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A Generic Assessment of Response Options

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SUMMARY

In this chapter, current response options for dealing with climate change are assessed on the basis of their feasibility, acceptability, cost-effectiveness, and applicability. As much as possible, specific attention has been given to the applicability of these various options in the developing countries and countries in transition. The chapter does not, however, contain an evaluation of the (macro)economic effects that large-scale applications of the various options might have in different regions of the world.

Conceptually a distinction must be made between mitigation and adaptation options on the one hand, and indirect options – that is, options not designed to have an impact on the greenhouse effect but that nevertheless do – on the other. Indeed, many technological developments and various policies have an impact on energy use and thus on the global climate. An effective climate change response strategy should therefore preferably pay attention to possibilities of joining climate response options with responses to other socioeconomic transition phenomena, as in the application of an integrated systems approach.

The various response options can be assessed in fundamentally different ways. At one extreme is the engineering efficiency approach, which focusses only on costs and how these are related to internal and external economies of scale and learning effects. At the other extreme is the welfare economic approach, which, in addition, considers such welfare aspects as social, political, or environmental resistance to the option's application. Costs associated with the diffusion of technologies, public education, and lifestyle changes are also taken into account.

A number of CO_2 mitigation options have been proposed, including

- Energy conservation and efficiency improvement
- Fossil fuel switching
- Renewable energy technologies
- Nuclear energy
- Capture and disposal technologies
- Enhancing sinks and forestry options

Attention has also been focussed on reducing emissions of methane.

With respect to *energy conservation and efficiency improvement,* reductions in energy intensities during recent decades have varied widely across countries and also within the group of developing countries. Some of this variation, however, reflects differences in how the underlying variables have been measured.

Because reductions in national energy intensities are related to structural changes in national economies, the growth of the secondary sectors in developing countries may give a biassed view of their energy efficiency improvement results. In most industrial countries, in contrast, a trend towards "dematerialization" (i.e., a shift away from the highly energy-intensive secondary towards the less energy-intensive tertiary sector) has favoured lower energy intensities.

There is a broad consensus in the literature in favour of efficiency improvement, because it is seen as directly beneficial irrespective of any impact on greenhouse warming and because it has significant scope for negative net cost (i.e., no-regret) applications. The potential for energy efficiency improvements in production seems promising, especially in the power production, transportation, steel and cement production, and residential sectors. However, because the end use phase is the least efficient part of an energy system, improvements in this area would produce the greatest benefits. The potential for efficiency improvements in the developing countries is roughly similar in magnitude to that in industrialized countries. By contrast, energy conservation may be achieved somewhat more easily in the industrialized countries.

Optimism about the scope for no-regret options with respect to energy efficiency varies considerably and depends to a large extent on the discount rate that is employed. Revealed consumer discount rates for household investments can be very high indeed. Similarly, in developing countries a lack of access to information and limitations of institutional capacity, human skills, and financial resources may cause the revealed time preference to be much higher than commercial interest rates.

The potential for energy savings is estimated at 10-40% for production and 10-50% for residential use. However, to achieve such results, institutional and information factors are crucial. So too is the degree to which the option may help in deriving other environmental benefits.

With respect to *fossil fuel switching,* relatively little information about costs is available, although it is recognized that fossil fuels will remain the dominant energy source for several decades yet. Estimates of the costs of switching vary to a large extent, depending on the type of measure, the fraction of natural gas lost to the atmosphere from leakage during production and distribution, and the opportunity costs of the option (which depend to a large extent on the availability of, for instance, coal reserves).

These opportunity costs may be particularly large in populous countries with massive coal reserves, such as China and India. In fact, in developing countries growth may even result in a transition from less carbon-intensive biomass to more carbon-intensive fossil fuels.

Renewable energy technologies may be sustainable with respect to energy inputs but may not always be socially and environmentally benign in other respects. This is particularly so in the case of large-scale applications (for example, of major hydro or biomass projects) in developing countries.

The technical potential of the renewable options not currently utilized varies from 50% for biomass to 75% for hydro to several thousand per cent for wind. Many renewable technologies, however, tend to be site-specific (i.e., their application is limited to a finite number of specific sites). Other problems include potential environmental risks, technological readiness, and cost-effectiveness.

Though some renewable options are almost mature, others are still in the demonstration stage. Practicable potentials therefore vary to a large extent, although much will depend on the costs of the various options.

Cost estimates diverge widely, mainly due to the time horizon adopted, the discount rate chosen, and the capacity and useful lifetime assumed. Moreover, costs are strongly influenced by site-specificity, variability of supply, and the form of final energy delivered. Other aspects that influence cost behaviours are learning effects, economies of scale, and the need for immediate storage or transport of the energy generated.

The promise of renewables lies mainly in their large potential and modest price on the spot. These factors are particularly relevant for developing countries, which, by using local renewables, could reduce their dependence on imported fossil fuels. Local communities could benefit significantly from small-scale applications and their net positive side effects.

In view of these considerations, the future role of renewables is hard to predict precisely; the share of renewables in the 2020 energy mix will, however, probably not exceed 25%.

Nuclear energy technology is long past the demonstration stage, but the issue of the safe storage of nuclear waste remains unresolved. Because of their long design and construction time (10-15 years) and the enormous investment costs of nuclear power plants, the nuclear option is also rather inflexible.

In view of the waste disposal problem and the consequent lack of public support, the share of nuclear energy in total energy use is expected to increase only to a limited extent during the coming decades.

Capture and disposal have potential in cases where a switch from coal to other fossil fuels is difficult for one reason or another. Some technologies already exist; others are being developed.

The disposal option is ultimately limited not only for technical reasons but also because disposal cannot permanently prevent the reentry of carbon into the atmosphere. This is irrespective of the way in which disposal would take place. The practicability of this option is still a matter of discussion, because in some types of disposal (e.g., in aquifers or oceans) environmental impacts are uncertain.

The scope of *forestry options* is determined by the large expected potential, modest costs, low risk, and positive side effects. However, there is still a large amount of uncertainty with respect to the net carbon release from deforestation and land use changes on the one hand and the long-term carbon absorption capacity of afforestation efforts on the other. Basically, forestry measures, like removal options, are to be seen as an intermediate response policy.

Uncertainties in assessments of the global potential for halting or slowing deforestation and for reforestation are linked to the extent of human encroachment into the forests, the area available for forestry measures, and the annual and cumulative carbon uptake per hectare.

Mitigation policies using forests are generally considered relatively cost-effective, especially if applied in developing countries. With the costs of afforestation, much depends on whether one assumes that the forests can be exploited sustainably or, instead, should be left alone to mature, and on the acceptance of the newly planted forests by the local population.

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

Estimates of cost-effectiveness of forestry measures depend strongly on whether one takes a static or dynamic point of view. There is a clear tendency to focus increasingly on cost functions rather than point estimates; the former approach seems clearly more relevant in the case of large areas. Moreover, the cost assessment methodology has been increasingly refined (for example, by the inclusion of discounting procedures). Cost estimates, which are now probably more realistic, tend to fall within a range of \$30-\$60/tC for large annual uptakes.

With respect to *methane,* the emission data available reveal wide discrepancies between various regions. Information about methane leakage and distribution is also rather scanty, and some of it is unreliable. The same applies to information about the costs of methane control options.

Information about the cost functions of the various mitigation options is still weak, because the functions are not only time-specific but also region- and context-specific. The weakness of information also relates to the remarkable fact that the scope for no-regret options seems to be significant, especially in developing countries. This apparent scope is most likely due to the high actual time preference rates, lack of information, and limitations of human capacity. All this and the different assessment perspectives mentioned earlier may explain why virtually no studies exist in which the optimal mix of options is designed on the basis of their underlying cost functions and feasibility.

The few studies of this kind that have been done provide only tentative results but do indicate – given present knowledge about the cost functions of the various options – that the pure application of the cost minimization principle would require a significant share (probably more than half) of the emission reduction targets to be achieved via the application of options outside the OECD area. In addition, in terms of the size of the emission reduction, energy conservation and efficiency improvements and the forestry option seem to provide the largest potential from a cost minimization point of view. 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.

To illustrate how an optimal mix of response options might look, the result of a (linear programming-based) cost minimization simulation using the available cost-function information disaggregated by region is presented in Table 7.13 for a predetermined emission reduction target of 2.4 GtC. In view of the tentative and uncertain character of the underlying data, the outcomes can only be seen as an illustration of what an optimal policy mix might be (recognizing that marginal costs per option per region generally tend to increase to the point where they eventually become prohibitive). Obviously technological or political breakthroughs may significantly affect the optimal mix.

Adaptation options can be surveyed in many ways. One is to consider what should be adapted to and how it should be done. No systematic cost data on the various adaptation options are available, although information about land protection costs against flooding and sea level rise is rapidly increasing. Many efforts are now underway, however, to reduce the vulnerability of agricultural production to climate change through adaptation policies. Especially in developing countries there is an urgent need for both more information and a better infrastructure for the actual implementation of adaptation techniques.

Finally, the point has to be made that when it comes to the introduction and application of the various options, the developing countries occupy a special position. The application and acceptance of these options often crucially depends on the international transfer of technologies as well as the countries' own local institutions and abilities to build their human capacity. Therefore, the conditions needed to ensure the success of these processes, such as joint implementation and technology transfers from developed to developing countries, deserve a high priority on the academic research agenda.

7.1. Introduction

In recent years a host of response options has been proposed 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, that is, *mitigation, adaptation,* and *indirect policy options.* Many response options are thoroughly discussed in Volume 2 of this report, with a major emphasis on technological feasibility. Some aspects of these options will be taken up here and assessed generically, that is, not only from an engineering efficiency point of view but also from that of welfare economics.[1]

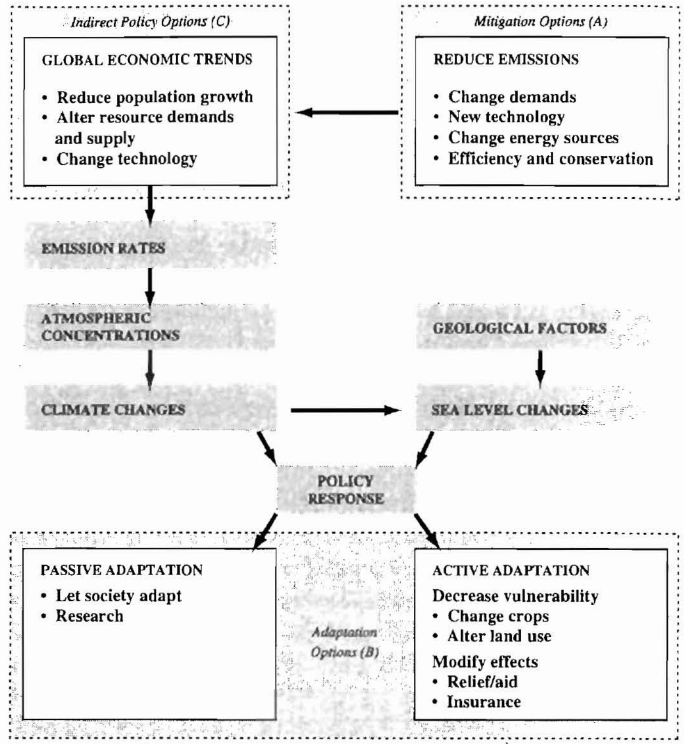
The present chapter surveys the set of options that are feasible from a comparative economic perspective in order to assess the scope and priorities of potential policies. The main purposes are

- To set up a structure so the various options can be put into proper perspective and the assessment to be made can be truly generic (Section 7.2)
- 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 7.3)
- To review the various options in terms of (technical and practical) applicability, cost-effectiveness, and social acceptability, both as far as mitigation options (Section 7.4), and adaptation options (Section 7.5) 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 7.6)
- To analyze to what extent currently available information about various options might provide a basis for international policy cooperation (Section 7.7)

Sections 7.1 to 7.3 therefore provide the methodological base; Sections 7.4 and 7.5 survey the mitigation and adaptation options, and Sections 7.6 and 7.7 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 macroeconomic effects assessment of the various options has not been carried out here. (See in this respect also the sections in this report dealing with integrated response options.)

