, and this is one reason why their results differ from those of other scenarios. However, climate feedbacks are quite uncertain; thus 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 emissions.

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 fulfil the most important criteria for this purpose. Specifically, their global results span the range of results from other scenarios, and in this sense 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 sulphate 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

an 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 interesting to ask whether they are useful for any of the other purposes. They should not be used for Purpose 2 (evaluating the consequences of intervention to reduce emissions), because five of the six IS92 Scenarios have emission estimates that are substantially higher than policy scenarios published in the literature.

The IS92 Scenarios are inadequate for Purpose 3 (estimation of feasibility and costs of policies) because five out of the six scenarios do not include mitigation measures specifically targeted towards climate change. The IS92 Scenarios have limited value as reference scenarios for mitigation studies because their input assumptions and results do not have sufficient detail for geographic regions and sectors. Another reason that the IS92 Scenarios are inadequate for purpose 3 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 (as input to negotiating possible emission reductions) because of the high uncertainty of current greenhouse gas estimates from many sectors and countries. However, the IS92 Scenarios 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 IS92 scenarios were not intended for Purpose 4.

For the reasons noted above, it is recommended that researchers use the IS92 Scenarios solely as input to atmosphere/climate models for examining the consequences of not acting to reduce greenhouse gas emissions (Purpose 1).

Is One Scenario More Likely Than Another?

In some ways IS92a is an intermediate scenario. Its global CO₂ emissions fall near the middle of other scenarios at least up to the 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 organisations. In other ways, however, IS92a 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 any of the scenarios. Furthermore, given the degree of uncertainty about future emissions, we recommend that analysts use the full range of IS92 Scenarios rather than a single scenario as input to atmosphere/climate models.

Users of the IS92 Scenarios are cautioned, however, that the lowest scenario (IS92c) has emission levels and some input assumptions that are more characteristic of an intervention than a non-intervention scenario.

The Question of New Scenarios

Because the IS92 Scenarios are neither designed nor suitable for Purposes 2, 3, and 4, new scenarios may be needed to fulfil these purposes. It is worth repeating that this report 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 current scenarios, it is likely that new reference scenarios will be needed for the following:

- (i) to take into account the latest information on economic restructuring, especially in the CIS, Eastern Europe, Asia and Latin America (We note that economic 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.);
- (ii) to evaluate the possible consequences of the Uruguay Round amendments to the General Agreement on Tariffs and Trade;
- (iii) to explore a variety of economic development pathways (e.g., a closing of the income gap between industrialised and developing regions);
- (iv) to examine different trends in technological change; and
- (v) to take into account the latest information about current emission commitments in connection with the Framework Convention on Climate Change.

The current commitments to stabilise emissions under the Convention, if maintained over the course of the next century, 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 (relative to the IS92a Scenario). This percentage reduction is somewhat greater or less depending on the year and scenario. This is an optimistic scenario, in particular because it assumes that countries will freeze their emissions after the year 2005 according to their current commitments.

New scenarios are also needed that are consistent with limits on atmospheric concentrations of greenhouse gases by specified dates. These scenarios should be related to the carbon stabilisation modelling exercises being performed by IPCC Working Group I.

The Process of Developing Scenarios

It is recommended that the IPCC or another suitable organisation 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 harmonising scenarios and model calculations and should emphasise:

- *Openness*: scenario development should be open to wide participation by the research community, particularly from developing countries. Openness requires extensive documentation of modelling assumptions and inputs.

- *Pluralism*: A diversity of groups, approaches and methodologies should be encouraged, although they should be harmonised as noted below.
- *Comparability*: Reporting conventions for input and output should be standardised.
- *Harmonisation*: Input assumptions and methodologies for the scenarios should be harmonised to provide a common benchmark for scenarios from different groups.

To accomplish Purpose 3 for emission scenarios (estimation of feasibility and costs of mitigation measures), it is important not only to analyse 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 and *integrated* scenarios of global change.

Current and new scenarios should be widely disseminated to countries, international organisations, non-governmental organisations 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 the input assumptions used to derive the scenarios. In addition, special effort is needed to improve the capabilities of researchers to analyse and develop scenarios, especially in developing regions. The IPCC can play a role in these activities.