7.2. A Conceptual Framework

Figure 7.1 shows the policy options available to counter greenhouse warming and their possible feedbacks. The diagram may serve to illustrate that one can basically distinguish between three strategic categories of options to deal with the greenhouse issue:



Source: After Viner and Hulme (1994).

Figure 7.1: Schematic overview of available options to counter the greenhouse effect and their possible feedbacks.

(1) *Mitigation options* (Block A in the figure) are 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 8.2.2.2.

(2) *Adaptation options* (Block B) are options that focus on reducing the expected damages due to rapid climate change by combatting or avoiding their detrimental effects.

(3) *Indirect policy options* (Block C) are 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. For example, a population policy, as part of a broader policy mix that slows 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 intensity of energy and materials use 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 and other options. For conceptual reasons, however, the preceding distinction between the various types of options seems a useful starting point. Before moving on to the details, though, it would be only proper to point out what this chapter is not about. Only the broad principles underlying the response options are emphasized here. Their actual application would depend on a host of factors that are very much country-specific and include many economic, social, political, and legal considerations. Thus, they would need to be analyzed on a country-by-country basis for policymaking at national levels.

7.2.1 *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, for example, 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, the country or 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 change in the course of time, sometimes quite rapidly. 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 CO_2 and measures concerning other greenhouse gases, because the former are in actual practice largely associated with energy-related activities (i.e., both energy production and consumption) whereas the latter are also associated with other types of activities. Thus, except for some "exotic," mainly effect-oriented options such as geoengineering, orbital shades, iron fertilization, creating algal blooms, and weathering rocks, mitigation options can generally be divided into those affecting CO_2 and those affecting other greenhouse gases.

Measures concerning CO_2 include the following:

(a) Source-oriented measures
- (1) energy conservation and efficiency improvement
- (2) fossil fuel switching
- (3) renewable energy
- (4) nuclear energy

(b) Sink-enhancement measures
- (5) capture and disposal of CO_2
- (6) enhancing forest sinks

Measures concerning other greenhouse gases include phasing out HFCs (in addition to HCFCs, via the Montreal Protocol) as well as a variety of measures for reducing emissions of methane (CH_4), nitrous oxide (N_2O), 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 CO_2 mitigation effort can be concentrated here. Each of the four source-oriented options addresses elements of the energy conversion process, from primary energy production to end-use services.

Both energy conservation and energy efficiency aim to reduce total energy use without changing the current fuel mix or the fundamental structure of the energy conversion process. Energy conservation is used here to mean a reduction in energy needs resulting from a change in the nature or level of energy services (e.g., lighting areas only when they are occupied rather than during specified periods). Energy efficiency means providing the same type and level of energy service with less total energy (e.g., using more efficient lamps to provide the desired lighting level). Since energy conservation is strongly linked to the preferences and behaviour of various economic agents (such as households, firms, and governments), policies aimed at achieving it are more likely to lead to ambiguous conclusions. Consequently, most studies focus on energy efficiency.[2]

A fossil fuel switch alters the mix of fossil fuels in favour of the less carbon-intensive ones such as natural gas (and perhaps oil) and away from coal. Nuclear energy substitutes for fossil fuels as primary energy. Renewable energy is characterized by an extensive natural supply, which is vast compared to current levels of commercial energy use, and by a large long-term potential because of its regeneration capability. Mobilization of this natural supply can in some cases result in severe environmental and societal impacts.

Removal technologies (option 5) extract carbon in one form or another 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 combatting deforestation or by afforestation.[3] It may also refer to activities designed to preserve or enhance carbon uptake by soils.

7.2.2 *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. 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, in other words, assess the welfare implications of no-action scenarios, or on the net investment cost involved with adaptation measures. Since Chapter 6 of this report focusses on the former, Section 7.5 of this chapter will mainly consider the latter.

7.2.3 Indirect policy options

Potential climate change is perceived as a problem, mainly because it would interfere with the world's economic, social, and ecological systems, and eventually with its political system. Just as the precise scope and risks of climate change are subject to uncertainty, so is the future development of technology, resources, and the organization and structure of the economic, social, and political systems. However, it seems most likely that the changes in the global climate and the structural changes in the economic and political system differ significantly in at least one respect: the speed or time lag of changes to be expected. Whereas possible severe global climate change generally is expected to take approximately 50 to 100 years (although exceptions can be possible), the economic, social, and political systems may change several times within a similar period.

This difference poses a fundamental dilemma when assessing the various response options to climate change: The changing climate system has to be superimposed on economic, social, and political systems that are in constant flux due to numerous factors, with (potential) climate change being only one of them. This dilemma significantly complicates 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 be undertaken vigorously, as in the case of the Montreal Protocol (see Benedick, 1991) and the Convention on International Trade in Endangered Species.

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 – driven by such forces as 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 (e.g., in waste management and in redesigning products) – may also be expected to play an important role in shaping the economic, political, and social systems of tomorrow, especially if the policymakers' 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, and 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 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 the possibilities of joining climate change response options with responses to other socioeconomic transition phenomena, and thus increase the probabilities of actual implementation.

Examples of this approach can be found in applications of the integrated systems approach. For instance, in many developing countries crop agriculture is at present highly dependent on energy use, both directly and indirectly, and farmers have to depend on outside sources for much of their energy supply. In addition, many of these agricultural systems are based on monocultures (e.g., high-yielding varieties of wheat and rice, which increase soil exhaustion and are more vulnerable to massive infestations of pests and disease). Alternatives like low-external-input sustainable agriculture reportedly lower the need for external and energy-intensive inputs and increase productivity in farming in an ecologically robust way while at the same time reducing concerns for national food security (Reijntjes *et al.,* 1992).

Yet another example of a "multifunctional system" is wave energy. In that case the production of energy is combined with other functions, such as coastal protection or water desalination. However, this technology may also have adverse environmental side effects. All these systems can be particularly promising if applied on a relatively small scale in developing countries.

7.3. Criteria for Assessment

In discussing the assessment of response options, the application possibilities of the options themselves are evaluated rather than the policies 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 distinguish between two fundamentally different approaches for assessing response options. These approaches, however, 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 CO_2 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 forgone 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 according to 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 purpose of the present chapter, which is to provide a generic assessment of the various response options.

An afforestation programme may serve to illustrate the differences between these approaches. What investment has to be made to achieve a predetermined target in terms of net CO_2 absorption during some time interval? Using the engineering efficiency approach, one would try to determine the discounted value of the costs of land acquisition, tree planting, maintenance, security, and other needs. Any future (sustainable) harvesting returns would equally be discounted, so that the net levelized costs could be determined in dollars. On the basis of this information, and by comparing this option with other options' cost-efficiencies, one could then 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 of using the same land for agricultural purposes is forgone. 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 programme, if applied on a large scale, may have additional impacts, either positive or negative (e.g., through its effect on local climate and soil fertility, social and cultural life, on infrastructure, tourism, etc.). Ensuring that such side effects are beneficial depends on the establishment of effective monitoring and extension services at the local level. In the assessment, attention can also be paid to the distorting 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 programme 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 5).

A priori, there is no reason why the outcomes of the engineering efficiency and welfare economic assessments 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, nonmaterial 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 account fully for the various interests and impacts inside and outside the societies concerned, including the external effects and the social and political acceptability of the options. A welfare economic approach would therefore imply an assessment based on a general equilibrium model, an exercise conspicuous by its almost total absence in the literature. In this chapter, therefore, response options are evaluated on the basis of important opportunity costs and externalities.

In actual practice, even public agents may not be fully aware of the various externalities and indirect, nonmaterial, and distributional impacts of the application of response options. For one reason (e.g., pressure from special interest groups), they may not want to take these various aspects into account. For another, the information available for a full welfare assessment may simply be insufficient. What is more, even if all information for assessing the various options is available, obstacles in setting up the institutional machinery can impose serious bottlenecks, so that appropriate action will not follow.

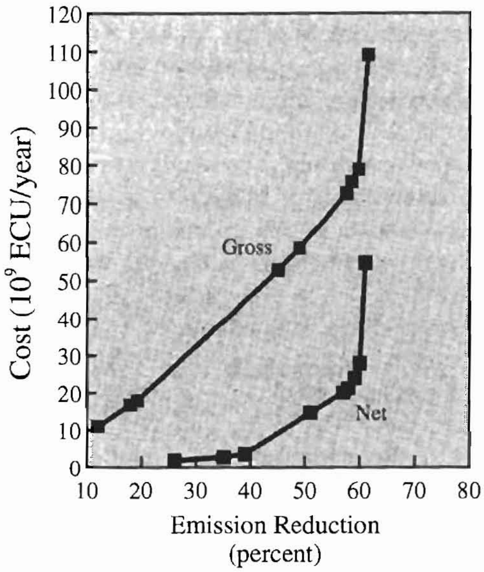
As preceding chapters have already noted extensively, a welfare economic assessment of climate change response options faces some large practical obstacles, particularly in the developing countries. First, the policy priorities, especially with respect to the greenhouse issue, will often differ from those in industrialized countries. Second, information about externalities at the local level may not fully reach the public sector because of limitations in data collection, processing, and communication; on the other hand, policies dealing with externalities may fail to reach part of the local population. Third, most developing countries face a severe lack of institutional and human capacity to deal with these issues.

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

(a) Average costs may decrease at a larger scale of application (internal economies of scale).
(b) Costs of a given option may decrease when other options are applied on a larger scale 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 on a larger scale; this problem may be particularly relevant if response technologies require a high level of technical expertise.

If one focusses mainly on items (a) to (c), optimism about the options' economic potential may rise. This is the perspective taken by the engineering efficiency approach. If, however, one focusses instead on items (d) to (e), one might easily take a much more pessimistic view, associated with the welfare economic perspective.

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



Source: TNO (1992).

Figure 7.2: Options for CO_2 emission reduction in the EU, net and gross costs, and effectiveness.

renewable energy, besides achieving a carbon emission reduction, also produce energy and are therefore substituting for traditional fossil energy resources. This consideration 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 (see Figure 7.2). Differences between gross and net costs turned out to be notably relevant for the options of energy saving, renewables, nuclear energy, and energy farming.

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 biassed view. A more complete assessment must recognize different priorities within countries, the impact of externalities, the political acceptability at various levels, and a variety of distributional aspects. In this respect it seems that, although both approaches raise analytical concerns that 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 countries in transition.

In other chapters (especially Chapters 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 are fewer studies for economies in transition or developing country economies. Moreover, where the potential for political, social, and economic change in these economies is great, future predictions are probably more uncertain. In view of the structural changes that are underway in these regions, it is imperative to improve further the understanding of the potential for reducing or absorbing greenhouse gas emissions in these economies, particularly their sensitivities to other important considerations such as economic and technological development.

7.4. Mitigation Options

This section will treat in some detail the mitigation options listed in Section 7.2.1, along with their costs and potential.

7.4.1 Energy conservation and efficiency improvement

In order to put the energy efficiency option into a proper perspective, the Kaya identity (Kaya, 1989) may provide a useful starting point:

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

where 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 CO_2 emission reduction target can only be achieved by a reduction in carbon intensity (CO_2/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 the targets set with respect to GDP increase. This relationship obviously reinforces the need to pay specific attention to developing countries.

Historically, carbon and energy intensities in most countries 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 (2.6% in IEA member countries during 1980-1984) in most Western countries in the 1970s and much of the 1980s (Nakicenovic *et al.,* 1993). 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. Moreover, the carbon and energy intensity in a number of large rapidly growing developing countries today is much higher than in virtually all presently industrialized countries at a similar stage of technological development (Nakicenovic *et al.,* 1993). Also, in contrast to the postwar trend noticed in industrialized countries, some developing countries have not succeeded 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, for example, the estimated energy intensity in Japan fell by more than 35% (Ogawa, 1992), with the energy intensity of electric refrigerators falling by nearly 67% between 1973 and 1987 and the efficiency of motorcars increasing from around 9.4 to about 13 km/litre (49%). During the same period, the U.S., (the then) West Germany, and France lowered their energy intensities by 27%, 22%, and 17% respectively, and IEA member countries by 25% (IEA/OECD, 1991). In most cases, changes have been most apparent in the industrial sector. However, low oil prices and economic recession caused a slowdown in energy intensity reduction in the late 1980s and early 1990s.

Over the 1980s, various developing countries managed to lower their industrial energy intensity: China by approximately 30% (Huang, 1993), Taiwan (between 1970 and 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), and Mexico (Guzman *et al.,* 1987), energy intensity actually increased. In addition, Imran and Barnes (1990) have reported energy intensity increases in Brazil (+20%), Pakistan (+26%), India (+25%), and Malaysia (+48%) for the period 1970-1988.

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, also shows a declining trend globally. From 1860 to the 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 fossil fuel switching and using nuclear and renewable energy as fossil fuel substitutes. However, various projections with respect to developing countries indicate that, without serious policies and changing trends, not only will total emissions increase rapidly but also 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 *et al.,* 1991).

The two factors that underlie reduced energy intensities are improvements to the energy efficiency of individual production processes and structural changes in the economy (in particular, the increasing economic predominance of less energy-intensive sectors, such as many of the service sectors, and the energy efficiency of spatial planning). Only a few studies explicitly incorporate the impact of structural changes. Most focus on energy efficiency measures, which are generally considered to be the most relevant factor.[4] To illustrate, it was estimated that energy efficiency improvements were responsible for about three-quarters of the 26% reduction in U.S. energy intensity during 1973-1986 (Schipper, Howarth, and Geller, 1990).

Disregarding the impact of structural shifts on energy intensity in an intercountry comparison may easily create a biassed view, because the industrialized economies have generally shifted away from the highly energy-intensive secondary towards the less energy-intensive tertiary sector (a process known as "dematerialization"), whereas the developing countries in general are increasingly entering the secondary sector.

Among virtually all studies, there is a 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, as long as 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 ratio of useful energy (i.e., the amount of energy that provides useful services) to overall primary energy (i.e., the amount of energy recovered or gathered directly from natural sources) is estimated at only 34% globally. It is lowest, at 22%, in the developing countries and highest, at 42%, in the countries in transition (Nakicenovic and Grübler, 1993). This ratio, in turn, is the product of two other ratios:

- The final energy (energy delivered to the point of consumption) to primary energy ratio (with a global average of 74%, a maximum of 80% in the developing countries, and a minimum of 69% in the countries in transition)
- The useful energy to final energy ratio (with an average of 46% globally, 28% in the developing countries, 53% in the industrialized countries, and 60% in the countries in transition)

These numbers suggest that the scope for improving energy efficiency is particularly promising with regard to increasing the useful-to-final energy ratio. Efficiencies are lowered further if seen from an "exergy" point of view, that is, if the actual services (work) supplied by the energy source are related to the corresponding inputs minimally required: The exergy efficiency of primary inputs in the market economies is only a few percent (i.e., of the order of 2.5-5%) if the energy service is fully taken into account.

Indeed, a back-of-the-envelope calculation shows that, if energy efficiencies of the current structure of the OECD technologies were 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 instantaneously replaced the current ones, 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 the 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 for reducing energy consumption exists in many sectors

Table 7.1. *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[a] (%)	(D) Existing Market/Inst. Barriers[b] (%)	(E) Potential Energy Savings Not Likely to Be Achieved[c] (%)
Residential space heating & conditioning	11.4	11	10–50	Some/Many	Mixed
Residential water heating	3.4	3.6	Mixed	Some/Many	Mixed
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 & 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[d]	4.1	4.6	15–25	Few/Some	0–15
Chemicals[d]	8.4	5.9	10–25	Few/Some	0–20
Pulp and paper[d]	2.9	1.2	10–30	Few/Some	0–10
Cement[d]	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

[a]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.
[b]Extent of existing market and institutional barriers to efficiency investments.
[c]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).
[d]Energy use only.
Note: How to read this table: For example, for residential 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.
Source: IEA/OECD (1991).

and regions, 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 that is related to the OECD area is IEA/OECD (1991), as shown in Table 7.1. In this respect it should be mentioned that several policy and regulatory reforms have recently begun to address some of these barriers. In the U.S., 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 *et al.*, 1988; Kaya *et al.*, 1991; Gupta and Khanna, 1991; and ESCAP, 1991) or focus on specific sectors. To illustrate, recent estimates for the U.S. 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-fuelled cook stoves can be increased from a range of 10-20% to 25-35% using improved stove designs at a capital cost of under $10 per stove. Cooking efficiency can be further increased to the 40-65% range by shifting from biomass-based fuels to kerosene, liquefied petroleum gas (LPG), or electricity, but at a significantly higher capital cost (U.S. 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, in other words, if interindustry demands are included during sectoral comparisons. A comparative study of 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 total emissions (one-third of the 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 7.2. *Regional potentials for reducing industrial carbon emissions by cost categories (in Mt Carbon)*

	Cost Saving or at Moderate Cost		Cost (< 100 $/t C)		Cost (> 100 $/t C)		Sum†	
Market economies		116		47		207		370
Efficiency improvement	15		45		84		144	
Structural change/recycling	95		n/a		25		120	
Fuel substitution	6		n/a		n/a		>> 6	
Process technology process	0		2		98		100	
Reforming economies		223		113		> 46		382
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 process	0		10		46		56	
Developing countries		34		78		> 56		168
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 process	0		8		56		64	
World		372		238		309		920
Efficiency improvement	75		139		84		> 298	
Structural change/recycling	279		> 79		> 25		> 383	
Fuel substitution	19		n/a		n/a		>> 19	
Process technology process	0		20		200		220	

†Total reduction potential could be higher because not all measures have been assessed.
Note: n/a = not assessed.
Source: Grübler *et al.* (1993a).

The issue of energy conservation and efficiency in the developing countries differs in some respects from the issue in industrialized countries. First, a substantial part of the demand for energy is often met from renewable energy sources like biomass. This is likely to remain so in the short to the medium run, and 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 socio-economic perspective (U.S. Congress, 1992). Second, energy efficiency in industrial activities generally showed little or no improvement (Imran and Barnes, 1990). Third, the demand for electricity is growing at a rate that is often hard to keep up with. There are developing countries that 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 presently low level of energy efficiency in the developing countries and the consequently large scope for improvement, the potentials for energy saving in these 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; U.S. Congress, 1992). Finally, the the energy market in developing countries is often distorted by energy pricing policies.

By contrast, energy conservation may be achieved somewhat more easily in the industrialized countries, insofar as a trend towards lower material and energy consumption appears to be underway. Various indicators, such as the increasing service orientation of the industrial economies, seem to point in this direction.

Much of the discussion seems to focus increasingly on the extent to which improved energy efficiency and conservation can be economically viable in the present while saving energy and reducing CO_2 emissions (a no-regrets option). 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.[5]

Various studies have been carried out focussing on both the potential for carbon emission reduction via energy efficiency improvement and the net costs involved. An overview of the potential for emission reductions in the industrial sector is presented by Grübler *et al.* (1993a) in Table 7.2. They argue that a potential reduction of 920 MtC (over 40% of current emissions) could be achieved overall. Of this, 372 MtC could be achieved at net negative or modest positive costs (with about two-thirds of this amount coming from 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 lifetime 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 that vary (depending on income classes and other factors) from only a few percent to well over 50%. Train (1985) found a range of 10-32% for improvements to the 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.

Thus, it is clear that the scope estimated for no-regrets options is crucially dependent on the discount factor employed. If one were to use an interest rate (whether based on market or normative considerations) that was considerably lower than that applied by the actual investor or consumer, a no-regrets option would not materialize, even if access to information and the availability of human capacity and financial resources did 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 seldom fulfilled.

Consider, for example, the problem of how to increase energy efficiency in the consumption of wood fuels in the developing countries. Here institutional measures and proper distribution (keeping in view local societal and cultural factors) are probably 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). Nongovernment efforts in this area may go a long way towards solving the problem (Asaduzzaman, 1995).

As a general remark with respect to the above, it should be noted that a high implicit discount rate does not mean that substantial energy efficiency improvements and consequent benefits for the economy 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 U.S. nearly tripled between 1972 and 1993. This large and steady improvement was due primarily to the adoption of minimum efficiency standards, first at the state level and then at the national level (Geller and Nadel, 1994).

The choice of a discount rate can affect the overall magnitude of energy efficiency improvements that are considered economical. Meier (1991) argued that by assuming an annual discount rate of 10% more than a quarter of U.S. electricity demand for refrigerators could be reduced by cost-efficient measures; using a 30% rate results in positive costs for all these measures. Similarly, the Committee on Science, Engineering, and Public Policy (COSEPUP, 1991) has shown how the percentage savings in electricity, at the point where the costs of conserved electricity equal the typical operating costs for an existing U.S. power plant, vary according to the discount rate: At a 3% rate the electricity saving potential is almost 45%; at a 10% rate, it is about 30%; and at a 30% rate, it is about 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 *et al.*, 1992; Jackson, 1991; Blok *et al.*, 1993; UNEP, 1993; Robinson *et al.*, 1993).

Table 7.3. *Energy mix: Annual past and future global fuel use (Gt oil equivalent)*

	1960	1990	in 2020			
			A	B1	B	C
Coal	1.4	2.3	4.9	3.8	3.0	2.1
Oil	1.0	2.8	4.6	4.5	3.8	2.9
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
Renewables						
"Traditional"	0.5	0.9	1.3	1.3	1.3	1.1
"New"	—	0.2	0.8	0.8	0.6	1.3
Total	3.3	8.8	17.2	16.0	13.4	11.3

Source: WEC Commission (1993).

Finally, in addition to the potential for energy efficiency improvement, 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 ample opportunity for increasing energy conservation in the industrialized countries through the imposition of stricter standards with respect to energy and materials use and, most of all, through alterations and adjustments in lifestyles.

7.4.2 *Fossil fuel switching*

According to most studies, the present dominance of fossil fuels in global (primary and noncommercial) energy consumption will continue to exist in the decades to come. According to recent authoritative World Energy Council scenarios[6] (WEC Commission, 1993) (Table 7.3), fossil fuels will account for between 66% (scenario C, where renewables are fully explored) and 76% (scenario A, where fossil fuels remain dominant) of world energy consumption in 2020, compared to 77% in 1990.

All the scenarios reflected in the table show that:

- Fossil energy remains dominant
- The share of natural gas, environmentally the least damaging of the fossil fuels, increases from the present quarter to one-third at most
- The share of nuclear remains modest
- The relative potential of the presently modest "new" renewables is not insignificant, as opposed to the limited size of the projected shifts for large hydro and "traditional" energy sources (in this respect, see also Chapter 9 and, for a different point of view, Kassler, 1994).

The remaining dominance of fossil fuels is due to the large resource base,[7] the strongly vested position of 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] 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 the least and coal the most carbon-intensive.[9] Natural gas also produces minimal sulphur emissions and virtually no airborne particulates (World Resources Institute, 1994). Therefore, a switch from coal and/or oil to natural gas is 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 hydrogen, a potentially massive renewable energy source for later in the next century.[10]

The 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 more remote urban areas with gas fields. Estimates of the costs of switching, even without extending the existing networks, depend to a large extent on the type of measure. For example, switching building heating from electric to natural gas (improving overall efficiency by 60-70%) would, according to Rubin *et al.* (1992), yield a net benefit of \$90/tCO_2 in constant 1989 dollars (assuming a 6% real discount rate). According to the same source, however, switching coal consumption in industrial plants to natural gas or oil, where technically feasible, would involve net direct implementation costs of some \$60/tCO_2 in constant 1989 dollars.

Ettinger *et al.* (1991) have estimated the investment costs of exploration and extraction for a fuel switch scenario involving a natural gas supply growth rate of 3.3% per year between 1988 and 2005 plus the costs of extending the existing supply network into a global gas distribution system (based on 1989 data from the Dutch Gas Union and an average transport distance of 2500 km). They calculate that total costs 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 sizable fraction evaporates into the air by leakage during production and distribution. This is due to the substantially higher global warming potential of methane (CH_4), which is about 24.5 times that of CO_2.[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 7%[13] for switching from coal to gas and at 3% for switching from oil to gas (adopting a global warming potential index for CH_4 of 24.5 for a 100-year time horizon). These figures point to the need for strict control of leakage rates.[14] Additional questions revolve around what happens to leakage rates in the 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. For countries such as China and India that dispose of massive coal reserves and that may contribute increasingly in an absolute sense to the global greenhouse problem, the opportunity costs of fossil fuel switching may be considered large, especially if the environmental costs of coal are not taken into account.

7.4.3 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 carbon in net terms.[15] Consequently, 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 from the use of traditional biomass fuels (fuelwood, dung, and crop residues) or changes 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 that underlie the costs and energy potential of renewables as a group, a detailed treatment of their diversity is required.[17] Most of them, with the exception of biomass, are variable in supply, and some of them (especially traditional biomass, wind, and solar) are relatively more cost-competitive with fossil sources when they are produced on a small scale and near the spot of consumption. These latter aspects make them a potentially attractive option in remote and underdeveloped areas.

Further, large differences exist in the technical and economical readiness of these options. Hydro, wind, and traditional biomass are relatively well-developed, whereas some ocean technologies are still in a demonstration stage, although tidal and wave technologies may soon become more practical economically. 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).

Table 7.4 breaks down the contribution of the various technologies to renewable energy production in 1990 and makes clear that traditional biomass and large hydro are presently the most prominent renewable energy sources.

Some estimates of "practicable"[18] potentials (relative to current use) are given in Table 7.5. It clearly shows how small current use is when related to various estimates of practicable potential, whatever discrepancies may exist in estimates of that concept. Notable exceptions are large hydro and traditional biomass, which, according to the data presented, are exploited at about a quarter to half of probable capacity. Judging by these figures only, the potential contribution for renewables is promising. However, a truly comprehensive assessment must also consider the costs involved.

Table 7.4. *Contribution of various technologies to renewable energy production in 1990*

Energy Technology	Mt Oil Equivalent		% of Total	
New renewables				
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	
Total new renewables		164		10.5
Traditional biomass†		930		59.6
Large hydro		465		29.8
Total		1559		100

†Includes fuelwood and dung.
Source: WEC, 1993.

Table 7.6 gives a selective overview of cost estimates of renewable energy technologies. As usual, figures diverge widely. This variation is mainly due either to (1) the calculation method used or (2) the inherent peculiarities of the technology. As for (1), the time horizon adopted, the level of discount rate chosen, and the assumed capacity and useful lifetime are important factors. As for (2), costs are strongly influenced not only by the site specificity and temporal variability of supply as mentioned above but also by the form of final energy delivered.[19]

Other aspects relevant to 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). Immediate storage or transport needs occur not only when the timing of supply and demand fail to coincide, as is commonly the case with 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. Different, but equally difficult to assess, are the problems of location and transportation associated with storable biofuel.

On the basis of the prices in Table 7.6, it has been concluded that hydro, wind, and some solar and biomass technologies are already becoming more competitive with conventional sources. Although many wind and solar power applications are still subsidized or legislatively supported, substantial cost reductions are to be expected within the next few decades.[20] Whether these technologies actually become competitive, however, will also depend on local conditions that shape a renewable's attractiveness and complementarity between renewables and nonrenewables.

In contrast to fossil fuels, renewable energy at the moment is less portable: Consumption currently seems to be more strongly bound to the production location. Whereas fossil fuels can be relatively easily stored or transported with the existing infrastructure, similar exploitation of the new renewables would in most cases require new investment. The competition between renewables is generally more complex than that between fossil fuels. Solar and geothermal energy, for example, 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 the availability and prices of conventional sources. Moreover, by using local renewables, countries could reduce their dependence on imported fossil fuels and also 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 this respect, local renewables, like energy efficiency measures, offer a basis for no-regrets policies.

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 technologies designed to shave commercial building demand during peak load periods is under active consideration in the U.S. and elsewhere and might become commercially feasible in the foreseeable future (Byrne *et al.,* 1994; Wenger *et al.* 1992).

As the preceding discussion implies, the future role of renewables is hard to predict precisely. Although some scenarios are more optimistic than others, the share of renewables in the 2020 energy mix will probably not exceed 25%.[21] However, most studies agree that the new renewable mix will tend to be a hybrid that will exploit a variety of renewable energy sources backed up by fossil fuels, which will remain dominant for decades to come.

7.4.4 Nuclear energy[22]

Nuclear energy now accounts for about 5% of all primary energy production or 17% of the world's electricity generation. Its production, like that of renewables, emits relatively little CO_2.[23] Moreover, its technology has passed the demonstration stage, except for the large but still unresolved issue of nuclear waste storage. On the other hand, further dissemination could be strongly prohibited by lack of public acceptance due to major concerns about reactor safety, the risk of theft of nuclear technologies or materials, the proliferation of nuclear weapon capabilities, and the final treatment and disposal of fission products.

Barring these limitations, nuclear energy, if evaluated on the basis of the engineering efficiency approach, can be competitively applied, and in various countries it is, albeit to a largely different degree. (For comparison with gross costs, see Figure 7.2; for an estimate of the UK cost-effective potential, see Jackson, 1991, who used data from the mid-1980s.) Because of the long design/construction time (up to 10-15 years) and the enormous per plant investment costs, the nuclear option is rather inflexible now. According to Table 7.7 (note that the figures in the table are based on averages from existing plants rather than new plants), costs to produce electricity with nuclear energy ($/kWh) appear to fall within the range of renewable options, though nuclear costs seem to have been rising and not falling (MacKerron, 1992).

Table 7.5. *Current use and practicable potentials of renewable energy technologies (TWh/yr)*

		Practicable potential estimate			
	Current use	Johansson *et al.* 2020	Swisher *et al.* 2030	WEC 2020	Read average to 2050
Solar	54		1395	489–1592	
Wind	3.2		4931	20148	
Hydro	2281.2[a]	6000–9000	7077	8295[b]	
Geothermal	37–57	>53	1499	178–405	
Ocean	0.6		247	48–240	
Traditional biomass	4170		8003	7031–7269	
Modern biomass[c]	543				about 35,000[d]

[a]Includes 81.7 TWh/yr for small hydro.
[b]Includes 211-308 TWh/yr for small hydro.
[c]Modern biomass refers to the use of biomass (e.g., timber or sugar cane) for the production of electricity, liquid fuels, and heat using modern technology.
[d]Assumes 740 million hectares become available for biofuel production by 2050 (proportionately less according to technical progress with biofuel productivity per hectare) with a slow start and more rapid build up after 2010. The 35,000 TWh would yield about 18,000 TWh of electricity given advanced generating technology expected to be in use next century.
Source: Johansson *et al.* (1993), WEC (1993), Swisher *et al.* (1993), Read (1994b).

Table 7.6. *Estimates of current[1] and future costs of renewable energy technologies (U.S.¢ per kWh)*

						Biomass	
Source	Solar	Wind	Hydro	Geothermal	Ocean	Electric	Fuel ($/GJ)
IEA[2]	0–14[a] 7.6–41.9 (15–174)[b] 5.2–26 (22.61)[c] 5(50)[g]	3.5–4.2[h] (4.48–7.62) (20)[i]		(3.6–9.2)	5–20[m,3] (11.5–50) 6.7–8[n]		7.58–12.80 (1.85–16.68)[q] 12.70–20.85[t] 15.64–23.70[u]
Johansson *et al.*[2]	4.5–11.7 (7.5–32.8)[c] 4.9–9 (8.5–28)[g]	3.13–4.46 (4.29–8.4)		3–12[k] 0.15–2.5[l]	(5–30)[m] 12–25[n] 22–30[o]		1.86–2.73 (2.73–3.86)
Swisher *et al.*	5–10[d](12) 4–8[e](25) 4–8[g](30)	3–6(7)	5–10(5)[j]		8–10[m]	5	6[r](8) 7[s](13) 10[t](15) 1[v]
WEC	no storage[w] 0.4–2.5(0.5–10)[c] 1–11 (1.2–28)[f] 4–14 (28–45)[g]	3–9 (5–10)		n/a	(5–12)[m] (5–7)[n] (12)[o] (10–14)[p]	n/a	n/a

Note: n/a = not assessed.
[1]current costs in parentheses.
[2]1984 cents.
[3]UK pence per kWh.
[a]passive solar; [b]active solar; [c]solar thermal (line focus); [d]solar thermal (line focus); [e]solar thermal (point focus); [f]solar thermal-electric; [g]photovoltaic; [h]small/medium wind energy conversion systems; [i]large wind energy conversion systems; [j]small hydro; [k]electric; [l]direct heat; [m]tidal; [n]wave; [o]salt gradient; [p]ocean thermal; [q]ethanol from corn; [r]ethanol from sugar; [s]ethanol from wood; [t]methanol from wood; [u]methanol from herbage; [v]methanol from biomass; [w]costs exclude storage systems.
Sources: IEA/OECD (1987); Johansson *et al.* (1993); Swisher *et al.* (1993); and WEC (1993).

Table 7.7. *Examples of avoided emissions and their costs: Electricity*

Electricity[a] (Cost of avoided resource (coal):$0.44/kWhe)	Measure Resource Cost ($/kWh)	Avoided Emissions (g Carbon-eq/kWh)	%	Cost of Avoided Carbon-equivalent (CaCeq) ($/tonne)
End-use efficiency[b]				
Available technologies				
Lighting (incandescent to 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
U.S. field data, multifamily, leaking retrofits	0.038	318	100	- 19
Retrofits in 450 U.S. commercial buildings	0.026	318	100	- 54
No-cost or behavioural measures	0	318	100	-137
Electricity production (busbar costs)				
Available technologies				
Biomass steam-electric (woodfuel)	0.041	318	100	- 9
STIG[c] (gasified coal)	0.041	9	3	-313
STIG[c] (natural gas)	0.027	163	51	-103
Wind (1988)	0.054	318	100	- 33
Solar thermal electric (1988)	0.114	318	100	-221
Solar photovaltaics (1988)	0.231	318	100	-588
Nuclear	0.057	318	100	- 41
Emerging technologies				
ISTIG[d] (gasified coal)	0.034	57	18	-176
ISTIG[d] (natural gas)	0.024	187	59	-106
Chemically recuperated gas turbine	0.029	204	64	- 73
Solar thermal electric				
(2000)	0.043	318	100	- 1
(2010)	0.036	318	100	- 24
(2020)	0.031	318	100	- 40
Solar photovoltaics				
(2000)	0.072	318	100	89
(2010)	0.050	318	100	22
(2020)	0.036	318	100	- 24
Wind				
(2000)	0.033	318	100	- 33
(2010)	0.027	318	100	- 51
Nuclear – industry target for U.S.	0.040	318	100	- 11
Fuel choice (STIG[c] technology in all cases)				
Avoided resource cost (gasified coal:$0.071/kWh)				
Gasified coal to natural gas (1990)	0.027	155	50	- 91
Gasified coal to biomass (sugar)(~ 2000)	0.033	309	100	- 25

[a]Unless noted, the annualized costs of efficiency and supply measures are calculated with a 6% real discount rate and no taxes. For details on the other assumptions, see source.
[b]Lighting and refrigeration measures calculated using a 7% real discount rate.
[c]Steam-injected gas turbine.
[d]Intercooled steam-injected gas turbine.
Source: Mills *et al.*, 1991.

Social opportunity costs will remain high until a full and credible investigation of the safety aspects of nuclear power plants is completed. 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, advantages, and uncertainties now also have to be taken into account explicitly. This holds not only in the industrialized countries, but also in the developing countries and the countries in transition. In addition, any future use of nuclear energy, like any switch from fossil to nonfossil fuels, will depend on the underlying cross-price elasticities and energy price assumptions, inflation, public policy, and technological progress. Taking these complicating factors into account – namely, that there is no established technology for decommissioning nuclear plants, that there are hidden external costs regarding nuclear power-related 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 at 6.1% by 2010; the WEC C-scenario (see also note 6) projects the share of nuclear at 6.2% in 2020.

7.4.5 Capture and disposal

CO_2 capture and disposal is understood as any sequence of processes in which carbon is recovered in one form or another 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 in combination with coal gasification is thought to have significant intermediate potential, especially for coal-rich countries such as China, India, the U.S., or the Russian Federation (see also Nakicenovic and Victor, 1993, and the outcomes of the OECD Model Comparison Project as discussed in Chapter 8).

Since places of recovery do not generally 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 manufacturing, fertilizer, and power plants.[24] To date, most research effort has been spent on power plants. For these, two types of recovering technologies exist:[25] those that combine separation of the CO_2 from the flue gases (scrubbing) with modifications to the energy conversion process and those that rely on CO_2 scrubbing only. Modifications to the energy conversion process, which are now in experimental use, include an Integrated Coal Gasifier Combined Cycle (ICGCC) system, modification of boilers, and modification of gas turbines.[26] The main separation options are chemical or physical absorption, the use of membranes, and cryogenic fractionation. Of these, chemical and physical absorption are most developed and membrane separation and cold distillation least.[27]

Depending on the place of disposal, transport will take place onshore or offshore. Onshore, pipelines are most economical. Estimated transport costs vary between \$1 and \$4/tCO_2 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 one-half to three times the costs onshore (Hendriks, 1994; TNO, 1992).

After the carbon is recovered, it has to be handled so that reentry into the atmosphere is prevented or at least delayed as much as possible, that is, so that the mean retention time is large compared to the residence time of CO_2 in the atmosphere (since not all applications ensure entire or long-term storage of the carbon).[28]

Disposal can occur in two ways: The gas can be utilized for the production of long-lived materials,[29] or it can be stored underground, either in aquifers (which, technically, have almost unlimited storage potential), or in the ocean.[30] Environmental risks seem to be involved, however, especially in the latter cases.

7.4.6 Enhancing sinks: Forestry options[31]

Unlike removal options, options that enhance sinks remove carbon after it has been dispersed into the atmosphere. All sources seem to agree that much more carbon is stored in soils than in forests. This would suggest that significant attention be given to measures that promote soil conservation, reduce carbon mobilization from soils to air, and increase soil storage of atmospheric carbon through the action of soil microorganisms. Nevertheless, the main option for enhancing carbon sinks – except for iron fertilization and weathering rocks, which are both still in their experimental stage – relates to forestry measures. Their importance is due to their expected large storage potential and relatively modest costs. The enhancement of forest sinks is also one of the lowest-risk options and offers substantial positive side effects in the environmental and sometimes also in the socioeconomic sphere.

Just as the potential for forestry measures in enhancing sinks is probably sizable, 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. The 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 the rest of the 1980s, compared with global emissions of slightly less than 6 GtC from burning of fossil fuels, manufacture of cement, and flaring of natural gas (Grübler *et al.*, 1993a; see also Houghton, 1990). The large amount of uncertainty about the net quantity of carbon released by deforestation and land use changes relates to the extent of the area undergoing land use change, 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:

(1) Halting or slowing deforestation
(2) Reforestation and afforestation[32]
(3) Adoption of agroforestry practices
(4) Establishment of short-rotation woody biomass plantations
(5) Lengthening forest rotation cycles
(6) Adoption of low-impact harvesting methods and other management methods that maintain and increase carbon stored in forest lands
(7) Sustainable forest exploitation cum sequestration of carbon in long-lived forest products[33]

The first six measures sequester carbon by increasing the standing inventory of biomass or by preventing a decrease thereof. This amounts to a once-for-all uptake of carbon. In contrast, the seventh measure aims at continuing to break the carbon cycle, thereby, in principle, enabling its permanent application. This option becomes even more efficient and attractive if the timber is used to substitute on a large scale for products such as bricks, concrete, steel, and plastics whose manufacture releases much greater quantities of CO_2.

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

In assessing the global potential for halting or slowing down deforestation and for reforestation, there are three main sources of uncertainty:

(1) The potential for slowing deforestation depends on resolving complex problems that are linked to societal and economic pressures, such as large-scale settlement on forest lands and the sale of timber for export earnings in tropical countries or policy distortions (e.g., below-cost sales of timber on government lands) in industrialized countries.
(2) The potential of the option depends on the amount of area globally available for some kind of forestry measure (see also Volume 2, Chapter 24).
(3) The incremental (i.e., annual) and net cumulative carbon uptake per hectare[34] for the main forest species[35] have yet to be reliably determined.

In addition, it should be noted that large-scale monoculture forestry may not be acceptable to many environmentalists; moreover, local ecosystems may be destabilized.

With respect to the first of these uncertainties, there is a near consensus in the literature that most deforestation in tropical countries occurs because standing forests are converted to crop and pasture land. This happens because those encroaching on the forests consider them to have lower economic value than crop and pasture land. The potential for slowing deforestation is therefore hard to estimate. Furthermore, slowing deforestation requires the application of effective solutions to highly politicized problems such as inequitable land distribution and lack of secure land tenure. It also requires effective means of increasing the per hectare productivity of crops and livestock. The solutions to these problems are partly technical but mostly economic in nature and include improved price structures for farmers (e.g., higher crop and livestock prices versus lower prices for inputs such as fertilizer) and better access to markets.

As for tropical deforestation rates, estimates of these 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 and 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 Grübler *et al.* (1993b).

A similar discussion has arisen on the issue of the global land area that would be suitable and available for carbon sequestering plantations. One study of the maximum worldwide potential of this approach, Sedjo and Solomon (1989), suggests that 2.9 Gt of atmospheric carbon could be sequestered annually 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, but many factors will determine whether such high rates of uptake can be achieved.

Clearly, a large potential for the enhancement of forest sinks exists in the tropics. A recent survey, carried out under the auspices of the Asian Development Bank in eight Asian countries (Pakistan, India, Sri Lanka, Bangladesh, Indonesia, Malaysia, Vietnam, and the Philippines) 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 willingness of the local population to cooperate, given their perceptions of the most appropriate land use.

Keeping these limitations in mind, one can compare the preceding findings with the estimate of Grübler *et al.* (1993b) that at present 265 million ha globally would be available and suitable for forest plantations and 85 million ha for agroforestry. Other sources (Winjum *et al.*, 1992) suggest significantly larger areas (some 400-1200 million ha). These figures are in sharp contrast with the potential in the OECD countries, amounting to 15-50 million ha in future in the EU, mainly due to redundancy of farmlands, and 30-60 million ha in the U.S.

Carbon sequestered in global annual wood production is currently estimated at some 1 GtC (TNO, 1992). Such a high rate may not represent the actual "net" addition to the wood products pool and may not be sustainable in the future, but it gives some indication of the potential of carbon sequestration through wood products, depending on the price, product lifetime, and the trend in timber demand (which is commonly projected to rise). Some authors argue that a considerably higher demand for wood could be achieved if it were used to produce electricity (and liquid fuels such as methanol). This would replace fossil fuel CO_2 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; for a discussion of the institution building needed to monitor and account for the global realization of this concept, see Read, 1994a.)

With respect to the problem of estimating carbon uptake, only rough estimates exist for the carbon content of biomass and soils in disturbed areas. Estimates of average annual carbon uptake vary considerably, depending on, among other factors, 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.)

7.4.6.1 Costs

Mitigation policies using forests are generally considered relatively cost-effective, especially if applied in developing countries. An early U.S. high cost estimate of $100/tC (Nordhaus, 1990) now seems to have ignored changes in soil carbon through tree planting and to have underestimated the carrying capacity and length of productivity of forest plantations. Richards *et al.* (1993a, 1993b) estimate that the overall costs of stabilizing U.S. carbon emissions could be reduced by as much as 80% by forestry options.

Most of the studies, which deal with the costs of afforestation or halting or slowing down deforestation, take the engineering efficiency approach rather than the welfare economic approach. With respect to afforestation, the assumption is commonly made that the forests would not be harvested but would be 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. Sometimes, however, land required for establishing carbon plantations may be considered free, therefore implying that opportunity costs would be zero (e.g., Winjum *et al.*, 1992).

One generally recognizes that the second option, halting or slowing down deforestation, is probably one of the most urgent and most cost-effective options (Grübler *et al.*, 1993b). However, 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, large losses have occurred in Angola, Nigeria, Morocco, and several other countries, and in China the rate of survival of reforestation efforts is estimated to be not higher than 20% (Nakicenovic and John, 1991).

There are two crucial factors that appear to determine 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 sold at commercial rates, or whether it instead should be left alone. Second, much depends on the acceptance of the newly planted forests by the local population, as might be expected if they were to derive an economic benefit from it.

If, for instance, the forest can be harvested through the exploitation of timber and nontimber products, and if, in addition, carbon sequestration credit can be given to trees that are harvested, then the net costs of afforestation could easily become negative. In that case, afforestation would become a no-regrets option, and initiatives could allow the payback period to be left to the market. However, not all externalities can be incorporated in the prices of the timber and nontimber products (e.g., trees may provide environmental benefits but may also contribute to productive losses by shading adjacent field crops or competing with them for water).

Even if afforestation with sustainable exploitation offers a net positive return, many other factors may still form an obstacle to its implementation. 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,

> [T]ropical forestry programmes 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] 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 of the cost-effectiveness of forestry measures in the engineering efficiency approach are also subject to uncertainties about the availability of land area, carbon uptake per hectare, and costs of establishment and maintenance per hectare. In addition, figures diverge depending on the methodology adopted. In this respect, two problems should be discussed: (1) the derivation of point estimates or of cost *functions,* and (2) forestry cost function methodology.

With respect to (1), most effort so far has been spent on deriving point estimates from average costs. Some selected cases are given in Tables 7.8 and 7.9. Note that the estimates generally assume a "tree cemetery" approach. Tables 7.8 and 7.9 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 de-

Table 7.8. *Costs of sequestering carbon through forest projects: Some selected cases ($/tC)*

Source	Tropical		Temperate Plantation	Boreal	
	Agroforestry	Plantation		Plantation	Protection
Andrasko (1993)	3–5	3–6	0–2		
Dixon *et al.* (1993)	4–16	6–60	2–50	3–27	1–4
Krankina and Dixon (1993)			1–7	1–8	1–3
Houghton et al. (1991)	3–12	4–37			

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

Table 7.9. *Establishment costs of cost-efficient practices*

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 (254–699)
Reforestation	7 (3–26)	450 (303–1183)

†The numbers in parentheses are interquartile ranges (middle 50% of observations).
Source: Turner *et al.*, 1993.

tailed assessment see Turner *et al.* (1993) and Volume 2, Chapter 24, of this report.

Though these point estimates may give a satisfactorily accurate description of cost effectiveness for small areas and single plantation programmes, 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:

(1) Diminishing uptakes as less suitable or less well-managed land is forested, resulting in a lower carbon uptake per hectare
(2) Increasing public resistance and social and legal objections by the local population against interference with present land use
(3) Rising opportunity costs as fallow land is used up and plantations move on to land suitable for alternative uses[36]
(4) No or negligible economies of scale in operating and maintenance costs

Together these factors generally mean that marginal costs will rise as the area being forested increases. 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 have a number of somewhat more sophisticated studies begun to appear that do take increasing marginal costs explicitly into account. Such studies also do more justice to the welfare economic point of view by explicitly recognizing that an expansion of the area forested will most likely increasingly interfere with the expanding domestic demand for agricultural land. Table 7.10 sketches this feature.

When comparing Tables 7.8 and 7.9 with Table 7.10, it is apparent that the figures correspond roughly only for low levels of sequestering effort. For higher levels, the divergence grows rapidly. Therefore, the conclusion seems justified that point estimates, though valid for small areas, seriously fail to describe actual costs for larger areas.

With respect to the second issue, a number of more sophisticated studies have recently begun to appear. These include Moulton and Richards (1990), Adams *et al.* (1993), Parks and Hardie (1992), Richards *et al.* (1993a), and Read (1994b). These studies refine the approach to estimating the cost of establishing carbon sequestering tree plantations in three ways. First, they estimate a cost function, not a point. Second, they refine the cost estimates for establishing tree plantations by recognizing differences associated with location and site considerations. Third, they build discounting procedures into the methodology – a common practice in the assessment of other options, but until recently one that was virtually ignored with respect to this option (see also Richards, 1993). 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

Table 7.10. *Estimates of cost of carbon sequestered by tree planting: some comparative results for the U.S.*

	Total Carbon Sequestered (Mt)			
	140	280	420	700
Study	Costs ($/tC)			
Moulton/Richards (1990)	16.57	20.69	23.24	34.73
Adams *et al.* (1993)	18.50	25.11	37.21	95.06
Parks/Hardie (1992)	175.00	n/a	n/a	n/a

Note: n/a = not assessed.
Sources: As shown.

marginal costs per tonne of carbon roughly doubling, from about $30 to $60, 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. Nevertheless, sustainable forest management can make an important long-term contribution to providing a continuous flow of substitutes for net-emitting energy sources such as coal.

7.4.7 Methane

Methane currently accounts for about 20% of expected warming from climate change. This contribution is a result of methane's potency as a greenhouse gas and dramatically increased anthropogenic emissions. Currently, about 70% of global methane emissions are associated with human-related activities such as energy production and use (coal mining, oil and natural gas systems, and fossil fuel combustion); waste management (landfills and wastewater treatment); livestock management (ruminants and wastes); biomass burning; and rice cultivation.

Technologies and practices for reducing methane emissions from their major anthropogenic sources have been identified and reviewed through a number of expert meetings and studies, many under the IPCC. Many of the technological options currently available are cost-effective in many regions of the world and have been implemented to a limited extent. The available options represent different levels of technical complexity and capital needs and therefore should be adaptable to a wide variety of country situations. In total, it appears to be technically feasible to reduce methane emissions by about 120 Tg (75 to 170 Tg) per year through reductions in emissions from the following methane sources.

Coal mining. Techniques for removing methane from gassy underground mine workings have been developed primarily for safety reasons, because methane is highly explosive in air in concentrations between 5% and 15% and is the cause of mining accidents. Some of these same techniques can be adapted to recover methane in concentrations of 30% or more, so the energy value of this fuel can be put to use. Methane emissions into the atmosphere can be reduced by up to 50-70% at gassy mines using available techniques such as gob gas recovery (IPCC, 1990a, 1990b, 1990c; U.S. EPA, 1993; IPCC, 1993).

Oil and natural gas systems. Methane is the primary constituent of natural gas, and significant quantities of methane can be emitted to the atmosphere from components and operations throughout a country's natural gas system. The technical nature of emissions from natural gas systems is well understood, and emissions are largely amenable to technological solutions through enhanced inspection and preventative maintenance, replacement of equipment with newer designs, improved rehabilitation and repair, and other changes in routine operations. Reductions in emissions in the order of 10 to 80% are possible at particular sites, depending on site-specific conditions (IPCC, 1990b; U.S. EPA, 1993; IPCC, 1993).

Landfills. The methane generated in landfills as a direct result of the anaerobic decomposition of solid waste can be reduced by recovering this medium-BTU gas for use in electricity generation equipment or for direct use in heating or cooking equipment. At many sites reductions of up to 90% are possible. Additional benefits that result from landfill methane recovery include improved air and water quality and reduced risk of fire and explosion (IPCC, 1990b; U.S. EPA, 1993; IPCC, 1993).

Ruminant livestock. Many opportunities exist for reducing methane emissions from ruminant animals by improving animal productivity and reducing methane emissions per unit of product (e.g., methane emissions per kilogram of milk produced). In general, a greater portion of the energy in the animals' feed can be directed to useful products instead of wasted in the form of methane. As a result, herd size can be reduced while productivity remains the same. Current technologies and management practices can reduce methane emissions per unit product by 25% or more in many animal management systems (IPCC, 1990a, 1990c; U.S. EPA, 1993; IPCC, 1993).

Livestock manure. Methane emissions from anaerobic digestion of animal manures constitute a wasted energy resource which can be recovered by adapting manure management and treatment practices to facilitate methane (biogas) collection. This biogas can be used directly for on-farm energy or to generate electricity for on-farm use or for sale. The other products of anaerobic digestion, contained in the slurry effluent, can be used as animal feed and aquaculture supplements and as a crop fertilizer. Additionally, managed anaerobic decomposition is an effective method of reducing the environmental and human health problems associated with manure management. Current reduction options can reduce methane emissions by as much as 25-80% at particular sites (IPCC, 1990c; U.S. EPA, 1993; IPCC, 1993).

7.5. 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. The literature on the subject is limited but growing.[37] In any case, it is clear

Table 7.11. *Agricultural yield changes under a 2 × CO_2 climate (percentage of gross agricultural product)*[a]

	UKMO Model[b]			GISS Model[b]			GFDL Model[b]		
Region/Scenario[c]	1	2	3	1	2	3	1	2	3
OECD America	-20.0	-5.0	-5.0	10.0	10.0	10.0	-5.0	10.0	10.0
OECD Europe	5.0	5.0	5.0	10.0	10.0	10.0	-5.0	-5.0	-5.0
OECD Pacific	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
Central and Eastern Europe and former Soviet Union	-7.5	-7.5	-7.5	22.5	22.5	22.5	7.5	7.5	7.5
Middle East	-22.5	-22.5	-7.5	-7.5	-7.5	7.5	-7.5	-7.5	7.5
Latin America	-22.5	-22.5	-8.5	-15.0	-15.0	-1.0	-10.0	-10.0	4.0
South and Southeast Asia	-20.0	-20.0	-10.0	-10.0	-10.0	0.0	-10.0	-10.0	0.0
Centrally Planned Asia	-7.5	7.5	7.5	7.5	22.5	22.5	7.5	22.5	22.5
Africa	-20.0	-20.0	-20.0	-7.5	-7.5	7.5	-15.0	-15.0	0.0

[a]After Rosenzweig *et al.* (1993); cf. also Fischer *et al.* (1993), Rosenzweig and Parry (1994), and Reilly *et al.* (1994).
[b]The climate change scenarios are based on equilibrium 2 × CO_2 experiments using the General Circulation Models of the UK Meteorological Office (UKMO), the Goddard Institute for Space Studies (GISS), and the Geophysical Fluid Dynamics Laboratory (GFDL).
[c]The scenarios are (1) no adaptation, (2) minor shifts, and (3) major shifts in behaviour.
Source: Tol (1994).

that society now already incurs large costs in adapting to climate extremes; climate change will just increase these costs.

When talking about adaptation, the central questions relate to (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; no attention will be given to the aspect of insurance, which could be viewed as an adaptation option in its own right (see also Chapter 6). The question of when to adapt is one of implementing no-regrets adaptation options now (possibly 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 the modelling of adaptation.

7.5.1 Adaptation to what?

Adaptation in various degrees and in some form or other may be necessary to cope with ecosystem changes that have interfaces with human (economic, social, political, legal, and cultural) activities (for a more detailed assessment of adaptation options, see Volume 2). The extent of these changes and their subsequent impact on human affairs will depend on the sequence, severity, and characteristics of the climatic changes that initiated them. Changes in temperature and associated rainfall regimes may lead to more droughts in some localities and heavier rainfall in others, thus affecting worldwide surface and groundwater availability, which in turn will affect agronomic practices and yields in agriculture. Fisheries and forestry will be affected by changes in temperature and the availability and quality of water (e.g., salinity). Temperature rise may also affect livestock populations and output through heat stress and climate-related influences on infestations of parasites, insects, and disease.

Climate change may cause accelerated sea level rise, possibly attended by increased flooding, changes in regional temperature, increases in the frequency of storms and hurricanes, and changes in surface runoff and river discharges resulting from changes in the mean value and variability of precipitation. Impact scenarios differ considerably, however, as a result of differences in their starting assumptions: IPCC (1994), for example, assumes a 1-m sea level rise over 100 years, whereas other scenarios are based on a 50-cm rise. In addition, the response options that are considered adequate or appropriate differ significantly from study to study.

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 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 Rhine in the Netherlands is predicted to fall by 10-15% due to an assumed temperature increase of 4°C in the Alpine part of the basin (Kwadijk, 1991, as cited in Penning-Rowsell and Fordham, 1994). 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 nonclimate-related factors, such as subsidence and excessive groundwater withdrawal, which may be equally important determinants in *relative* sea level rise.

Table 7.12. *Annual costs of sea level rise*†

Region	Wetland (mln. $)	Drylands (mln. $)	Protection (mln. $)	Total (mln. $)	Total (% of GDP)
OECD America	5,000	2,000	1,500	8,500	0.15
OECD Europe	4,000	500	1,700	6,200	0.14
OECD Pacific	4,500	4,000	1,800	10,300	0.45
Central and Eastern Europe and former Soviet Union	1,250	1,250	500	3,000	0.07
Middle East	0	0	0	0	0
Latin America	1,500	500	1,000	3,000	0.35
South and Southeast Asia	1,500	1,000	2,000	4,500	0.65
Centrally Planned Asia	500	0	500	1,000	0.29
Africa	500	500	500	1,500	0.43

†All estimates ± 50%.
Source: Tol, 1993.

Quite obviously, countries where sea level rise may become prominent may face challenges beyond what only a climate change would have entailed. Effects on agriculture may be caused by regional changes in temperature and by sea level rise. A sea level rise of 1 m would affect the supply of rice of more than 200 million people in Asia (IPCC, 1994). Changes in temperature would have mixed regional effects (Tol, 1994, based on Rosenzweig *et al.,* 1993). Effects on agriculture would depend on the full range of possible impacts of climate change (as well as CO_2 fertilization) and not just temperature (see Table 7.11).

Similarly, a sea level change would pose problems or present opportunities for numerous other activities, including fishing and mangrove forestry. Human habitation would also be affected (through changes in water quality) as would industry and trade (through relocation of industries and loss of infrastructure). Both these factors may also affect human health and nutrition.

Human adjustment, however, will be affected by a complex array of factors over time. Thus, a study by the Asian Development Bank (1994) shows that, whereas the agronomic yield of rice may increase, the "realized" increase may be lower than the agronomic potential due to the interplay of demand and supply factors.

7.5.2 How to adapt

Options for adapting to sea level rise can generally be categorized as retreat, accommodation, or protection.

Retreat will cause loss of dry land and loss of wetlands. IPCC (1994) computes that a 1-m sea level rise could threaten 170,000 km^2 (or 56%) of the world's 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 such factors as coastal infrastructure. An overview of costs (on an annual basis) for both wetland and dryland losses is given in Table 7.12.

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 people leaving (and of the hardships they may endure) on the other. 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 and 0.03% of GDP for the OECD and the countries in transition, and between some 0.3 and 0.8% for the developing regions (Tol, 1993).

Accommodation to sea level rise involves not only the adaptation of existing structures to a higher sea level but also a variety of other responses, such as the elimination of subsidized insurance in industrialized countries for building new structures along sea shores. In a state of transition it may also involve the need to respond to inundations causing loss of life and damage to assets, agriculture, and the environment (Penning-Rowsell and Fordham, 1994).

Protection against sea level rise would involve major costs, but estimates of these differ. Tol (1994), assuming a 0.5-m rise, estimates annual global coastal defence costs at $9.5 billion in constant 1988 dollars. IPCC (1994), assuming a 1-m rise, computes costs of $10.0 billion per year in constant 1994 dollars, whereas Ayres and Walter (1991, as cited in Winpenny, 1994) derive a figure of $50-100 billion in constant 1981 dollars. Protection costs for an increased intensity of storms are not available on a global scale.

Adaptation to changes in river water discharge involves the same choice of options as adaptation to sea level rise: retreat, accommodation, or protection. Unfortunately, no global costs are available for any of these. For a European example, however, see Penning-Rowsell and Fordham (1994).

Adaptation to changing temperatures involves adjustments in health care, heating and cooling facilities, and household activities, and the adaptation of agriculture and fisheries. Improvements to infrastructure, including urban buildings and construction as well as water control and storage systems (such as dams, drainage and sewer systems, dikes, and locks), would also be needed.

In agriculture various types of technical responses are available. These include changes in farming strategies and crop management as well as changes in crop variety, irrigation, fertilizer, and drainage. Some salt-tolerant crops, to give an example, can be very successfully grown along the shoreline of coastal deserts when irrigated with ocean water. Global and regional estimates for different levels of adaptation in agriculture are presented in Table 7.11.

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 approach at the moment. The following options deserve special attention:

- 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 the effects of natural climatic variability and of potential future climate changes.
- 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.
- Improvements in food security policies and reduction of postharvest losses. Given that postharvest losses – due to deficient systems of storage and transport – amount in many developing countries to 50% of production, or more, major scope for improvement does seem to exist.
- Conversion to "controlled environment agriculture." Massive introduction of integrated "controlled environment agriculture" in developing countries might easily require an investment of several tens of billion of dollars, or billions of dollars per annum if introduced over some decades.
- 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, given recent dramatic advances in marine biotechnology. The almost sterile, nutrient-rich bottom water from Ocean Thermal Energy Conversion (OTEC) systems holds considerable promise as a culture medium for kelp, abalone, oysters, and a range of fish species.

It should also 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 themselves. As a final remark, it may be pointed out that patterns of scarcity and surplus will change across regions and over time, presenting new opportunities for trade between nations as they respond to stabilize supply.

7.5.3 *Adaptation measures in developing countries*

In developing countries, as elsewhere, adaptation 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 may be delayed. In the 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 began. Countries in arid and semi-arid zones have tried to find long- and short-term responses to recurrent droughts for some time now, while countries in heavy rainfall regions and those affected by storms and cyclones in their coastal areas have tried to find both structural (engineering) and nonstructural (institutional) means for dealing with recurrent floods.

Short-term responses to recurrent droughts include improvements in drought preparedness and focus primarily on drought relief and drought recovery activities. Drought relief typically includes supplementary food programmes and programmes to protect and replenish 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 include regional and national research efforts to develop drought-resistant crops and breed hardy livestock. The 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 research capacity and financial support for research, are necessary and will almost certainly prove to be cost-effective. In areas where water resource management will become crucial because of large changes in rainfall regimes, 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 already had to develop adaptation responses to problems outside the context of climate change. Facing massive river and dam silting and below-average precipitation to replenish hydroelectric installations, some 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.

7.5.4 *Modelling adaptation*

Climate change adaptation models have been developed for sea level rise, storminess, and changes in river discharges. A methodology for assessing damages can be found in Howe *et al.* (1991) and in Green *et al.* (1994). Penning-Rowsell and Fordham (1994) present a general methodology for adaptation, whereas models for flood hazard assessment and management can be found in Klaus *et al.* (1994). Correia *et al.* (1994) present a framework for the analysis of river zone management, including the institution setting.

Two important problems can be mentioned with respect to the modelling of adaptation. The first of these includes the general set of greenhouse assessment problems, such as the handling of time, uncertainty, and discount rate. The second is specific to adaptation and involves the valuation of intangibles, such as wetlands and species. A valuation in dollars per person for protecting threatened species, for example, cannot be compared with a valuation in dollars per kilometre for protecting threatened coasts.

7.6 An Integrating Approach

A major part of the literature on response options focusses on the various technologies and their cost-effectiveness within a specific option. The options themselves, however, are not assessed on the basis of broader comparisons. The main explanation for this "partial" approach 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 on the assumptions employed about the efficiency of the baseline scenario used in the analysis (see also Chapters 8 and 9).

A truly generic assessment, however, requires an integrating framework that allows a simultaneous evaluation of the various technologies. If emission reduction targets are to be achieved in an optimal way, not only economically but also in terms of flexibility and spreading of risks, a full picture of all the alternatives should be available, so an integrated portfolio of options can be determined that minimizes the costs of a given level of carbon reduction. (The integrating approach in this chapter should not be confused with the integration of costs of a given option, or with the integrated modelling approach treated elsewhere in this report.) One option, drawing on economics, is to apply a cost-benefit or cost-effectiveness criterion for decision making. That approach is highlighted here. Other approaches to decision making are also possible. One could rely, for example, on the concept of safe minimum standards (which may be particularly important in evaluating investments in nuclear power plants).

The need for an integrating approach is reinforced by the fact that many of the options' cost functions appear to show internal diseconomies 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, for example, Kram, 1994b, and Southern Centre/Risö, 1993; for a broader analysis, see, e.g., TNO, 1992). The implication is, therefore, that, after reaching a certain scale of application, the most efficient option will become more costly than another option, and this, in turn, may eventually become more costly than yet another option. The discussion of the marginal costs of CO_2 abatement in Chapters 8 and 9 is relevant in this respect.

The need for an integrating approach is further reinforced by evidence that cost functions per option also differ from place to place because of regional variations in supply conditions, levels of technology, infrastructure, and other factors. Evidence suggests that even within a relatively 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 in one place than in another (McKinsey & Company, 1989).

A number of integrating studies have been carried out. Those using a "top-down" methodology attempt to provide a comprehensive analysis based on generalized estimates of the cost functions of the various options (McKinsey & Company, 1989; Nordhaus, 1991a; Jepma and Lee, 1995). Others using a "bottom-up" approach commonly pursue a greater level of detail (Jackson, 1991; Rubin *et al.,* 1992; Mills *et al.,* 1991; Kram, 1994b).[38]

In the "top-down" studies, the regional differences between the cost functions of the various options provide a strong case for their joint implementation, if the ultimate CO_2 reduction target is to be achieved with the least cost (see also Article 4.2.B of the Framework Convention on Climate Change). This result is valid, irrespective of which parties take the main responsibility for financing the options.

However, a number of other considerations may affect these conclusions. 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. Furthermore, as was explained in Section 7.3, cost functions may differ depending on whether they have been designed according to the engineering efficiency approach or the welfare economic approach. These differences will obviously have a strong impact on the outcome of integrated assessments. To the extent that welfare considerations will cause cost functions to shift upward (especially for countries in transition and developing countries) in comparison with those calculated on the basis of engineering efficiency, the anticipated scope for joint action may be reduced.

In addition, the global costs of achieving ambitious long-term emission reduction targets (such as reducing annual emissions to half the present level) – 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, efficiency improvement, and fossil fuel switching.

The top-down studies also indicate that in the optimal case all options must be applied at the same time and in all regions, albeit to different degrees. The largest potential in overall emission reduction at current cost estimates seems to be in forestry (especially in developing countries) and energy conservation and efficiency improvement (especially in the OECD and Eastern Europe). Renewable energy (particularly in developing countries) and fuel switching (especially in Eastern Europe if methane leakages can be limited) are also important, though to a lesser extent. Needless to say, the optimal mix may easily change as a result of future technological progress.

To illustrate, the results of a linear programming optimization procedure have been presented in Table 7.13 (Jepma and

Table 7.13. *Base case simulation: Optimal mix of options for a global emission reduction of 2.4GtC (marginal costs: $50/tC)*

	Level of emission reduction (MtC)			
Option	OECD	Eastern Europe	Rest of the World	Total
1. Energy conservation and efficiency improvement	250 (250; 250)	250 (250; 250)	100 (100; 100)	600 (600; 600)
2. Fuel switching	50 (50; 50)	50 (50; 50)	50 (50; 50)	150 (150; 150)
3. Removal and disposal	100 (100; 150)	50 (50; 100)	0 (0; 50)	150 (150; 300)
4. Nuclear energy	50 (50; 50)	50 (50; 50)	0 (0; 50)	100 (100; 150)
5. Renewable energy	50 (100; 50)	50 (100; 100)	100 (150; 150)	200 (350; 300)
6. Forestry	250 (250; 250)	250 (250; 250)	700 (550; 400)	1200 (1050; 900)
Total	750 (800; 800)	700 (750; 800)	950 (850; 800)	2400 (2400; 2400)

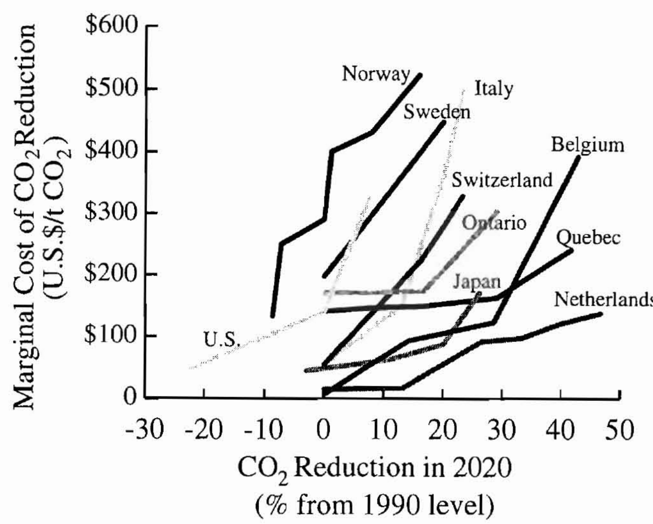
Note: Figures in parentheses give the results for a 50% reduction in the marginal costs of renewables and for a doubling of the marginal costs of forestry respectively over all intervals.
Source: Jepma and Lee (1995).

Lee, 1995). The procedure starts from a predetermined emission reduction target and is applied to the cost functions of the various options per region, featuring stepwise increasing marginal costs and based on data from a combination of sources (McKinsey & Company, 1989; Jackson, 1991; Mills *et al.*, 1991; and Rubin *et al.*, 1992). The table shows the optimal mix of options both in terms of types of options and of regions of application if a medium-term emission reduction target of -2.4 GtC is to be achieved. (The figures in parentheses show the outcomes if the marginal costs of the renewable option are assumed to be 50% of those in the base case and if the marginal costs of the forestry option are doubled compared to the base case. This sensitivity test suggests that the outcomes are fairly robust. Obviously, various other sensitivity tests, e.g., on the impact of changing lifestyles, could be carried out.)

Kram (1994b) is a detailed integrating response study in the bottom-up tradition. Here an overall assessment was made on the basis of long-term bottom-up country models (MARKAL) for nine Western countries, which integrate more than 70 technologies (including more than 30 supply technologies and more than 40 end-use technologies). A range of targets for CO_2-emission reductions by 2020 was tested to determine the mix of energy technologies that would produce the reductions at the least total energy system cost. The results revealed considerable diversity in the optimal paths of the different countries in terms of the mix of energy technologies and the cost and amounts of reductions that could be achieved. This diversity resulted from the future energy needs of the various countries, as well as their existing energy systems, natural resources, technology options, and energy policies (especially with regard to hydroelectric and nuclear power).

Second, the study calculated the marginal costs of CO_2 reduction for the 1990-2020 period for several countries (Figure 7.3). 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, these results provide further justification for implementing options on a joint or cooperative basis.

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 for them are likely to be very context-specific.



Source: Kram (1994a).

Figure 7.3: Marginal costs of CO_2 emission reduction.

7.7. 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 and some 80-85% of cumulative historical carbon emissions (Fujii, 1990). Clearly, such numbers require the industrialized countries to assume their historic responsibility, which has been translated into the concept of "common but differentiated responsibilities" mentioned in Article 3.1 of the FCCC. This has also been elaborated in Principle 7 of the Rio Declaration, which states: "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 envi-

Table 7.14. *Comparison of the 1990 development and energy situations in the main (sub-)regions*

Region	Tr (%)	Fossil Fuels (%) Co	Oi	NG	ΣF	Al (%)	Σ Ener (Mtoe)	Popul (million)	GNP (billion US$)	GNP ($ per capita)	Toe per capita	Toe per thousand US$
West	1	22	41	19	82	16	4296	849	14840	17473	5.06	0.29
North America	2	22	38	24	83	15	2289	276	5738	20809	8.30	0.40
Western Europe	1	22	43	16	80	19	1456	430	5901	13726	3.39	0.25
JANZ	1	21	51	12	84	16	551	144	3202	22279	3.83	0.17
East	1	25	29	36	91	8	1745	414	3047	7367	4.22	0.57
Eastern Europe	1	46	25	19	90	9	352	125	388	3101	2.81	0.91
ex-USSR	1	20	31	40	91	8	1393	289	2660	9215	4.83	0.52
North	1	23	38	24	85	14	6040	1263	17888	14163	4.78	0.34
Africa	37	21	27	9	57	6	360	642	385	600	0.56	0.93
North and South Africa	5	na	na	na	92	3	154	150	227	1507	1.02	0.68
sub-Sahara	61	na	na	na	30	9	206	492	158	322	0.42	1.30
Asia	15	49	25	4	78	7	1475	2810	1237	440	0.53	1.19
China	6	72	15	2	89	5	718	1139	393	345	0.63	1.83
India	25	41	23	4	68	7	253	853	287	337	0.30	0.88
Other	23	19	39	8	66	11	504	817	557	681	0.62	0.90
Latin America	15	4	45	14	63	22	556	448	842	1880	1.24	0.66
Brazil	30	5	34	2	41	29	185	150	375	2495	1.23	0.49
Mexico	5	5	49	22	75	20	142	89	170	1920	1.60	0.83
Other	9	4	51	20	74	17	228	209	297	1421	1.09	0.77
Middle East	1	1	64	32	98	1	233	129	370	2860	1.81	0.63
South	17	31	33	10	74	10	2624	4029	2835	704	0.65	0.93
World	6	25	36	20	81	13	8664	5292	20723	3916	1.64	0.42

Note: Tr = traditional (woodfuel, crop residues, and animal dung); Co = coal; Oi = Oil; NG = natural gas; ΣF = total fossils; Al = alternatives (nuclear, hydro, wind, geothermal, etc) (all % of total energy); ΣEner = total energy; (M)toe = (million) tons of oil equivalent; popul = population; GNP = gross national product in 1989; na = not available. Western Europe = OECD Europe (includes Turkey); Eastern Europe = non-OECD Europe (includes Cyprus, Gibraltar, and Malta); JANZ = Japan, Australia, and New Zealand.
Source: Ettinger (1994), based on *BP Statistical Review 1992* and *World Resources 1992-93.*

ronment and of the technologies and financial resources they command."

Table 7.14 compares economic development and energy use in the main regions of the world as of 1990. This comparison highlights the following striking differences between and within regions and may serve to clarify why the involvement of the developing countries in greenhouse policy formulation and implementation is imperative:

- GNP per capita varies from an average of $440 for Asia to $17,473 for the West, a ratio of 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 (a ratio of 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 traditional fuels account for 5% of energy use for all Africa 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 all 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 all Africa and 9% for sub-Saharan Africa.
- The share of the main energy source as a percentage of total energy use varies from 36% for the East (natural gas) to 64% for the Middle East (oil). For Africa the main source is traditional fuels, for Asia coal, and for the West and Latin America oil.
- In terms of energy use per capita, the regions vary from 0.53 tonnes of oil equivalent (toe) for Asia to 5.06 toe for the West, or by a ratio of 1:10. Between Western subregions it still varies from 3.39 for Western Europe to 8.30 toe for Northern America.
- 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 is an unreliable yardstick for comparisons between regions, especially between developed and developing countries, because of differences between nominal GNP and real GDP in purchas-

ing 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 developing countries would become 0.35 but that of the developed countries would remain 0.34. However, this would still ignore the relatively higher energy content of the developing countries' imports and the lower energy contents of its exports. If these two factors are taken into account, energy intensity in the developing countries would be higher than that in toe/$1000 PPP but probably lower than that in nominal terms (Ettinger, 1994).

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 Alcamo *et al.* (1995), the mean world annual growth rate of CO_2 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, according to one of the scenarios in that study, ECS 92 (dynamics as usual), the share of developing countries in global CO_2 emissions is projected to reach 46% by 2020 (as compared to 34% for the OECD and 20% for countries in transition). However, according to the various World Energy Council (WEC) scenarios, the developing countries' share in 2020 would be over 60%. In any case, it seems most likely that the developing countries as a group will start to become the major CO_2 emitters within a few decades. This picture is reinforced if the emissions of CH_4 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 one example, does not guarantee their adoption on a large scale. There may need to be a 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 coupled with freedom from distortionary policies can effectively transform energy use markets so that large energy savings and emission reductions are achieved along with net economic savings (Geller and Nadel, 1994).

The literature on the adoption and diffusion of technology clearly indicates that while profitability is probably the most straightforward determinant of the adoption of a new idea, a new technology, or new equipment, various other factors may also be important. A review of recent research into the diffusion of energy technologies in developing countries shows that there are many financial, institutional, and other factors that influence the successful adoption of these technologies (Barnett, 1990; Ghai, 1994). In Africa, for example, social resistance has impeded the diffusion of drought-tolerant crop varieties, and such resistance could also inhibit the adoption of new energy technologies. Often the initial awareness of benefits and new opportunities may be contingent on such factors as winning the support of women for more energy-efficient cooking stoves.

Moreover, one necessary ingredient for the adoption of new technology, namely a pool of local skills to draw on, may be lacking or 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 helped Indonesia, South Korea, and Thailand, for instance, make greater headway in the scope and coverage of their energy efficiency policies and programmes (Byrne *et al.,* 1991).

Endnotes

1. The "engineering efficiency" approach determines the financial costs and benefits of various options to an individual agency or other entity in terms of CO_2 emission reduction/absorption; in the "welfare economics" approach the broadly defined costs and benefits of options to society are determined. These two approaches will be further discussed in Section 7.3.

2. For an example of energy conservation, see, for example, Rubin *et al.* (1992). Here 25% of employer-provided parking places are eliminated and the remainder taxed to reduce solo commuting by 15-20% in the U.S. Net costs are estimated to be -$22/tC (a negative cost is the same as a saving).

3. It may seem that, although the above categories are conceptually distinct, in real life they 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 used for energy purposes. These measures seem to fall into both category 3 (renewable energy) and category 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 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, thereby avoiding the alternative use of fossil fuels. In the following, (1) and (2) are discussed in Section 7.4.6 (forestry options), whereas (3) belongs to the renewable/biomass category. With respect to (3), it should be borne in mind that sometimes a significant amount of additional energy may be required to turn the biomass into energy. This is, for instance, the case for the production of ethanol from corn, where additional energy requirements are of the order of the energy content of the produced ethanol itself (Swisher *et al.,* 1993).

Another example would be to classify an Integrated Gasification Combined Cycle (IGCC) or the hydrocarb process in both category 1 (energy saving and efficiency) and category 3 (clean fossil technologies). In the present chapter, both are considered primarily clean technologies and both change the energy conversion process to the extent of violating 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, 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. In the case of Poland, Sitnicki *et al.* (1990) suggest that baseline emissions of 260 Mt could be reduced to 117 Mt by 2030; for the former USSR, Makarov and Bashmakov (1990) suggest that a reduction of 40% would be feasible.

5. For a more detailed discussion of top-down versus bottom-up modelling, see Chapters 8 and 9.

6. The WEC distinguishes four scenarios for the energy mix in 2020: Scenario A assumes high annual world economic growth (especially 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 taken from Rogner *et al.* (1993) is used 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 are 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 to 10 TWyr in 1990, whereas identified fossil energy reserves are estimated at 1,280 TWyr (Rogner *et al.* 1993). Obviously, the use of an aggregate figure for fossil fuels (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, 45 years for oil, and 235 years for coal.

9. IPCC carbon emission rates are 15.3, 20.0, and 25.8 kg of carbon per GJ for natural gas, crude oil, and (bituminous) coal respectively (IPCC, 1995).

10. This is because transport and combustion technologies are roughly the same for natural gas and hydrogen (H_2).

11. Assuming a 100-year time horizon. For the various ways the GWP measure for methane could be calculated, see, for example, Reilly and Richards (1993).

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

13. $BEP = A/[(MER \times GWP) + A]$, with BEP = break-even point, $A = (25.8-15.3) \times 3.67$, MER = mass:energy ratio for methane = 22 Tg CH_4/EJ, GWP = global warming potential index of methane = 24.5. The term A is the additional mass of carbon dioxide released by coal compared to methane per GJ of energy and is composed of the difference between the carbon emission rates of coal and methane (25.8 and 15.3 kgC/GJ respectively; see note 9) times the mass ratio of CO_2:C (3.67). The calculation assumes a zero leakage rate of methane in coal production.

14. See, for example, Jackson (1991) for an analysis of cost-effectiveness in the UK, explicitly incorporating CH_4 leakage.

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

16. See, for example, IPCC (1991), Johansson *et al.* (1993), WEC Commission (1993), or WEC (1994). With respect to the classification of renewables, it should be noted that the classification of 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 into 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, a 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 exists, 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 describe the concept of "practicable," i.e., realizable, potential. The most common categorizations are physical, technical, and economic, in that order, with each ensuing category being a subset of the earlier mentioned one. The physical potential would denote the maximum potential that is constrained by geological, geophysical, 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 economic constraints (such as a prohibitive level of costs, institutional constraints in the energy markets, etc.) would pass for economic 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 would now be defined as somewhere between technical and economic 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. For example, wind energy costs depend heavily on wind speed and solar energy costs on solar irradiance, features that are not equally favourable for all locations, seasons, or times of day.

20. It is not possible to derive cost developments for individual subclasses of technologies from the listed figures, as they are aggregated into ranges of similar technologies. The same holds for disparities stemming from differences among sites. It should be realized that these limitations significantly hamper direct comparison. However, greater detail was avoided for the purpose of clarity.

21. Estimates are 21.3-29.6% in 2020 (WEC, 1993), 15% (6% of which comes from hydro) in 2020 (Grübler *et al.,* 1993a), and close to 43% in 2025 (Johansson *et al.,* 1993). According to Grübler *et al.* (1993a) 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 (Grübler *et al.* 1993a). In the past the mean interval for replacing most technological systems has been about 30 to 40 years.

22. For an extensive discussion of the nuclear option, see Volume 2 of this report.

23. Relatively minor fossil fuel inputs are used to support the overall functioning of breeder reactors.

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, CO_2 and H_2 are obtained. The former can be extracted by absorption at a 98% rate and the latter can be used either 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 involves changing the oxidant from air to pure oxygen. The gas turbine of an ICGCC or a STIG (steam-injected gas turbine) can be modified by changing the combustion medium into an O_2/CO_2 medium.

27. Cost information suggests that absorption and oxyfuel combustion are the 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 pulverized coal-fired installations.

28. In enhanced oil recovery, part of the injected CO_2 reenters the atmosphere, and in food packaging CO_2 is released within days or weeks. Obviously, insofar as CO_2 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 the food, chemical manufacturing, metal processing, and oil industries. Enhanced oil recovery, in which carbon dioxide is pumped into the production well to increase recovery rates, has the highest potential.

30. The combined potential of the other applications is limited to several hundreds of MtC per year. Storage capacity of the ocean is very uncertain, as it already contains nearly 40,000 GtC as (dissolved) CO_2 (compared with some 750 GtC in the atmosphere). Moreover, most of the injected carbon will come out after fifty to several hundreds of years, depending on the depth and method of injection. There may also be objections to ocean storage because of potential environmental impacts from the methods used.

31. Here, forestry measures are distinguished from the use of biomass as a renewable energy resource. Forests, like 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. Net carbon emissions are reduced *only if* the forest or biomass energy substitutes for fossil energy.

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

33. See Volume 2, Chapter 24, Management of Forests for Greenhouse Gas Emissions, 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.

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

35. 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 any more; in other words, the incremental uptake is nil. Annual uptake is usually described by one figure only, this being an average annual uptake rate. However, for plantations 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).

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

37. For an overview of the costs of greenhouse damages, see also Chapter 6 of this report.

38. Note that the distinction between bottom-up and top-down modelling employed here does not coincide with a similar distinction elsewhere in the literature, where top-down approaches are associated with macroeconomic modelling techniques assuming fixed behaviourial patterns, and bottom-up approaches with identifying the (technical) opportunities presented by a changeable world.

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